Control Strategies for a simple Point-Absorber Connected to a Hydraulic Power Take-off

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Abstract

Among the various types of wave energy converters currently being developed, heaving point absorbers are one of the simplest and most promising concepts, possibly due to their ease of deployment and integration in larger arrays structures.

A typical efficient energy conversion system for point absorbers is based on hydraulic power take-off (PTO) systems, consisting in a double-acting cylinder and two or more accumulators, reserving fluid at different pressures and linked between them by a hydraulic motor connected to an electric generator. For the purpose of control and modulation of the power output the hydraulic circuit might include a certain number of valves that can set the pressure levels within the accumulators.

This paper presents a simple model of a heaving oscillating buoy, represented by a surface-piercing cylinder, extracting power by means of a hydraulic system. The hydrodynamic behaviour of the absorber is modelled through application of the linear water wave theory. Apart from the basic elements listed above, the model of the hydraulic system includes leakages and pressure losses and takes into account the compressibility of the fluid. Also possible extra accumulators are considered in order to improve the performance of the hydraulic system by means of properly controlled valves. The function of these extra accumulators consists in storing and releasing energy to the system when this is desirable for the improvement of the power output.

Simulations were carried out through a time-domain approach making use of the Cummins equation and considering regular monochromatic waves and irregular wave-trains.

The control of the system is managed by means of control valves whose opening will be depending on the sign of the velocity of the buoy and the pressure levels. Three possible aims were assumed for the control strategies investigated: maximisation of the average power output, stabilisation of the output (in terms of rotational velocity and/or electrical power) and stabilisation of the pressures inside the accumulators (also for survivability of the hydraulic equipment).

Different control variables are analysed depending on the wave inputs considered in order to improve the power extraction of the converter: Firstly the torque of the electric generator is considered as a primary way to modify the load of the PTO. Then extra accumulators are used as storing devices to perform a kind of phase control on the buoy. The benefit of this effect will be dependent on the instant of activation of the valves that connect them to the circuit and the influence of possible delays or anticipations will be investigated

The results prove that it is possible to achieve a great enhancement of the power extraction with the implementation of these control strategies and that a possible combination of some of them might be beneficial for a better efficiency of the components. Moreover the application of sophisticated strategies could imply a less demanding requirement for specific equipments; such as the case of the electrical generator

Keywords: Hydraulic PTO, phase control, point absorber, wave energy converter,

Nomenclature

$A(\omega)$	=	added mass of the floater
A_∞	=	added mass at infinite frequency
A_p	=	surface area of the piston
A_v	=	surface area of the valve
C_d	=	discharge coefficient of the valve
D_m	=	displacement of the motor
F_e	=	wave excitation force
F_r	=	wave radiation force

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

F_h = hydrostatic force
F_{ext} = external force
F_{PTO} = power take-off force
K = radiation impulse response function
g = gravity acceleration
J = inertia moment of the ensemble motor
x = position of the floater
$\dot{x}$ = velocity of the floater
$\ddot{x}$ = acceleration of the floater
m = mass of the floater
p = pressure within the accumulator
P_i = incident hydrodynamic power
P_h = hydraulic power
P_u = useful power
q_m = volume flow to the motor
ρ = water density
ρ_o = oil density
S = hydrostatic surface
t = time
(t) = time dependency
T_g = torque of the generator
V = volume of the accumulator
ω_m = angular velocity of the motor

Subscripts

a1 = first control accumulator
a2 = second control accumulator
b = high-pressure accumulator
c = low-pressure reservoir
d = cylinder upper chamber
e = cylinder lower chamber
0 = initial value
j = generic accumulator
1 = first section of the hydraulic circuit
2 = second section of the hydraulic circuit
control = section connecting the control accumulator

1 Introduction

Many Wave Energy Converter (WEC) concepts currently being developed are largely based, at least on a hydrodynamic basis, on the Point Absorber principle, introduced by Budal and Falnes ([1]) and extended by subsequent works of many others. The design and optimization of WECs, however, also includes the definition of proper PTO equipment and many other issues such as control devices, moorings and structural loads. A consistent effort is currently devoted to all of these aspects, requiring more and more realistic models in order to deal with these complexities and define suitable and profitable solutions.

Particularly the problem of the selection and control of an adequate PTO system has been covered by several researchers during the recent years with an extensive range of solutions proposed, some of which have proved to be quite effective. The definition of an energy extraction mechanism is clearly coupled with the elaboration and implementation of an efficient control strategy, whose theoretical advantage must be translated to practical and economical convenience.

Many different concepts for energy conversion have been proposed during the last decade for wave energy devices. In some cases these solutions include wholly novel machines, in some other they are simply based on conventional technology. It can be argued that the two most successful kinds of PTO concepts in wave energy are represented by electrical direct-drive energy conversion and hydraulic systems based on the pressurisation of a liquid flow. For heaving converters, such as the one we will be modelling, direct-drive extraction is usually achieved through linear generators (see [2] for an introductory review).

