Modelling of the MGR Wave Energy Converter

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Abstract

The paper concerns the development of a non-linear model of the MGR. The linear wave theory has been modified, simplifying the wave input form (sinusoidal) and disregarding the radiation component of the hydrostatic force. The storage stage of accumulators has not been taken into account.

The MGR is a near shore submerged converter that takes advantage of the oscillating water column created by the wave when it passes on the converter's platform. The wave column moves the platform, transmitting the force to a single acting cylinder, that pumps sea water to the coast, where is turbined generating electricity.

The model has been made using the MatLab's Simulink module. The aim of the model is to asses the working principle, validating the variable system pressure control strategy. The results have been as expected with small waves, overlapping cycles as wave size increases.

Keywords: Wave energy, simulation, modelling, near shore device, resonance with waves

Nomenclature

Re = dimensionless number
P = variable
x, y = Cartesian co-ordinate system
P_accu, P_A = Optimal system´s pressure (Pa)
Pc = pressure in the cylinder (Pa)
P_D, d = Depth of the admission filter (m)
Hw = Half significant wave height (m)
Hwave = Momentary wave amplitude (m)
T = wave period (s)
d = depth (5 m)
g = gravity (9,8 m/s^2)
ρ = density (1025 kg/m^3)
b = platform´s width (5,5 m)
Δx = platform´s displacement (0,22 m)
Dc = cylinder's diameter (0,5m)
c = cylinder's stroke (0,55 m)
Q = Flow (m^3/s)
n = converter units
hf = pressure drop (m)
Δz (delta_z) = height between the WEC and turbine (22 m)
f = pipe friction coefficient (0,015)
Lp = pipe length (150m)
Dp = pipe diameter (0,175m)
Cv = components pass coefficient (7,5)
hf = pressure drop in the circuit (m)
hj = pressure at the turbine jet nozzle (m)
Q = flow (m^3/s)
u = optimal lineal speed of the turbine (m/s)
v_J = speed on the jet (m/s)
v_p = water speed in the pipe (m/s)
v_{piston} (= 2,5 $\dot{x}$) = velocity of the piston (m/s)
Tq = generator´s load torque, setpoint (Nm)
P = power (kW)
η = efficiency (0,634)
r = turbine's radius (m)
t = time (s) (frequency ω = 2π/T)
A_P = Platform area (22 m^2)
Ac = area of the piston (0,2 m^2)
x1 = spring initial displacement (0,44 m), permanent
x = platform displacement (m)
K = spring rate (10^6 N/m)
F_down = force needed to pump (N)
F_up = suction force on admission (N)
Fwave = Wave column force on platform (N)
Fspring = Spring force (N)
Wp = Platform's weight (N)
M = Platform mass (220 kg)

1 Introduction

The model is part of an initial design approach of a new concept of Wave Energy Converter (WEC), the MGR. The proposed WEC is a small-medium power facility that uses well-known and reliable technologies, as Pelton turbine, synchronous generator and hydraulic components.

The MGR is based on 'Up and down' working principle, and can be classified as 'second generation' WEC, 'near shore' device [1]. The converter is placed underwater (7 – 8m depth), 50 – 100m offshore. Its working principle bases on the oscillating water column created by the wave when passes over the submerged platform. The platform pushes a single-act cylinder that pumps high pressure sea water to the coast through a pipe. To assure constant flow and damp wave period irregularities, accumulators are used calibrated at different pressures. This high pressure water impulses the turbine generating electricity. The nominal power output can be fit connecting different modules in parallel placed in linear array.

The working principle, submerged and profiting oscillating water column, is similar to AWS and CETO I. The innovation is the use of springs working in vacuum to recover the original position, the constant platform´s displacement, and the variable working pressure. Instead massive energy production big power facilities, the MGR is thought for stand alone settlements, or connected to the grid.

