Modelling and Control of a Wave Energy Converter

Guilherme Nunes * **Duarte Valério** * **Pedro Beirão** ** **José Sá da Costa** *

* *IDMEC/IST, TULisbon, Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal, (e-mail: guilhermefnunes@gmail.com, duarte.valerio@ist.utl.pt, sadacosta@dem.ist.utl.pt)*
** *Inst. Sup. Engenharia de Coimbra, Dept. Mechanical Eng., R. Pedro Nunes, 3030-199 Coimbra, Portugal, (e-mail: pbeirao@isec.pt)*

Abstract: This work addresses an offshore oscillating water column for producing electricity from sea waves. It describes the modelling of this device and the study of control techniques that could improve energy extraction.
Optimisation techniques applied improved the device performance for a wide number of sea states. A control strategy was developed with the objective of improving the quality of the energy absorbed by the device. This proved to be effective. In a later stage of this work, some experiments considering a variable pitch Wells turbine were performed with the objective of applying phase and amplitude control: it was possible to prove the possibility of obtaining a resonant response to a sinusoidal wave with a frequency different from the device's natural frequency.

Keywords: Oscillating Water Column; Wave Energy Converter; Renewable Energy; Wells Turbine; Modelling; Control; Simulation.

1. INTRODUCTION

When the world realised its dependency on fossil fuels, research teams started to develop technologies to harness energy from renewable sources. One of the possible renewable sources that can be harnessed is wave energy. This is a highly energetic source that could, in the near future, play a major role in the world's energy production. In fact, the worldwide wave energy source is estimated to be around 2 TW, which is in the magnitude of the world's yearly power demand (Cruz and Sarmento, 2004). Wave energy is now beginning to appear as an economically viable manner of producing electricity. A proof of this is the recent deployment of the first world wave farm, installed in 2008 in Portugal. This was the first farm to inject electricity into the local electrical grid. Wave energy could, in the near future, become a very important solution for energy production in countries with high energetic near-shore seas and for islands which could become energetically independent.

This work addresses an offshore oscillating water column (OWC) for offshore deployment. It describes the modelling of this device and the study of control techniques that could improve energy extraction.

2. MODELLING

This section presents a time-domain dynamic model of the device in study, which is being developed by the Wave Energy Centre. The device is classified as a point absorber; that is to say, its horizontal dimensions are neglectable when compared to typical wavelengths. The device is around 35 metres high and has a top diameter of 12 metres. The body is fully pierced from top to bottom. The top part is a chamber where water and air interact; the top hole contains a pneumatic Wells turbine which extracts energy from the air flow. A scheme of the device is presented in figure 1.

The model of the device is based on first principles. The assumptions taken are:

(1) The device has a single degree of freedom, which is heave: the variable considered is ξ, the position of the device measured upwards from its steady-state position;
(2) The heave motion is restricted, so that both internal and external water free surfaces only contact the top cylindrical walls of the device;
(3) The thickness of the steel components will be neglected for most calculations, as this dimension is relatively minor;
(4) The device is assumed to be perfectly cooled, so that all its parts will always be at sea water temperature;
(5) The water and air flows are regarded as irrotational: the water free surface is modelled as a piston of negligible mass, and its height relative to the bottom of the device is denoted by h;
(6) Water surface tension is negligible as only gravity waves were considered;
(7) The air inside the device is assumed as an ideal gas; the processes of filling and emptying the chamber are assumed as being isentropic (Falcão and Justino, 1999).

* Guilherme Nunes was partially supported by grant PTDC/EME-CRO/70341/2006 of FCT, funded by POCI 2010, POS_C, FSE, and MCTES.

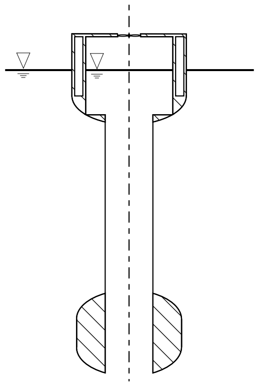

Fig. 1. Scheme of the device

The device and the water inside it were considered as two bodies: one consisting in the device structure, and another consisting in the varying mass of water inside the device. Both bodies are coupled by the air pressure inside the device which is controlled by the air turbine. The approach taken was based on Newton's second law of motion which states that:

$$\sum \overrightarrow{F} = \frac{\mathrm{d}\left(m\overrightarrow{v}\right)}{\mathrm{d}t} \tag{1}$$