Hydraulic PTOs have been introduced and tested on many devices. A key example of their application can be seen in the Pelamis ([3]) but many other developers are seeking to adapt this concept to their own technology.

These systems offer the advantage to store large quantities of energy through the use of gas accumulators allowing in such way smoother power output. Moreover they can be assembled with standard commercial components and are suitable to control implementation. A general treatment of a case similar to the one shown in this paper has been proposed by Falcão ([4] and [5]) with an extensive analysis of a possible phase control strategy.

Another relevant reference in this field is represented by the work of Eidsmoen ([6] and [7]), where a detailed modelling of a hydraulic PTO has been applied to a heaving converter with the introduction of a phase control mechanism based on a control valve. A similar study has been carried out also recently by Hals et al. ([8]) through the application of this same idea to the case of a two-body wave energy converter. A hydraulic extraction mechanism has been conceived also for the SEAREV concept ([9]) showing how this type of conversion system is fit to several kinds of devices.

Our work constitutes a general investigation within this frame: in this paper we will present a simple model of a heaving buoy extracting energy through a hydraulic circuit connected to a generator and three different control strategies, partially based on the cited references, will be defined and validated. The efficiency of these algorithms will be checked through the consideration of possible failures and practical requirements.

A previous preliminary study carried out by Ricci et al. ([10]) had indeed clearly shown the validity of the proposed strategies in monochromatic regular waves. The present paper focuses on their application to irregular random waves and looks further to possible novel implementations.

2 Formulation

Our system is composed by a single floating body oscillating in heave and linked to the seabed by means of a Power Take-Off mechanism. We neglect, throughout the whole analysis, other degrees of freedom. If we assume that our WEC is capable of extracting energy only from heave motion, this approximation may be regarded as realistic from the hydrodynamic point of view if we choose an axisymmetrical buoy because, in this case, hydrodynamic interference between the heave mode and other modes is practically negligible (theoretically equal to zero).

For the solution of the hydrodynamic problem, we adopt linear water wave theory, based on the assumptions of incompressible irrotational flow and inviscid fluid. This allows us to apply BEM methods and compute the velocity potential in its components (radiated and diffracted wave fields) and obtain the hydrodynamic coefficients of added mass, damping and the total excitation force for any given body.

The mathematical model can be subdivided in two parts: The first part involves the hydrodynamic part and the second part consists of the hydraulic PTO, the hydraulic motor and the generator.

Hydrodynamics

On a general approach the equation of motion for a single body oscillating in heave is:

$$m\ddot{x} = F_e + F_r + F_h + F_{PTO} \tag{1}$$

To take into account nonlinearities, particularly when they can be modelled as time-varying coefficients of a system of Ordinary Differential Equations (ODEs), it is useful to apply a linear time-domain model based on the Cummins equation ([11]), whose use is widespread in seakeeping applications. This is based on a vector integro-differential equation which involves convolution terms responsible for the account of the radiation forces.

For our case of a single body floating in heave, the Cummins equation can be expressed in the form:

$$(m + A_\infty)\ddot{x}(t) + \int_{-\infty}^{t} K(t-\tau)\dot{x}(\tau)d\tau + \rho g S x(t) + F_{ext}(x,\dot{x},t) = F_e(t) \tag{2}$$

where A_∞ is the added mass at infinite frequency, given by:

$$A_\infty = \lim_{\omega\to\infty} A(\omega) \tag{3}$$

and $K(t)$ is the radiation impulse response function (RIRF), also called memory function because it actually represents a memory effect due to the radiation forces originated by the past motion of the body.

In this formulation all the possible nonlinearities are included in the term F_{ext}, which represents the external forces that are applied to the system due, for example, to the PTO or to the moorings and could be possibly linked to other independent variables that form a set of ODEs.

The hydrodynamic parameters like added mass and damping have been obtained using a boundary-element code while the excitation force coefficients can also be found through use of the Haskind relationship ([12]).

The convolution term has been represented as a polynomial transfer function obtained through a frequency-domain identification method ([13]).

In the following we will consider a cylindrical buoy of radius equal to 5 meters and draught equal to 5 meters. No constraints or restrictions will be considered for the amplitude of the motions. This could be indeed an important factor to be taken into account when dealing with more realistic cases.

Hydraulic PTO

A preliminary scheme of a hydraulic PTO is shown in figure 1.

This system consists of a hydraulic circuit where the transmission fluid is considered to be oil. The motion of the buoy is transferred to a double-acting piston capable of sliding within a hydraulic cylinder. The two chambers of this cylinder are connected to a high pressure gas accumulator (B) and a low pressure gas accumulator (C) through a couple of control valves whose opening will be dependent on the sign of the velocity of the buoy and on the pressure. The compressibility of the oil inside the chambers of the hydraulic cylinder is taken into account through the introduction of two additional gas reservoirs (D and E). The thermodynamic transformations involving the gas contained in the accumulators are assumed to be isentropic, i.e. no heat exchange takes place between the accumulators and the environment. This is a fairly realistic assumption since the time-scale of the temperature changes in the water and inside the device that could determine heat exchange is expected to be much larger than the one corresponding to the pressure changes associated to the compression and expansion cycles. A fixed-displacement hydraulic motor links the high- and low-pressure reservoirs producing a useful torque dependent on the pressure difference.