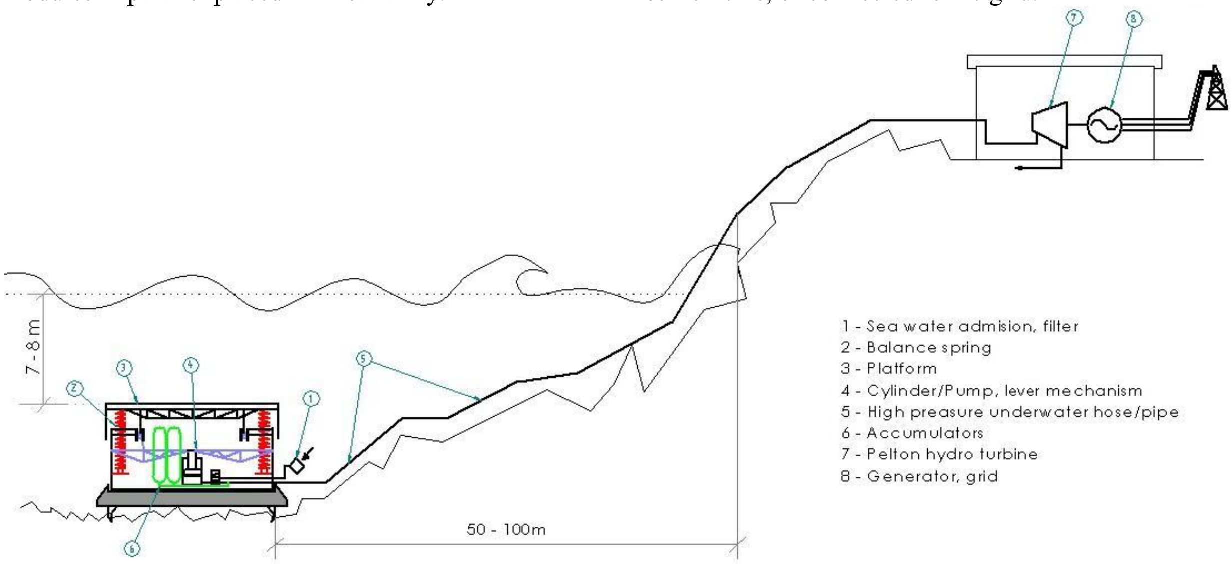

Figure 1: Proposed WEC diagram

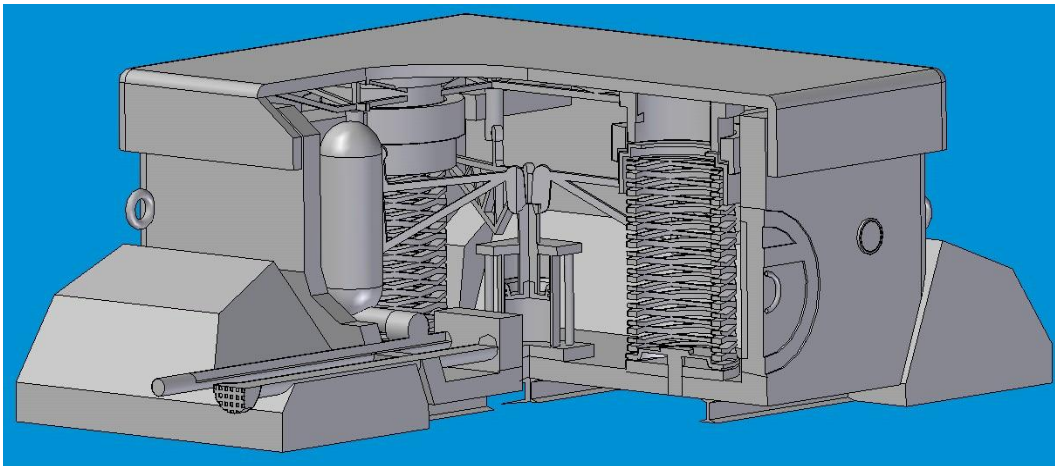

Figure 2: 3D CAD model of one MGR module

Fig. 2 describes a MGR module in 3D made by a CAD system (Solid Edge). The module is cut, showing the distribution of the components in the interior. Among others there can be clearly identified, the container covered by the platform and the sluice, and the prismatic moorings in both sides of the container. The container is detachable from the moorings. Inside the container there are located the springs, the cylinder, the four lever mechanisms, the accumulators and the admission and sending pipes.

2 Control strategy

In the dynamic behaviour of the platform two motions are distinguished,

- low frequency motion due to changes in tide, or atmospheric pressure: slow dynamics;
- high frequency motion due to the sea waves: fast dynamics

The control strategy takes on both motions, acting in the working pressure and generator's load control. The energy absorbed by the WEC is maximum when platform's movement is tuned to the incident wave frequency [2]. Resonance is then said to occur. Instead working with variable displacement (as AWS), the MGR works with variable system pressure. The PLC control the facility acting on the following features,

- system pressure: the cylinder must create the appropriate resistance to match the coming wave size. System pressure varies acting on turbine jet overture, controlling its needle position, according to the wave size signal sent by a measuring buoy

- generator's load torque: the output power is estimated according to the working pressure and the flow. The synchronous generator load torque signal is set according to the estimated power and turbine's optimal rotation speed (that depends only on system's pressure)

In other words, the measuring buoy's wave size data (H, T) is used to foresee the optimal system pressure. If the pressure is bigger than the adequate, the piston cannot reach to cylinder bottom, and if it is smaller, not all the available wave energy is absorbed. On the other hand, to get the maximum efficiency, the turbine must work in its optimal rotation speed, that relates the pressure and generator's load.

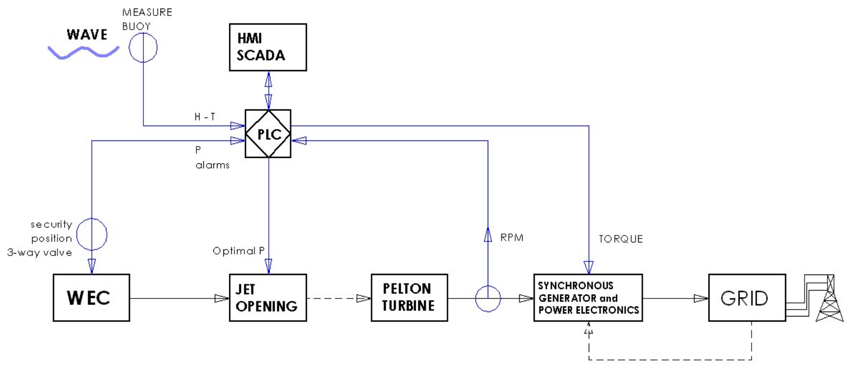

Figure 3: Control schema of the system

3 Platform's dynamics

The platform´s dynamic sub-model is the most significant part of the model, the one that validates the hypothesis taken when designing the WEC. The forces that act on the platform are different in the up and down movements, therefore the system has a clear non-linear behaviour upon the time. The cylinder only pumps sea water going down (single-act), as it is filled when it goes up overcoming the filter´s pressure drop. The effect of the inertial forces of the lever and cylinder can be disregarded simplifying the equation system. These forces are negligible comparing with the magnitude of wave and spring forces. The forces' diagram is shown in Fig. 4.