In what concerns water and body interaction, both hydrostatic and hydrodynamic forces were considered. Hydrostatic forces are the forces applied when the system is at rest. Regarding hydrodynamic forces, radiation and excitation forces were taken into account. Concerning excitation and radiation forces, `Aquadyn`, a hydrodynamic simulation model software, was used to compute the frequency domain values of these forces. To transform a wave into excitation force, the calculations must be carried out in the frequency domain, since the data from `Aquadyn` led to non-causal models.

Because the radiation force depends on body velocity and acceleration, data obtained with `Aquadyn` was identified using a frequency-domain method: the Levy method. The radiation force could then be computed by the convolution product between the linear impulse response function h_r of the radiation process and the floater vertical velocity $\dot{\xi}$ added to a term proportional to the floater's acceleration, where the constant of proportionality is the added mass at infinity frequency (Falnes, 2002; Beirão, 2007):

$$f_{rad}(t) = -\left(-h_r(t) * \dot{\xi}(t) - \ddot{\xi}(t)m_\infty\right) \tag{2}$$

2.1 Forces Applied on the Device

Concerning the device, applying Newton's law we shall have

$$\begin{aligned} &f_{excb}(t) - f_{rad_{bb}}(t) + f_{rad_{wb}}(t) + f_{impb}(t) + w_b + \\ &+ f_{turb}(t) + f_{vb}(t) + f_{pib}(t) + f_{inwater}(t) = m_b\ddot{\xi}(t) \end{aligned} \tag{3}$$

where f_{excb} is the excitation force applied on the buoy; $f_{rad_{bb}}$ is the radiation force of the buoy acting on itself; $f_{rad_{wb}}$ is the radiation force of the water acting on the buoy; f_{impb} is the impulsion force; w_b is the weight of the buoy; f_{turb} is the force exerted by the turbine; f_{vb} is the viscous hydrodynamic force acting on the buoy; f_{pib} is the force due to the internal pressure; $f_{inwater}$ is the force due to the water inside the buoy; and m_b is the mass of the buoy.

Impulsion Force The impulsion or buoyancy force is given by the Archimedes' law:

$$f_{impb}(t) = \rho_w g V_{displaced}(t) \tag{4}$$

Although the heaving movement of the inside water free surface h may have some impact in the impulsion force, only the variation of ξ will be considered, as predicted by the linear theory.

Weight of the Device The immersed volume of the device when there are no oscillations will have a mean density equal to the sea water density, i.e. the weight of the device is equal to the impulsion force for the desired steady-state position:

$$w_b = -\rho_w g \overline{V_{displaced}} \tag{5}$$

Forces Caused by the Turbine Considering linear theory, the force induced on the device by the air flowing through the turbine can be computed by:

$$f_{turb}(t) = p_{inside}(t)A_{turb} \tag{6}$$

where p_{inside} is the relative pressure of the air inside the device; A_{turb} is the area covered by the turbine which is given by πr_{turb}^2.

Forces Caused by the Viscous Hydrodynamic Drag The viscous hydrodynamic force is given by

$$f_{vb}(t) = f_{vbe}(t) + f_{vbi}(t) \tag{7}$$

where f_{vbe} is the external viscous hydrodynamic force, and f_{vbi} is the internal viscous hydrodynamic force.

In order to compute an estimation of the viscous hydrodynamic drag, an expression that computes the friction from a laminar flow parallel to a flat plate was used; it is thus assumed that the curvature of the cylinder is negligible. In that case, the force per unit width, or drag D is given by:

$$\frac{2D}{\rho U^2 L} = \frac{1.328}{\sqrt{\frac{LU}{\nu}}} \tag{8}$$

where U is the velocity of the fluid; L is the length of the flat plate; ν is the kinematic viscosity of the fluid. The denominator of the right-hand side fraction is Reynolds number. This is clearly a coarse approximation since the major source of energy dissipation will be the turbulence generated around those parts of the device where its diameter changes, which is being neglected here.