This is counteracted by a constant resistive torque imposed by an electrical generator that is directly connected to the hydraulic motor and feeds power into the grid.

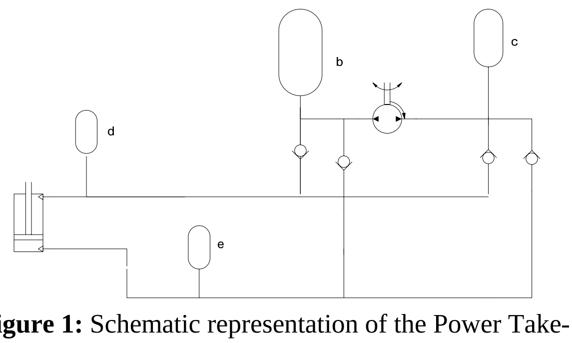

Figure 1: Schematic representation of the Power Take-Off mechanism

The state equations for this case can be written:

$$\dot{x} = \frac{F_e(t) - \rho g S x(t) - \int_{-\infty}^{t} K(t-\tau)\dot{x}(\tau)d\tau - A_p(p_d - p_e)}{m + A_\infty} \tag{4}$$

$$\dot{V}_d = -A_p\dot{x} + C_d A_{v_1}\sqrt{\frac{2}{\rho_o}\max((p_d - p_b),0)} - C_d A_{v_2}\sqrt{\frac{2}{\rho_o}\max((p_c - p_d),0)} \tag{5}$$

$$\dot{V}_e = -A_p\dot{x} + C_d A_{v_1}\sqrt{\frac{2}{\rho_o}\max((p_e - p_b),0)} - C_d A_{v_2}\sqrt{\frac{2}{\rho_o}\max((p_c - p_e),0)} \tag{6}$$

$$\dot{V}_b = -C_d A_{v_1}\sqrt{\frac{2}{\rho_o}\max((p_d - p_b),0)} - C_d A_{v_1}\sqrt{\frac{2}{\rho_o}\max((p_e - p_b),0)} + q_m \tag{7}$$

$$\dot{V}_c = -C_d A_{v_2}\sqrt{\frac{2}{\rho_o}\max((p_c - p_d),0)} - C_d A_{v_2}\sqrt{\frac{2}{\rho_o}\max((p_c - p_e),0)} - q_m \tag{8}$$

Assuming the gas compression/expansion process inside the accumulators to be isentropic, the pressure inside every accumulator is given by:

$$p_j = p_{oj}\left(\frac{V_{oj}}{V_j}\right)^{1.4} \tag{9}$$

The generator torque

A more realistic model of a hydraulic PTO would include also the modelling of the connection of a fixed-displacement motor to an asynchronous electrical generator. This is done in the following assuming that the hydraulic motor and the generator rotate at the same velocity although a gear change could be interposed in case it was necessary.

The flow rate across the motor can then be expressed as:

$$q_m = D_m \omega_m \tag{10}$$

$$\dot{\omega}_m = \frac{D_m(p_b - p_c) - T_g}{J} \tag{11}$$

Equations (10) and (11) could include a negative term to simulate some kind of losses in the motor for leakages and mechanical friction. Due to their hard estimation and considering the rather general equipment in case, we preferred not to include them in this work. The useful power *P* can be written as:

$$P_u = T_g \omega_m \tag{12}$$

The phase control accumulators.

An additional modification to the original design of the hydraulic PTO could be represented by an extra-accumulator of limited volume that could be use as a sort of energy storage to be released during more favourable moments (for instance in correspondence with a peak of the excitation force).

Budal and Falnes ([12]) were among the first to show that for point absorbers, one condition for maximising the energy production is to keep the velocity in phase with the excitation force. To this aim they introduced a phase control, or latching control, in order to achieve this condition on their heaving buoy wave energy converter.

This concept has been later applied by Eidsmoen ([6]) among others in adding an extra-accumulator, whose opening valve is controlled in order to increase the movement of the buoy few instants before the excitation force reaches its maximum value, with the purpose of enhancing the velocity in correspondence with the peak of the excitation force and reaching in this way a more favourable condition for energy absorption.

In our case, considering a double-acting cylinder, we could think to include an extra-accumulator on each one of the two sections of the circuit corresponding to the chambers of the cylinder.

The case corresponding to only one “control” accumulator is shown in figure 2.