DOWN

$$F\_wave + Wp - F\_spring - F\_cyl\_down = m\ddot{x} \quad (1)$$

UP

$$F\_wave + Wp - F\_spring + F\_cyl\_up = m\ddot{x} \quad (2)$$

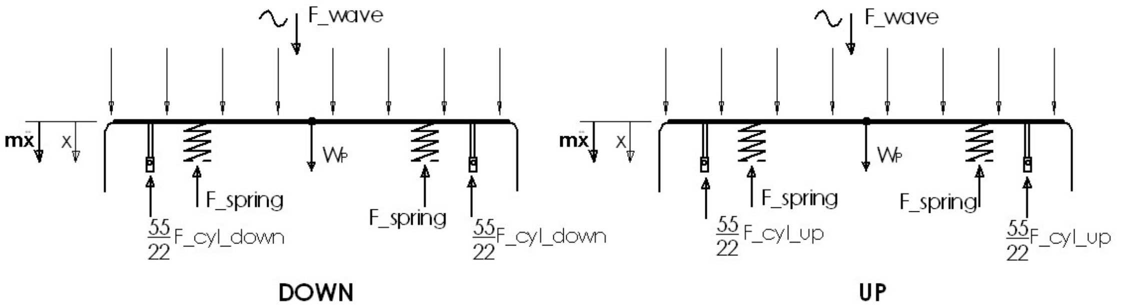

Figure 4: Forces acting on the platform, DOWN movement on the left and UP on the right

3 The model

The model has been made using MatLab's Simulink module. Simulink is an environment for multi-domain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems. Instead of numerical analysis that offers programs like MathLab or Mathematica, Simulink defines dynamical systems relating graphical blocks, that provides more intuitive overview of the model. There are programs with similar characteristics, but Simulink is the most used platform.

There are two models integrated in one: the 'Wave-To-Wire' global model and platform´s dynamic sub-model [3], which actually represents the energy transfer from waves to accumulators. The input is common in both: the wave size (H, T) and the depth (d, tide). In the 'Wave-To-Wire' model the output is the generator´s load torque used and turbine´s optimal rotation speed. The load torque is used as setpoint by the PLC to control the synchronous generator. This data leads generator's output estimation (not included in the model). On the other hand, platform sub-model describes platform's displacement ('x' position, 'v' speed, 'a' acceleration) as output. The following suppositions have been taken when defining the model,

- input waves are sinusoidal

- the energy transmission from the wave to high pressure sea water is given by the integration of the external water pressure on the platform
- accumulators filling cycle has been disregarded, supposing constant pressure in the circuit (provided by the accumulators)
- system pressure is optimal all the time
- there is no system pressure limit
- the generator has not been modelled, only its setpoint (torque) and the generated power
- inertial forces of the lever mechanism and cylinder piston have been disregarded
- four submerged modules connected in parallel

The model created with Simulink has followed the schema showed in Fig. 5. Each equation is represented by one bloc in the model.

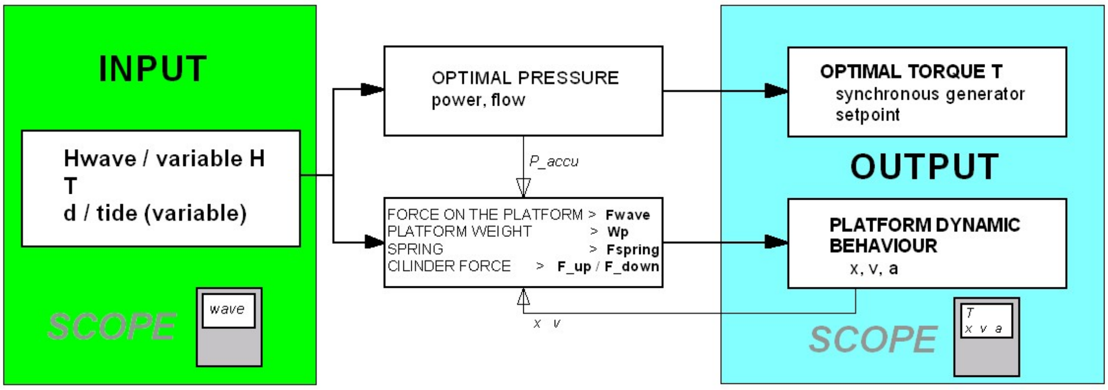

Figure 5: Strategy flow chart followed designing the model

3.1 Input parameters

As explain before, the input wave profile has been simplified to a sinusoidal wave train, defined by the amplitude Hw and the period T. The depth can be consider constant or sinusoidal, to take on the effect of the tides.

- Wave size →Amplitude Hw (m) →Scope_wave
  →Period T (s)
- Depth →d (m) constant or d +/- t (tidal, sinusoidal)

3.2 Output

The two branches of the model bring different outputs that show the behaviour of the converter under the imposed control settings. The 'Wave-To-Wire' model provides the generator´s load torque used; and platform sub-model describes platform's fixed displacement according to the optimal working pressure.