Force Caused by the Internal Pressure The forces caused by the internal pressure acting on the body are due to different areas of opposite surfaces. It is obvious that the body will not suffer any lateral force; however, there will be a vertical resultant if the radius of the turbine is different from the radius of the neck. The resulting force can be computed by

$$f_{pib}(t) = p_{inside}(t)\pi(r_{neck}^2 - r_{turb}^2) \tag{9}$$

Force Due to the Water Inside the Buoy The mass of water inside the top chamber, when the device is not in the steady-state position, will induce a vertical force. Whenever the relative position of ξ and h is different from zero, the water volume in excess or in shortage will act on the body as a negative spring. One can understand that, the more water inside the device, the easier it will be for the device to heave downwards and vice-versa. As explained above, this is due to the relative position of ξ

and h; however, this force will solely act on the horizontal surface, inside the device, below the water. The pressure due to the water column above the centre hole will act only on the water itself, so it is not accounted for. Concluding, we can write the mathematical expression as follows:

$$f_{inwater}(t) = -\rho_w g \left[\pi(r_{topin}^2 - r_{neck}^2)(h(t) - \overline{h_{immersed}} - \xi(t))\right] \tag{10}$$

2.2 Forces Applied on the Water Inside

On the second body, the same approach can be applied; however, the mass and obviously the weight of the water volume will be time dependent. Because the mass varies, its time derivative shall be included:

$$f_{excw}(t) - f_{rad_{ww}}(t) + f_{rad_{bw}}(t) + f_{impw}(t) + w_w(t) + \\ + f_{vw}(t) + f_{piw}(t) = m_w(t)\ddot{h}(t) + \dot{m}_w(t)\dot{h}(t) \tag{11}$$

where f_{excw} is the excitation force applied on the water; $f_{rad_{ww}}$ is the radiation force caused by the water on itself; $f_{rad_{bw}}$ is the radiation force caused by the device on the water; f_{impw} is the impulsion force; w_w is the weight of the considered water volume; f_{vw} is the viscous hydrodynamic force acting on the water; f_{piw} is the force due to the internal pressure applied on the water free surface; and m_w is the mass of water inside the device.

Impulsion Force The impulsion force acting on the water volume will depend on the device position. It can be computed by

$$f_{impw}(t) = \rho_w g \left[\pi r_{neck}^2 h_{tube} + \pi r_{topin}^2 (h_{straighttop} - \overline{h_{emerged}} + \xi(t))\right] \tag{12}$$

Force Caused by the Viscous Hydrodynamic Drag The force caused by the viscous hydrodynamic drag will be the symmetrical of the internal viscous hydrodynamic force stated in section 2.1.4.

Force Caused by the Internal Pressure The force induced by the internal pressure on the water surface will be given by

$$f_{piw}(t) = p_{inside}(t)\pi r_{topin}^2 \tag{13}$$

Weight and mass of the Water Volume The mass of water will not be constant. It will depend on the level of the water free surface inside the device $h(t)$.

$$m_w(t) = \rho_w(\pi r_{neck}^2 h_{tube} + \pi r_{topin}^2(h(t) - h_{tube})) \tag{14}$$

The weight of the water volume will be given by multiplying the above equation by $-g$.

2.3 Modelling the Turbine

For a Wells turbine, the mass flow through the turbine can be computed using the following linear relation:

$$\Phi(t) = \varphi_\psi \Psi(t) \Leftrightarrow \\ \Leftrightarrow \frac{\dot{m}_{inside}(t)}{\rho_{air}(t) N(t) r_{turb}^3} = \varphi_\psi \frac{p_{atm} - p_{absin}(t)}{\rho_{air}(t) N^2(t) r_{turb}^2} \Leftrightarrow \\ \Leftrightarrow \dot{m}_{inside}(t) = \frac{\varphi_\psi r_{turb}}{N(t)}\left[p_{atm} - p_{absin}(t)\right] \tag{15}$$

where Φ is the mass flow non-dimensional coefficient; Ψ is the pressure non-dimensional coefficient; p_{atm} is the atmospheric pressure; p_{absin} is the absolute air pressure inside the device; N is the rotation speed of the turbine in rad/s. We can group relation $\frac{\varphi_\psi r_{turb}}{N(t)}$ in a single variable K_t for a matter of simplification.