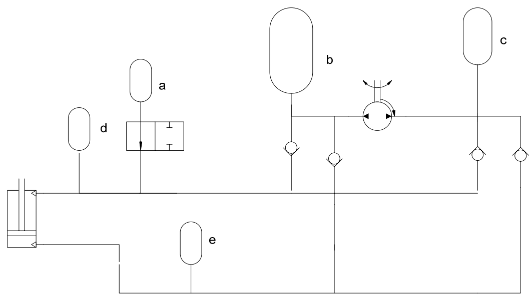

Figure 2: Scheme of the hydraulic PTO with one extra accumulator.

The equation of the extra accumulator is below:

$$\dot{V}_a = -C_d A_{v\,control}\sqrt{\frac{2}{\rho_o}|\,p_d - p_a\,|}\,sign(p_d - p_a) \tag{13}$$

This term will have obviously to be summed on the right-hand side of equation (5).

The case corresponding to two “control” accumulator is instead represented in figure 3.

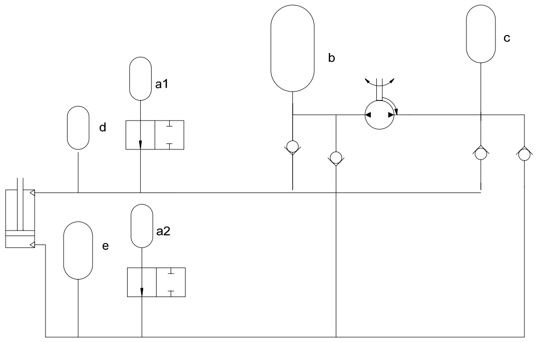

Figure 3: Scheme of the hydraulic PTO with two extra accumulators.

The equation of the second extra accumulator is below:

$$\dot{V}_{a_1} = -C_d A_{vcontrol} \sqrt{\frac{2}{\rho_o} | p_d - p_{a_1} |} sign(p_d - p_{a_1}) \quad (14)$$

$$\dot{V}_{a_2} = -C_d A_{vcontrol} \sqrt{\frac{2}{\rho_o} | p_e - p_{a_2} |} sign(p_e - p_{a_2}) \quad (15)$$

In this case, the right-hand side of equation (14) will have obviously to be summed on the right-hand side of equation (5) while the same applies to equations (15) and (6).

3 Results

Sizing and definition of the PTO

On the following we will assume constant values for several geometrical and dynamic parameters of the hydraulic PTO for the sake of convenience.

These values are the result of a preliminary sizing based on practical considerations and realistic requirements. They were not, however, aimed at any specified configuration and assembly within a real converter and might therefore need some changes assuming that a more detailed design is required.

For instance, limitations on the pressure peaks and on the amplitudes of the buoy, which were here not taken into account, as well as a deeper treating of pressure and hydrodynamic losses would likely lead to different choices.

The values of the parameters considered are presented in table 1.

Parameter	Value	Unit
V_{0b}	8	m^3
V_{0c}	4	m^3
$V_{0d}=V_{0e}$	0,05	m^3
V_{0a1}	0,5	m^3
V_{0a2}	0,5	m^3
p_{0d}	10	MPa
p_{0e}	10	MPa
ρ_o	850	kg/m^3
A_p	0.2	m^2
C_d	0.99	pure
A_v	0.002	m^2
D_m	$1.2x10^{-4}$	m^3/rad
J	7.5	kgm^2

Table 1: Parameter values considered in the simulations

Optimal torque of the generator

The torque of the generator is a parameter that can be modified in order to improve the efficiency of the PTO. It represents a kind of dissipative load on the system by means of which it is possible to control the flow rate across the motor and eventually the pressure levels inside the two reservoirs.

Under the action of a monochromatic wave, this kind of system tends to reach a stationary condition where the angular velocity is continuously oscillating around an average value.

Assuming the torque to be constant along a specific wavetrain, it could be found that there exists a value that maximises the power output of the system. This can be easily seen, for monochromatic waves of 1 meter amplitude, in figure 5.

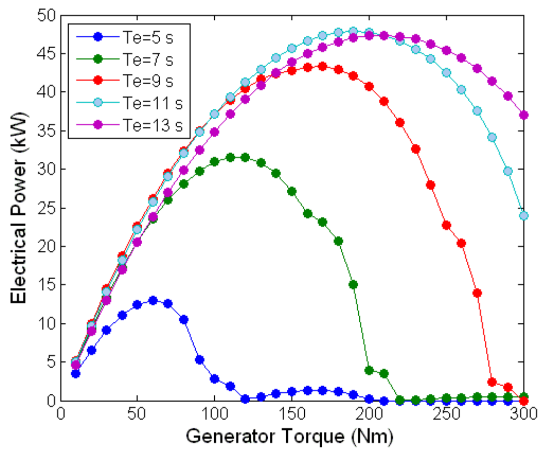

Figure 5: Performance of the system in regular wave of 1 meter amplitude with different torques

Optimal values of the generator torques are dependent on the wave period considered under a floater-specific rule. Dependence on the wave amplitude is instead approximately linear. This could have been expected as a larger value of the wave amplitude has the effect of proportionally increasing the excitation forces on the device. This translates in higher difference of pressures that correspond to higher torques as it can be seen from equation (11).