- Generator's load →Tq (Nm, torque) → Scope_Tq
- Platform's dynamic behaviour
  - x (m, displacement, 0–0,22m) → Scope_x
  - v (m/s, velocity) → Scope_v
  - a (m/s^2, acceleration) → Scope_a

3.3 Blocks: Wave-to-Wire model

This branch uses the following formulas to estimate the output for a given wave input,

- Optimal working pressure, P_accu (Pa): this is the main supposition to be proven in the MGR design. It is derived from the energy balance applied between the wave and the cylinder. This block is used in both models (Wave-To-Wire and Platform´s dynamics sub-model)

$$P\_accu = \left(\frac{T^2 Hw^2 g^2 b \rho}{16 \pi} - K \Delta x \right) \frac{2}{\pi Dc^2 c} \quad (3)$$

- Flow, Q (m^3/s): the single act cylinder only pumps once per period. Supposing complete displacement the flow is defined by cylinder's volume over the period

$$Q = n \frac{\pi Dc^2 c}{T} \quad (4)$$

- P_drop, Pressure drop, hf (m): the MGR is a hydraulic circuit indeed. The pressure drop in jet of the turbine is the sum of the height difference between n the cylinder and the jet, and the drop created in the components and the pipe (proportional to the speed square)

$$hf = \Delta z + \left(f \cdot \frac{Lp}{Dp} + Cv \right) \cdot \frac{v_P^2}{2g} \quad (5)$$

- Opt_u, optimal jet speed, u (m/s): the optimal jet speed depends only on working pressure, and is used to set the generator´s load maximising the efficiency

$$u = \frac{v_J}{2} = \frac{\sqrt{2gh_J}}{2} = \frac{\sqrt{2g\left(P_{accu}/10^4 - hf\right)}}{2} \quad (6)$$

- P, estimated power output (W): the generated power can be foresee in function of the working pressure and flow

$$P = \eta \rho g Q \left(P_{accu}/10^4 - hf \right) \quad (7)$$

- Torque, T (Nm): the synchronous generator uses the load torque as setpoint, that can be determined with the estimated power and the optimal rotation speed

$$T = \frac{P}{\omega} = \frac{P\,r}{u} \quad (8)$$

3.4 Blocks: Platform´s dynamic behaviour

The platform's dynamics sub-model determines the platform´s behaviour for a given wave input [2],[4],[5].

Its displacement range is fixed, and this is achieved with an adequate variable working pressure algorithm (see Formula (3)). As defined in Formulas (1) and (2), the forces applied on the platform are different in the up and down movements. The forces that act on the platform are,

- Force due to external water pressure
- Platform weight
- Force due to the single-act cylinder
- Force due to the springs

Each force is described in the following points, forming independent blocks in the Simulink model.

- Force due to external water pressure
  The vertical force F_wave on the floater surface is given by the integration of the external water pressure (p_e) over the surface of the floater [2], [6],

$$F_{wave}(t) = -\iint_{S_p} p_e(t) n_z dS \quad (9)$$

Instead using the linear theory of wave-body interaction, some terms have been neglected and others simplified: the velocity potential term Φ has been substituted by a sinusoidal wave train input; the hydrostatic pressure only includes the depth and the tidal effect; and finally the hydrodynamic pressure neglects the radiation term, acting only the diffraction forces. The considerations are acceptable due to the model only aims to assess the working principle. The external water pressure is determined using the Bernoulli equation and neglecting the second order terms, and it is defined as the water column defined by a sinusoidal function summed to the depth (variable or constant)

$$Hwave = Hw \sin\left(2\frac{\pi}{T}t\right) \quad (10)$$

$$Fwave = A_P \cdot g \cdot \rho \cdot (Hwave + d) \quad (11)$$

- Platform weight, Wp (N)

$$Wp = M \cdot g \quad (12)$$

- Force due to the springs, Fspring (N) : it depends linearly on the spring constant *K* and its displacement (the initial *x1* due to the depth and the variable therm *x* due to platform´s displacement)

$$Fspring = (x1 + x) \cdot K \quad (13)$$

- Force due to the single-act cylinder
  This term varies when going down (pumping) and up (filling). It is obtained taking into account the hydrodynamic viscous drag, applying Bernoulli's equation between the admission filter, the cylinder and the accumulators (see Fig. 6)

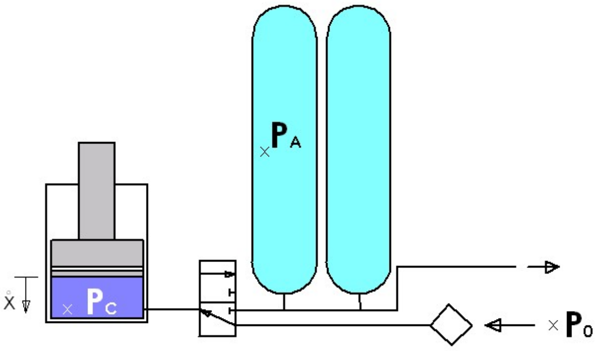

Figure 6: Bernoulli energy balance between the cylinder (Pc) and accumulator (P_A = P_accu) or seabed (Po)

Cylinder force pumping, F_down (–, N)

$$\frac{P_c}{10^4 g\rho} + \frac{v_{piston}^2}{2g} = \frac{P_A}{10^4 g\rho}$$

$$P_C = P_A - 10^4 \rho \frac{v_{piston}^2}{2}$$

$$F_{down} = 2{,}5\ P_c A_c = 2{,}5\, A_c\left(P_A - 10^4 \frac{\rho}{2} v_{PISTON}^2\right) \quad (14)$$

Cylinder force admission, cyl_up, F_up (+, N)

$$\frac{P_O}{g\rho} = \frac{P_C}{10^4 g\rho} + \frac{v_{piston}^2}{2g}$$

$$P_C = 10^4 P_O - 10^4 \rho \frac{v_{piston}^2}{2}$$

$$F_{up} = 2{,}5\ P_c A_c = 2{,}5\, A_c\left(P_O - 10^4 \frac{\rho}{2} v_{PISTON}^2\right) \quad (15)$$

Fig. 7 shows the Simulink model for the proposed new WEC design.