The instantaneous pneumatic power available for the turbine is given by the following expression (Perdigão, 1998):

$$P(t) = p_{inside}(t)Q(t) \tag{16}$$

where Q is the air volumetric flow, which can be computed dividing equation (15) by ρ_{air}. The energy absorbed by the device for a certain period of time can therefore be computed by:

$$E(t) = \int_0^t p_{inside}(t)Q(t)\,\mathrm{d}t \tag{17}$$

2.4 Modelling the Air Inside the Device

In steady-state conditions, the internal pressure is equal to the atmospheric pressure. In what follows the relative internal pressure will be reckoned.

The air mass flow rate through the turbine can computed by the following expression (Falcão and Justino, 1999):

$$m_{inside}(t) = \rho_{air}(t)V_{air}(t) \Rightarrow \\ \dot{m}_{inside}(t) = V_{air}(t)\frac{\mathrm{d}\rho_{air}}{\mathrm{d}t} + \frac{\mathrm{d}V_{air}}{\mathrm{d}t}\rho_{air}(t) \tag{18}$$

where ρ_{air} is the air density; V_{air} is the air volume inside the device.

Air compressibility should not be neglected in devices where the chamber height is in the order of several metres (Falcão and Justino, 1999); so, ρ_{air} was computed dividing the air mass inside the chamber m_{inside} by the air volume. m_{inside} can be computed integrating the turbine characteristic equation (15). When the air is flowing outwards the chamber, the relative air pressure inside the device p_{inside} is positive and the air mass flow is negative and vice-versa. Considering the process as reversible, it can be modelled as being isentropic. During the filling process, air does not maintain its specific entropy; however, for a matter of simplification, an isentropic process was considered, following Falcão and Justino (1999). Due to these assumptions, we can use the following isentropic relationship:

$$\frac{\mathrm{d}\rho_{air}}{\mathrm{d}t} = \frac{1}{\gamma R_{air} T}\frac{\mathrm{d}p_{inside}}{\mathrm{d}t} \tag{19}$$

Using equation (19) in equation (18),

$$\dot{m}_{inside}(t) = V_{air}\left(\frac{1}{\gamma R_{air} T}\frac{\mathrm{d}p_{inside}}{\mathrm{d}t}\right) + \frac{\mathrm{d}V_{air}}{\mathrm{d}t}\rho_{air} \tag{20}$$

The pressure can be computed integrating the following expression, knowing that the initial condition is equal to zero:

$$\frac{\mathrm{d}p_{inside}}{\mathrm{d}t} = \left(\dot{m}_{inside}(t) - \rho(t)\frac{dV_{air}}{dt}\right)\frac{\gamma R_{air} T}{V_{air}(t)} \tag{21}$$

R_{air} is a constant and T will indeed be assumed as a constant value.

3. SIMULATOR

The differential equations (3) and (11) presented in the previous section were implemented in MatLab Simulink so as to simulate various sea conditions in an effective way. The simulator is based on the one developed by Beirão (2007) which was built for the Archimedes Wave Swing (AWS) device. From this existing simulator, several features, and in particular the functions for wave generation, were used. Wave generation can handle regular or irregular waves by choosing their specifications: these are height and period for regular waves, and, for irregular waves, the type of spectrum, the significant wave height and other spectrum related values. The simulator developed includes now a 3D animation which shows in real time the positions of the wave elevation, the device and the water free surface inside the device. This animation was built using Virtual Reality Modeling Language (VRML).

The Simulink simulator solves the equations iteratively with a fixed step-size. The ode3 (Bogacki-Shampine) solver was chosen due to its precision and computation speed. Using this solver, a simulation of 600 s can run in 62.8 s in a computer with a 2.8 GHz processor.

3.1 Dimensional Optimisation

The top chamber internal radius r_{topin} and the turbine proportional parameter φ_ψ needed to be optimised so the device could work for a year-wide sea climate and, at the same time, maximise energy extraction. To perform this optimisation, real data from Leixões-buoy was used. Leixões-buoy is a wave data acquisition buoy, located at $41°12.2'$ N, $9°5.3'$ W, near the northern Portuguese shore. Information about the year-wide sea states is resumed in table 1, where, for each month, there is information about the mean significant height and the maximum and minimum energy periods. Using this data, forty-eight 600 s simulations were performed, four for each month of the year, using irregular waves following the Pierson-Moskowitz (PM) spectrum (Falnes, 2002). Four simulations were held for each month because the generation of waves is a random process; the value considered for the decision process was the mean of the four simulations. The combination which absorbed more energy over the whole year is $\varphi_\psi = 1.8$ and $r_{topin} = 3.5$ m.