Indeed the incident power on the buoy is proportional to the square of the wave amplitude. If the conversion system was linear, this relation would hold also for the output power. However, for the case under study, the electrical power output does not increase linearly with the square of the amplitude.

This can be clearly seen in figure 6, where the power output divided by the square of the amplitude is shown for three different values of the wave amplitude. The values on the x axis indicate the torque divided by the wave amplitude.

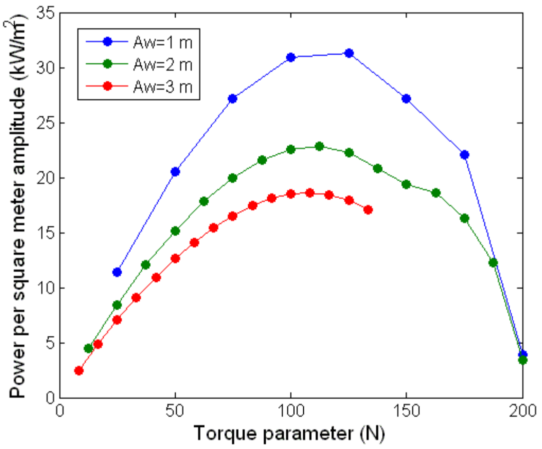

Figure 6: Power per square meter amplitude for different amplitudes

As it can be seen, power per square meter of wave is higher for lower waves. Moreover, it is clear from this image that the optimal value for power production is found at the same point, suggesting a linear relationship between optimal torque and wave amplitude.

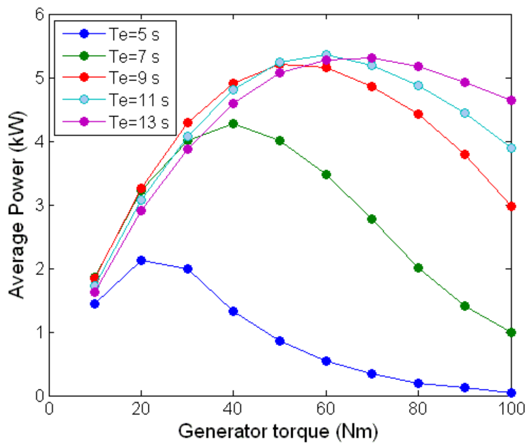

Figure 7: Performance of the system in irregular waves of 1 meter wave height with different torques

Considering these results, one might think to develop strategies that include a modulation of the torque in dependence of the wave measurements on a real-time basis. It is however interesting to observe the behaviour of the same system in irregular waves applying a constant torque at every sea state.

Figure 7 shows results given by random waves described by Bretschneider spectra characterised by 1 meter significant wave height.

The appearance is very similar to the one derived for regular waves. Optimal values of the torque can be clearly identified for different energy periods, pointing out that a preliminary control strategy for irregular waves might be the simple application of a variable torque in dependence of the sea state.

Besides, the same relationship between torque and wave amplitude is found for irregular waves if we take as term of comparison the significant wave height. In figure 8 the power output per square meter of wave height is plotted against the torque per wave height meter.

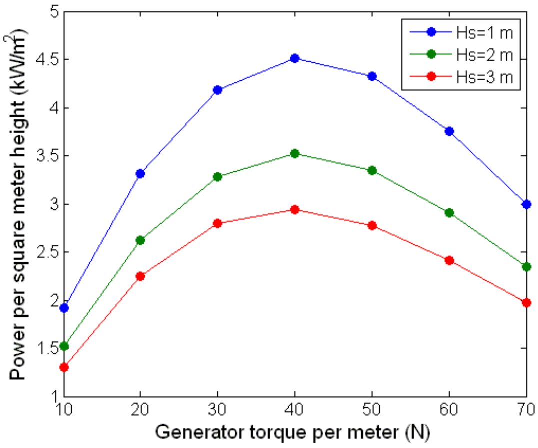

Figure 8: Power per square meter amplitude for different wave height in irregular waves

Again, it is easy to observe that the optimal torque is linear with the wave height as it could have been expected considering the previous example. Reduction of the power output per square meter with increasing wave heights is observed also in this case.

The control accumulators

In regular monochromatic waves it is relatively easy to implement an adequate control algorithm for the opening and closing of the control valves linking to the extra-accumulators.

The input to the control system is generally constituted by information on the excitation force or on the wave elevation. Since during our simulations the time series of the excitation force was exactly known because of being numerically generated, no consideration on the difficulties of the practical implementation of prediction algorithms needed to be considered. This should be obviously taken into account in a future application to a real device.