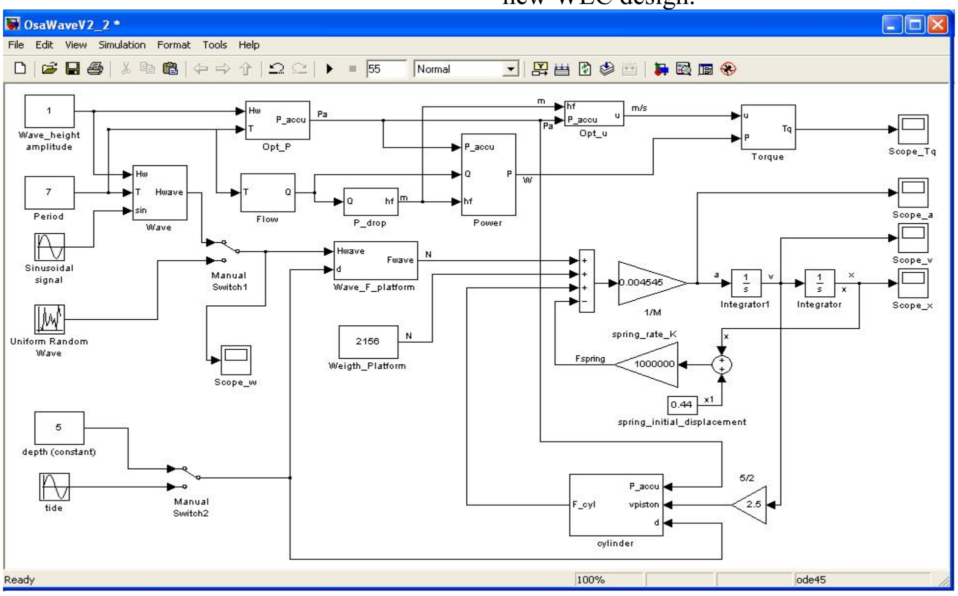

Figure 7: Simulink model, the upper branch forms the 'Wire-To-Model' global model, while the bottom the platform sub-model

4. Simulation results

The simulations have given the expected results for small waves, but the cycles overlap if certain wave height is exceeded. Results are discussed in the following sections.

4.1 Platform movement

Its displacement solution is known a priori: the platform is constrained to move 0.22m only. The speed profile is unknown but it is known that there is a clear direction change because the up and down forces are different, so its sign changes twice per cycle. Similar behaviour is expected for the acceleration.

4.1.1 Minimum design wave size

In this first case, the simulation is made with the minimum design wave size: 2m height and 7s period (the incoming wave profile Fig. 8a), obtaining the output platform movement in Fig. 8b, 8c and 8d, being the simulation time 33s.

Knowing that the positive direction is when the platform goes down, from these figure the following conclusions are derived:

- platform position 'x' is constrained between 0 and 0,22m, as defined in converter's energy balance
- position graph profile (x) starts increasing its value (positive sign means going down for the platform) and reaches the inflexion point delayed comparing the wave peak, similar delay appears when going down, with a decreasing wave
- position graph profile (x) has different shape that differs the platform down and up movement, with concave and convex profiles; this difference makes sense because the cylinder force changes, even its sign
- the speed graph (v), starts from a given value and decreases until zero, where opposite sign symmetric decreasing curve begins; this profile represents a progressive decrease of velocity and direction change in platform's movement
- in Figure 8d, the acceleration seems a pulse function in both directions at each peak of displacement function, that coincides with speed sudden change.
- Figures 9a and 9b are enlargements of Figure 8d. They show that the 10^4m/s^2 pulse function (Fig. 9a) is not zero in between, it oscillates positively or negatively according to platform direction, tending to zero, starting again with a pulse in the opposite direction. The pulse is supposed to be created by the switch that selects the cylinder force

In conclusion, these simulation results have been the expected, fulfilling all the characteristics defined in the design: the displacement is constrained in design limits (0 – 0,22m); different curve going down and up delayed respecting the wave; expected speed change in both directions, as behaves the acceleration. The bidirectional pulse function that describes the acceleration may be caused by the switch that selects the cylinder force.

4.1.2 Influence of wave height

The behaviour of the model under small waves has been proved with a 1,6m height, maintaining the period in 7s. The displacement graph resulted on the trial is presented in Figure 10.

The converter maintains its oscillating behaviour but it does not make the complete displacement: the movement range decreases from 0–0.22m to 0,04–0,17m. The wave has not enough energy to move the whole stroke down, pumping less flow than expected.

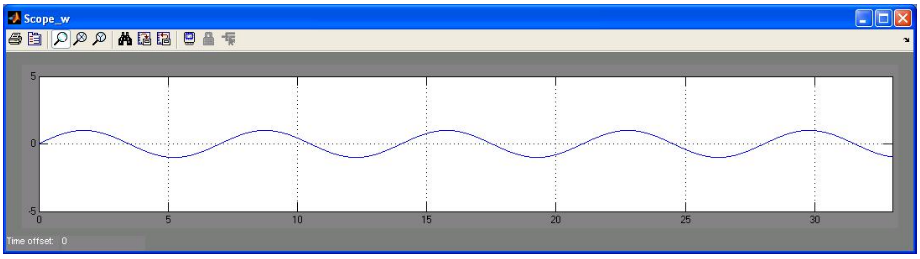

Figure 8a: Incoming sinusoidal wave profile (m)