4. CONTROL

4.1 Maximising Energy

In the first place, a simple Wells turbine was considered—that is, a Wells turbine where the linear relationship is maintained through time. However, it was considered that the proportional constant could change freely, though it was restrained to be always positive.

The objective of changing the turbine's characteristic value is to maximise energy absorbtion from incident waves. The effect of this kind of turbine in the phase is reduced, which means that no phase control can be performed, and thus other methods for energy maximisation were used. Initial tests proved that changing K_t online did not bring much benefits: this is obviously because of the assumption of an ideal turbine. Two methods were developed for optimising K_t. For both methods, linear models were identified using Levy's method. A model for the air pressure inside the device and another for the air volumetric flow, with the wave elevation as an input, were obtained in order to estimate the power by multiplying both outputs (i.e., applying equation (16)). Using these linearised models, it is possible to predict, for a given wave, which K_t absorbs the most energy. For the second case, a similar process was used, but this time, instead of power, the internal water height h was identified. The optimisation had the objective of choosing the K_t which produced the highest variance of h but remained within the physical limitations of the device, i.e. the maximum value of h must be smaller than h_{device} and its minimum should be greater than h_{tube}.

Table 1. Year-wide wave data for Leixões-buoy

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hs [m]	3.2	3	2.6	2.5	1.8	1.7	1.5	1.6	1.9	1.3	2.8	3.1
Te min [s]	5.8	5.8	5.2	5.5	5	4.7	4.6	5	5.2	5.3	5.5	5.3
Te max [s]	16.1	14.5	13.7	14.8	12.2	9.7	11.1	10.5	12	12.6	13.3	14.2

4.2 Energy Quality

One of the many problems concerning wave energy extraction is the energy quality that is provided by the generator—that is to say, its variability around its mean value. A very variable energy production cannot be fed to the grid without some previous processing. The intention of controlling the energy quality is to smooth out the energy absorbtion evolution by acting directly on the turbine, diminishing the investments on rectifiers located at the grid connection point.

In order to perform energy quality control, a predictive controller was developed. This controller looks ahead in time in a fixed time window. It then performs a spectral analysis, using the Fourier transform of the incident wave inside the chosen time window. From the spectral analysis, the dominant frequency is computed and, from this data, the reference can be constructed. The controller used was a PID controller. Its parameters were optimised using a minimisation function.

4.3 Phase and Amplitude Control

For an OWC, the optimal condition for energy extraction from waves is that in which air pressure is in phase with the diffraction flow (Perdigão, 1989; Justino, 1993). As the modelling addressed in this project is not based on diffraction and radiated flows, the analogous variable used is the excitation force induced on the water inside the device.

OWC phase control is based on the variable pitch Wells turbine. This turbine can act both as a compressor and as a turbine, thus the possibility of controlling the internal pressure. Regarding this turbine, the relation introduced in equation (15) is slightly changed by introducing a new factor α added to the right hand member of the equation.

Optimum phase control of an OWC is a non-causal problem (Perdigão, 1989; Justino, 1993), which means that the suitable controller should be predictive. A predictive controller for the device addressed in this document was not yet developed but should be studied in the future to understand the benefits it would bring. Predictive controllers are normally model-based controllers, which means that a linear or non-linear model of the device should be obtained so as to design the controller.

In order to obtain a coarse evaluation of the benefits from this kind of turbine control, experiments were made using a PID controller. All the experiments assumed a constant K_t, so only α was allowed to change unconstrained. In order to compute the optimum amplitude relationship between the air pressure and the excitation force, the MatLab `fminsearch` function was used. It was set to discover the proportional gain that maximised energy absorbtion when a proportional controller was used.

5. RESULTS

To show the results in a simpler and condensed way, the MatLab `imagesc` plot type was used. In this type of graphic, a matrix is normalised and plotted as a colour map. In this way, extensive tables are avoided and the perception of the qualitative performance for the device is improved, which, due to the early stage of the project, makes more sense than the actual power values obtained.