The optimal result of the opening of the extra-accumulator would be to generate an acceleration increase on the buoy in such a way that the velocity peak is reached exactly in correspondence to the peak of the excitation force. If there were no inertia with consequent delays in the hydraulic system the optimal opening instant would be located exactly a quarter of the resonance period of the buoy before the excitation force peak. However, due to the intrinsic configuration of the system that implies different time constant for every compression and expansion cycle, the determination of the optimal instant is rather empirical. Results based on the determination of the instant of the force peak and applied to regular waves were shown in [10].

One way to overcome the need for monitoring the excitation force time series (to define peaks) would be to activate the control valves depending on the absolute value reached by the excitation force, no matter if it is located at a peak or not.

A similar approach has been applied in [5] and recently also in [15] where an experimental validation of the methodology was also shown.

On the following we used this method to verify possible improvement in the power absorption by the introduction of one or two extra accumulators.

The dynamics of the controlled system can be clarified by observing figure 9 where we can see a comparison of the velocity of the buoy in three different working conditions (without extra accumulator, one accumulator, two accumulators). We can see that the velocity increases with one extra accumulator and even more with two extra accumulators. The enhanced secondary peak in the velocity is due to the acceleration provoked by the opening of the valve of the extra accumulators that provide with an almost instantaneous decrease of the pressure difference across the surface of the piston.

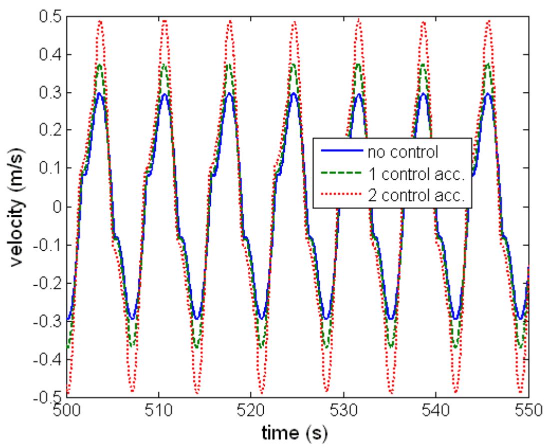

Figure 9: Comparison of the velocity of the buoy with different control and same excitation

The benefit of this strategy is particularly evident in figure 10, where a comparison for different strategies between generated power to the grid and hydraulic power is shown. The hydraulic power is the power absorbed by the piston within the hydraulic cylinder that can be computed as:

$$P_h = A_p(p_d - p_e)\dot{x} \qquad (16)$$

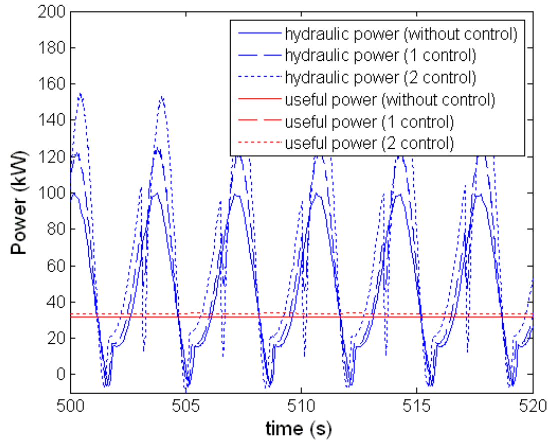

Figure 10: Comparison of the useful and hydraulic power with different control and same excitation

The hydraulic power can reach negative values when the velocity is close to zero but its average value is typically larger than the electrical one due to the losses in the valves (in this case modelled as orifices with turbulent dissipation).

It is interesting to notice that the introduction of the control accumulators might benefit the electrical power production but also worsen the efficiency of the system. This can be seen in table 2 where the different powers outputs are shown for the same case (monochromatic wave of 1 meter amplitude and 7 seconds period, torque of 110 Nm and threshold force of 300000 N).

For the sake of comparison also the incident hydrodynamic power is shown, computed in this case as:

$$P_i = F_e\dot{x} \qquad (16)$$

The efficiency is computed as the ratio between electric power and hydraulic power.

Variable	No acc.	1 acc.	2 acc.
P_i *(kW)*	50.05	50.45	71.86
P_h *(kW)*	47.99	48.36	67.35
P_e *(kW)*	31.52	31.81	33.63
Efficiency(%)	66	66	50

Table 2: Electrical, hydraulic and hydrodynamic powers with different control conditions for the same case

The benefit of the extra accumulators will be dependent in general on the applied torque and on the threshold force chosen. Indeed, when the latter is not properly defined, the performance could be even worse than without control.

For instance, when the system is "under-loaded", i.e. the generator torque is relatively small; the activation of one extra accumulator does not seem beneficial as it can be seen in figure 11. In this case the control seems to improve the performance only with larger torques.