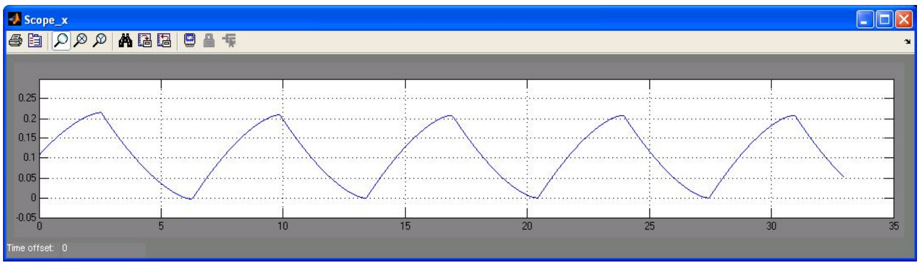

Figure 8b: 'x' platform displacement (m)

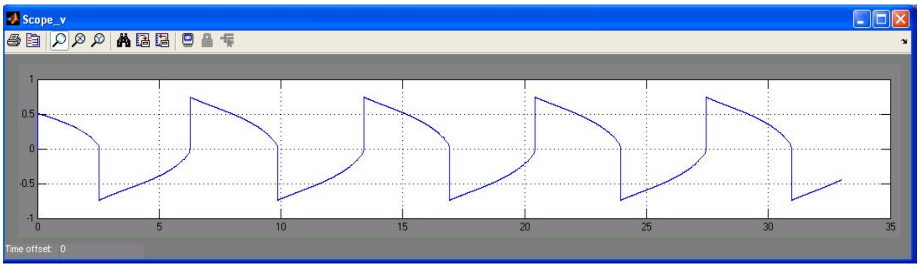

Figure 8c: 'v' platform speed (m/s)

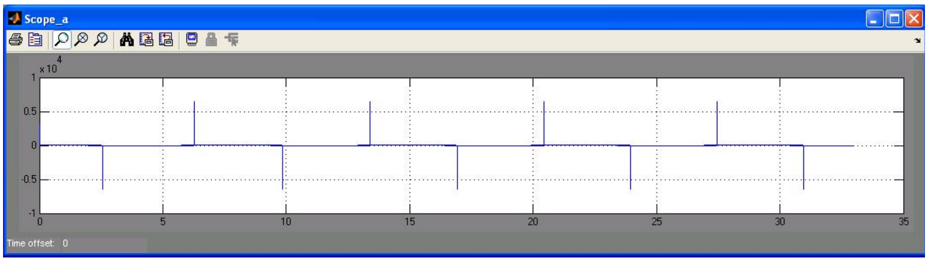

Figure 8d: 'a' platform acceleration (m/s^2)

Figures 8a, 8b, 8c and 8d: Simulink flows in the time domain (abscissas) for 2m height and 7s period wave; simulation duration 33s

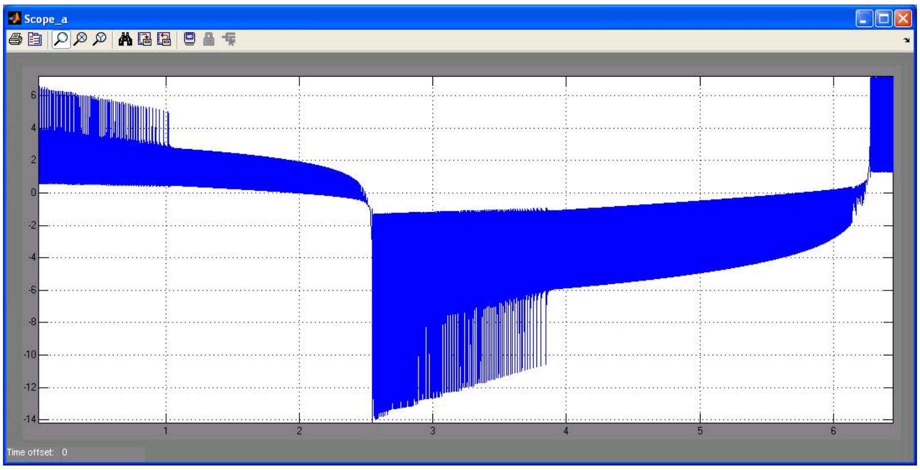

Figure 9a

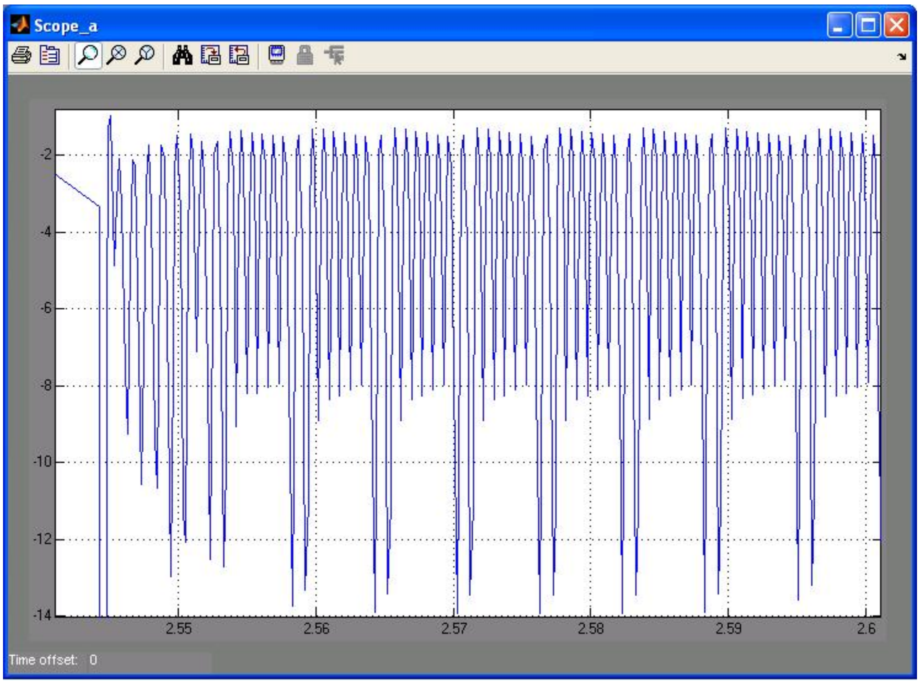

Figure 9b

Figures 9a and 9b: Zoom of acceleration graph (Fig. 8d): from 0 to 6,5s and 2,5 to 2,6s respectively. The 'Y' axis has been enlarged too (m)