5.1 K_t optimisation

When operating the model without any control scheme, the turbine was simulated as operating at constant speed, without any variation. To do so, the variables optimised in section 3.1 were used. It must be taken into account that these variables were optimised using the PM spectrum, which is a one parameter spectrum. When simulating for various significant heights and energy periods, using a two parameter spectrum introduced in Goda (2000) and used in Falcão and Rodrigues (2002), we are, for some cases, simulating storm conditions, with very severe conditions; thus the device shall be in survivability mode, not producing energy. Figure 2 (top) shows the energy absorbed by the device for each sea state. From the analysis of this figure, it is seen that only half of the sea states simulated are favourable to energy extraction from the device, the maximum power extracted being around 170 kW; for the other half of the sea states, the device shall be in survivability mode, and thus will not extract energy. It thus makes sense to optimise K_t in order to maximise the energy extraction for each sea state.

By applying both optimisation techniques described in the previous section the results for energy extraction were considerably improved. Each technique led to different results, so the best results from each optimisation were superimposed, leading to the results in the bottom plot of figure 2. Fusing both methodologies, 234 from a total of 336 sea states are used to produce energy, which is a great improvement over the uncontrolled case, where only 166 cases were favourable for the device to work. And energy absorbtion was for some cases improved by 500%.

5.2 Energy Quality

This control works with a fixed length time window, which can be varied to improve the performance of the controller. The controller follows a ramp reference which is the integral of the power predicted to be absorbed during the chosen time window.

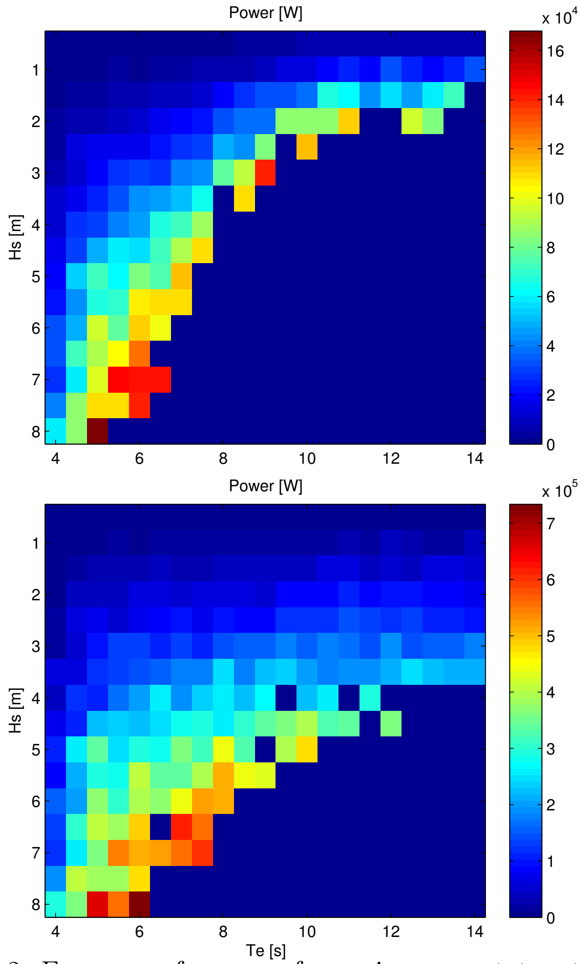

Fig. 2. Energy performance for various sea states; top: $\varphi_\psi = 1.8$, $N = 100$ rad/s and $r_{topin} = 3.5$ m; bottom: both optimisation methodologies superimposed

As can be seen in figure 3, the integral is reset for every time window: in this case, a 100 s window is used. The benefits that the controller brings are quite clear: as can be seen, the energy absorbed can follow the predicted reference with a reduced error—this is, of course, assuming that K_t can vary freely and instantly inside the $[0.003, 1]$ range; this range proved to be enough to have a significant impact on the device. In fact, the control action is highly variable (see the bottom plot of figure 3), which would be difficult to occur in reality; however, as the dynamics of changing K_t were neglected, this is possible in the simulator.