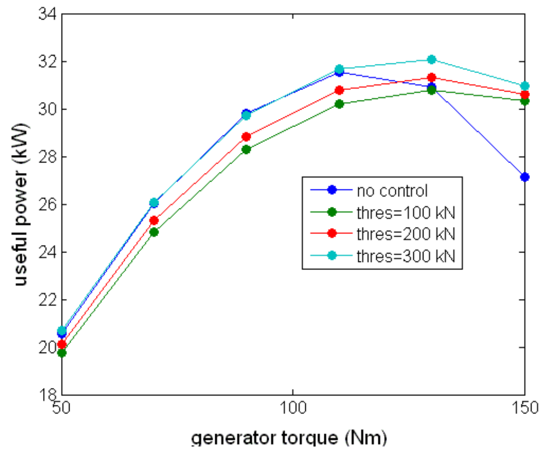

Figure 11: Comparison of generated powers with different torques and threshold limit for 1 accumulator activation (regular wave 1 m, 7s)

From figure 11, it is possible to observe that the optimal threshold is slightly less than the peak value of the excitation force (380 kN). Applying this kind of control, the performance of the system is practically unchanged with respect to the non-controlled case for small torques but is greatly enhanced for higher torques resulting in a different optimal value.

It is interesting to check the validity of this strategy in irregular random waves. On the following we will assume a Bretschneider wave spectrum characterised by a significant wave height of 1 meter and an energy period of 7 seconds.

Figure 12 shows a comparison of the velocity of the buoy with different control strategies applied. As it was observed in monochromatic waves, here as well the excursion of the buoy is greatly enhanced by the activation of the extra accumulators, particularly at the higher peaks.

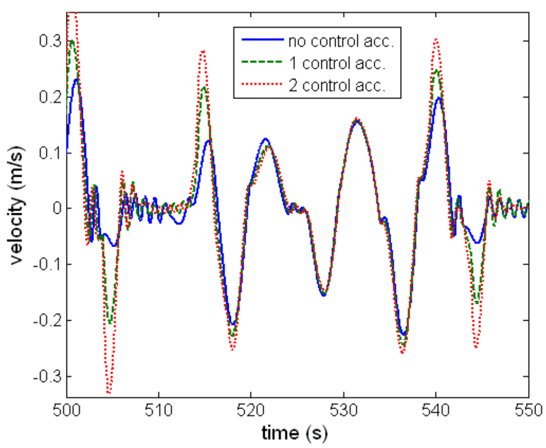

Figure 12: Comparison of the velocity of the buoy with different control and same excitation (Hs=1 m, Te=7 s, threshold=100 kN, torque=60 Nm)

The same conclusions outlined for regular monochromatic waves generally hold for irregular random waves. This can be seen in figure 13 where the power output of the system is compared for different torques and different control thresholds.

Again one can observe how improvement of the performance is particularly evident when higher values of the torque are being considered.

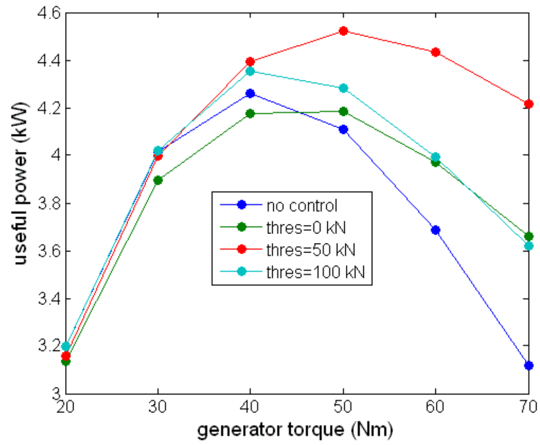

Figure 13: Comparison of generated powers with different torques and threshold limit for 1 accumulator activation (irregular wave H_s=1 m, T_e=7s)

Here as well an optimal value of the threshold force can be found (50 kN). Comparison for different control strategies and same sea state and threshold value is shown in figure 14, where the power output is plotted against different generator torques.

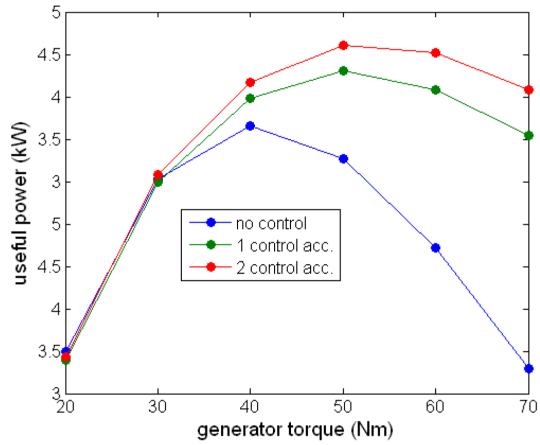

Figure 14: Comparison of generated powers with different torques and threshold= 50 kN for various strategies (irregular wave H_s=1 m, T_e=7s)

When considering a properly chosen value of the threshold force, the use of extra accumulators on both the two sides of the hydraulic circuit instead of one is typically preferable as it can be noticed in figure 14.