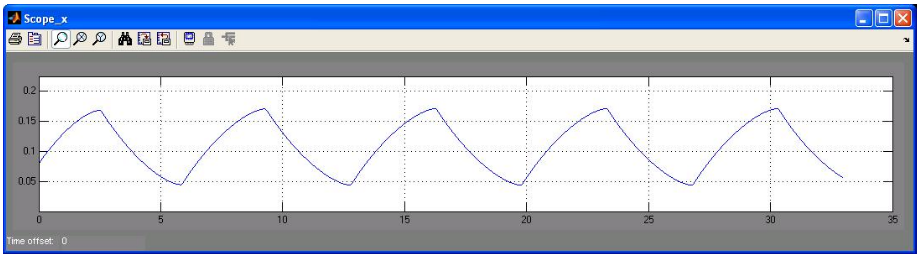

Figure 10: Displacement graph for 1,6m height – 7s period wave

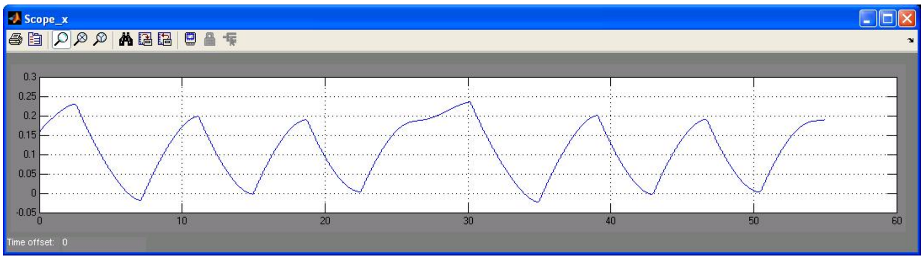

Figure 11: Displacement graph for 2,8m height – 7s period wave

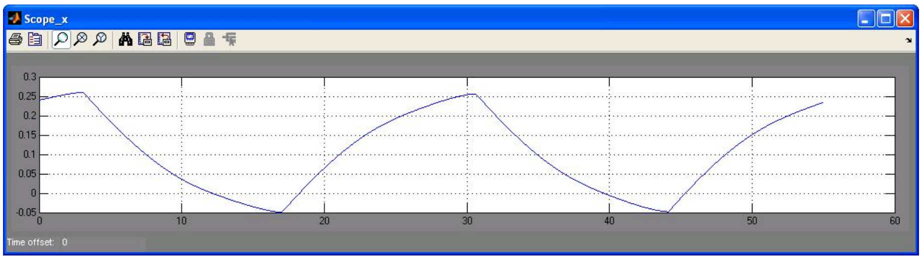

Figure 12: Displacement graph for 7m height – 7s period wave

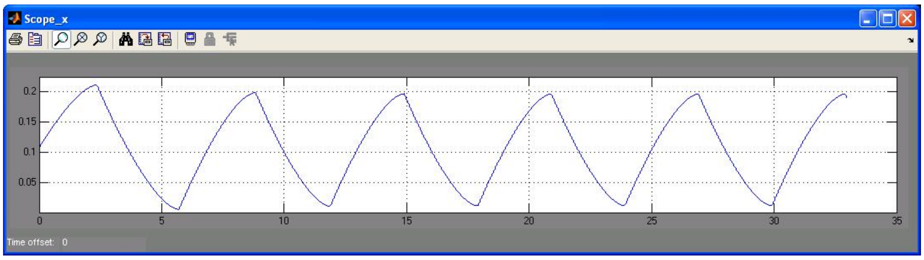

Figure 13: Displacement graph for 2m height – 6s period wave

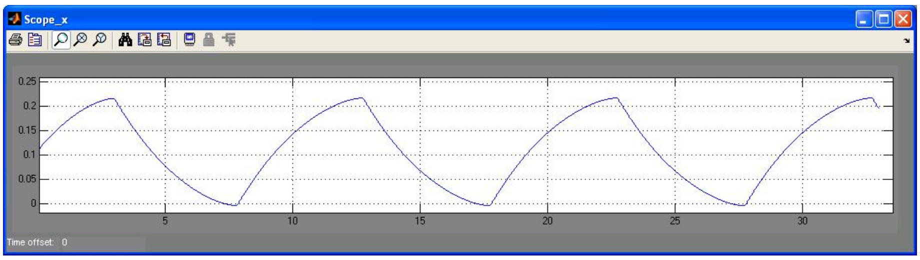

Figure 14: Displacement graph for 2m height – 10s period wave

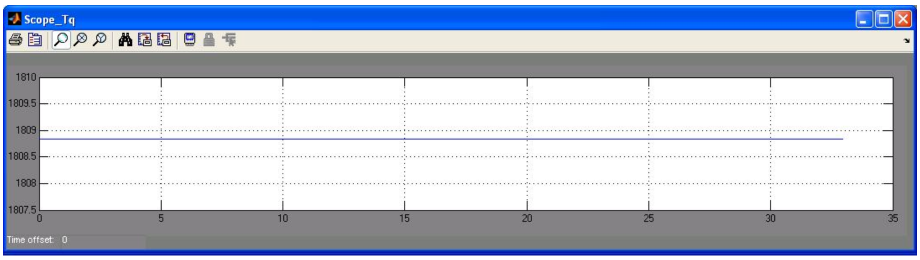

Figure 15: Torque graph for 2m height – 7s period wave

Increasing the wave height, the converter behave as described in Section 4.1.1, until 2,6m height. When the wave is 2,8m height, the displacement graph begins to present an unstable behaviour (see Fig. 11): after two valid cycles the third one joins the fourth one, getting again the stability. The overlapped peak surpasses the displacement limit too.