It is important to notice that the maximum extractable power is increased by up to 50% for the case of two control accumulators contemporarily working. Besides, this result suggests the application of a higher torque to achieve larger electrical output.

The effect of the different choice of the threshold force on the performance of the system can be seen in figure 15.

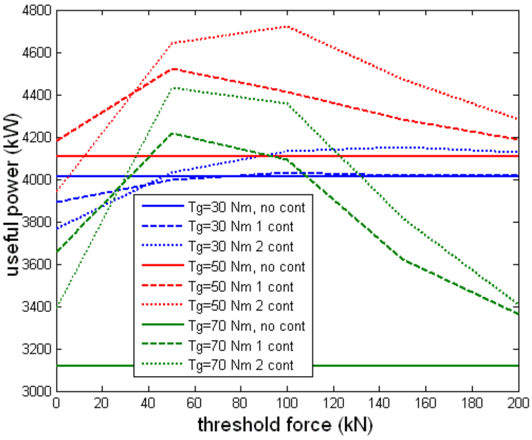

Figure 15: Influence of the threshold force of the control accumulators on the power production for various torques (irregular wave H_s=1 m, T_e=7s)

The choice of the appropriate threshold level is crucial when considering small generator torques. In over-loaded cases (large torques) application of the control accumulators is beneficial almost whatever threshold is defined.

4 Comparison of different control strategies

The effectiveness of the two control strategies outlined before has been proved in many cases but some questions might still arise on which one is more efficient or easier to implement and whether both of them can be coupled to improve the performance even more.

The modulation of the generator torque is an operation not particularly complicated nowadays. Control system based on the load variation of the generator have been successfully applied to wind turbines, the only additional requirement being adequate power electronics equipment to handle with different tensions load and possible power peaks.

In regular monochromatic waves the control strategy is rather simple since there is an optimal value of the torque that corresponds to a defined wave period (also almost linearly dependent on the wave amplitude) and few simulation runs are sufficient to identify it.

One can consider the torque as an expression of the load applied to the buoy and can easily observe that the optimal value is a compromise between over-loaded cases where the buoy is stopped for a large part of the cycle and under-loaded situations when the buoy is allowed to displace much more but consistently out of phase with respect to the excitation force. This means that the value of the torque is a kind of threshold that can be adjusted to achieve a sort of "phase control" of the device (see [5] for an extensive exposition of the concept). However since it represents a dissipative effect, it also influences a lot the amplitude of the motion performing then a contemporary "amplitude control".

It is easy to think of a similar control strategy to be applied to the case of irregular waves. It has indeed been shown that there are optimum values that maximise the power produced when the torque is assumed constant for a defined sea state.

The improvement of the performance due to the introduction of the extra-accumulators can be seen in the figure shown above. The value of the optimal torque is changed by the introduction of this control system and it is interesting to notice that the two accumulators are practically useless for very low torques when the system is under-loaded.

Moreover the power performance is consistently improved for much higher torques and the maximum is found at a higher value. This could be expected if we consider that under these torques the buoy motion is strongly limited and the enhancement guaranteed by the extra-accumulators is therefore largely beneficial.

A final investigation has been carried out on the influence of the choice of the threshold for determination of the instant of activation of the control valves. It can be seen that for most of the cases the adoption of the control through the extra-accumulators is largely beneficial.

This consideration could be different if we considered very low pairs where a bad choice of the opening instant might even cause a slight worsening.

Moreover it is likely that the adequate choice of the activation instant is dependent on the components of the PTO equipment in such a way that a characterisation of the system could be required every time an element is changed.

5 Conclusions

A simple oscillating wave energy converter has been modelled and coupled to a preliminary simplified hydraulic PTO whose behaviour proved to be consistent with more realistic configuration.

A more detailed configuration including the coupling with an electrical generator has been analysed and the possibility of modulating the resistant torque to achieve a maximum power output has been investigated proving to be an efficient control strategy in regular waves.

Another control strategy has been implemented through the use of two extra-accumulators capable of storing and releasing energy by the control of the opening of properly set valves.

The efficiency of this second alternative has been proved also when coupled with different torques and a maximum power output has been found for this case showing that a meaningful application of these two strategies might largely improve the performance of a wave energy converter.

The effectiveness of the second strategy has also been checked against different opening instants of activation of the control valves demonstrating that the application of this control system is most of the times beneficial.

It has to be noticed that all these results have been obtained neglecting several side-effects, including hydrodynamic drag, losses in the pipes and in the motor, pressure peaks etc. The possibility of defining a real-time control algorithm for the torque in irregular waves seems particularly interesting and is currently being addressed.

The extra-accumulator solution could require perhaps a lot of complexity in the system and its benefit should be validated through an analysis of the costs.

Acknowledgements

The first and the second authors acknowledge the Basque Government that has partially funded this work.

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