As the simulated wave is larger this effect generalises, overlapping two cycles in one and exceeding the displacement range (for example in Fig. 12 from 0/0,22m to -0,05/0,27m and double period 14s). Different period brings similar results for same wave size.

This instability stage may be produced by numerical rounding error, or optimal pressure simplified calculus. This effect has been the only unexpected and opposing solution found in the model.

When designing the converter the minimum wave has been set as 2m height and 7s period. The displacement graph for 2m height and 6s period wave is shown in Fig. 13.

The graph shows that the movement does not reach displacement range limits (only the first peak), even the platform oscillates correctly. The model confirms that the minimum design wave is 2m height and 7s period wave, and the design hypothesis taken are right. Waves from 2,2m with 6s period obtain correct graph profiles.

4.1.3 Period influence

The model gives logical solutions respecting the period: longer period waves have longer cycles (that coincide with the period) but the displacement maintains inside working range. As example, Fig. 14 shows the displacement graph obtained for 2m height and 10s period wave. But the overlapping effect described in Section 4.1.2, is repeated in the same manner as the wave height is increased.

4.2 Torque

If the input wave train is regular (as the sinusoidal used), the signal to be send to the generator is obviously constant too, and it depends only on wave size (H, T). Fig. 15 shows the torque output obtained when the input wave is 2m height and 7s size (see Fig. 8a).

Using a spreadsheet, the torque output can be calculated for each wave size (H, T) condition, because the equations are applied straight, without any feedback loop. The formulas applied are the same as in Simulink. Table 1 shows the results achieved with the spreadsheet.

T (s)	Hw (m) Wave Height									
	1	2	3	4	5	6	7	8	9	10
5	*198*	*1711*	2782	3805	4811	5808	*6801*	7790	8778	9765
6	*576*	*1794*	2834	3843	4841	*5833*	6822	7809	8795	9780
7	*710*	*1841*	2864	3865	*4858*	5846	6833	7818	8803	9786
8	*783*	1871	*2883*	*3880*	4870	5857	6843	7827	8811	9794
9	*830*	1891	2896	3889	4878	5864	6848	7832	8815	9798
10	*861*	***1905***	2905	3896	4883	5868	6852	7835	8818	9800
11	*883*	1916	2914	3904	4890	5875	6860	7843	8826	9809

Non working range

Table 1: Output torque value (Nm) depending on wave height and period, obtained with *MS Excel* spreadsheet

As resulted in the simulation, the spreadsheet gives 1841Nm torque for 2m height and 7s period wave. The spreadsheet, as Simulink model, does not take into account system pressure limit (400bar).

5. Discussion about simulation results

The presented model is clearly non linear, due the acting forces are different on the platform in the up- and down-movements. The results show that the model does not behave properly for all wave sizes. It seems that for big waves, the wave passes too fast and the system has not enough time to reach to the bottom, react and change its direction. Instead of that, two waves are overlapped pushing the platform once, exceeding slightly platform movement limits.

This overlap proves that the parameters of the algorithm are no valid if the wave exceeds a determined wave height. The algorithm has to be improved, or use variable parameters according to the incoming weight size to avoid the overlapping behaviour.

Other possible cause is that the pressure regulation is not modelled, in this case the Pelton turbine nozzle. It could be that the pressure variation made by the nozzle influences the converter performance, and it would be convenient to model.

Anyhow the model behaves as expected for small waves fulfilling expectations, being the displacement constrained in the movement range. That proves that the algorithm is valid, a least for small waves, and validates the working principle.

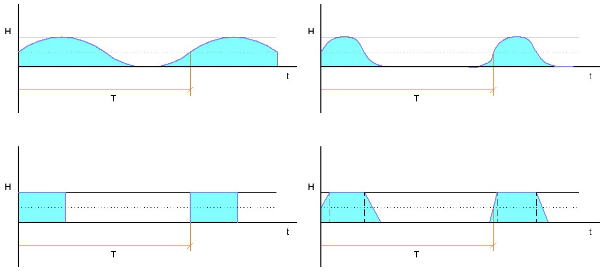

Figure 16: Different input wave profiles

Fig. 16 presents different input wave profiles [7]. The one used in simulations is the first one, sinusoidal. The second one approaches more to real near shore waves, taking into account the trough flattening in shallow waters. As the figure shows, the sinusoidal wave has the largest section (in blue), therefore the largest energy. The applied energy balance when designing the spring and cylinder has been also supposing sinusoidal waves. Further development on the WEC must use real wave profiles when designing the components. The two profiles of the bottom are proposed as approach to real waves, also easy to introduce as the input into the Simulink model.

Future improved model also should include accumulators storage cycle, to get more accurate and real behaviour description, using different wave profiles, even real random wave-trains, leading power optimisation by tuning the set of model parameters to the expected wave regime.

In addition to the storage cycle, the development of the model must comply the linear theory of wave-body interaction.

This study of the model had led a deeper knowledge of system behaviour and parameters optimization study.

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