To evaluate the controller's performance, the energy evolution for a simulation on which this controller was applied is fitted with a linear curve; after this, the VAF and the RMS are computed, comparing the model's energy absorbtion with its linear regression. The goal is to have a VAF value as close to 100% as possible and a RMS as close as zero. For the no control case, a fixed K_t equal to 0.009 was used. Various time windows lengths were experimented. It was concluded that using a 100 s prediction is the best scenario; however, the power absorbed is sacrificed in order to obtain a better energy quality. In fact, when using a window of 100 s, there is a power absorbtion drop of 8%, comparing with the no control case. Economic viability studies should be made in order to compare this proposed system with

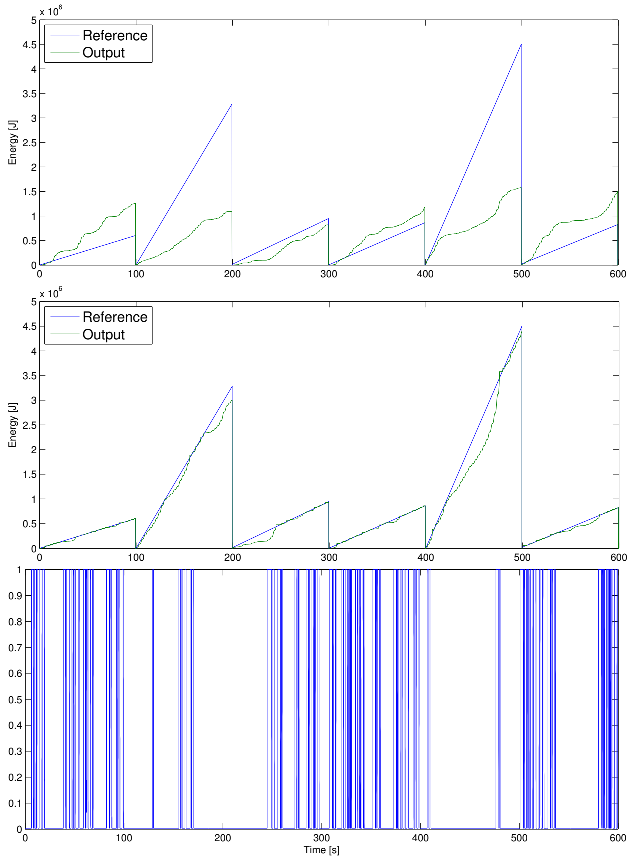

Fig. 3. Comparing the non-controlled and controlled cases for the energy quality; top: without control; centre: with control; bottom: control action

the implementation of electric rectifiers. Electric rectifiers may never be discarded, but their size can be decreased.

5.3 Phase and Amplitude Control

To prove the possibility and evaluate the benefits of such control, a regular wave with a period of 8 s is fed to the model. This wave has a frequency of 0.7854 rad/s which is far from the resonant frequency of the device which is around 0.52 rad/s. The intention of using phase control is to achieve a resonant response for frequencies where the device does not have such behaviour.

For the 8 s period wave, the ratio between the normalised excitation force and the air pressure was found to be 12510. Using this scheme, an increase of 351% of power absorbtion was achieved; however, this control strategy degrades the energy quality: this is mainly because this control technique consumes energy to absorb more energy.

For irregular waves, the control strategy implemented did not improve energy absorbtion.

6. CONCLUSION

It was possible to prove that the optimisation of the turbine's characteristic would bring a great improvement on the device rentability. It also was found that, optimising that value, power absorbtion could be improved in the order of 500% for some more energetic sea states. Throughout this optimisation, the device workability was also augmented: this means that the device can work in a wider range of sea states, avoiding the survivability mode when it does not produce energy; applying the optimisation techniques developed, the workability increased by 41%, which is a very significant improvement.

Energy quality control tries to give an idea of whether it would be possible to control the energy quality using a turbine based controller. The results obtained were rather good, as energy absorbtion could actually be smoothed using the controller developed; however, the control action obtained for an irregular wave presented a high variance, and thus its physical implementation may not be feasible. Neglecting physical limitations, the controller developed proved to work as intended, reducing energy absorbtion variability.

The experiments made using a variable pitch Wells turbine were certainly not extensive but were meant to prove that it is possible to induce a resonance response for a frequency which is not the device's resonant frequency. For a regular wave, it was proved that it is possible to improve energy absorbtion by using this kind of control; however, the controller used proved not to be effective when irregular waves were experimented due to a decrease in energy absorbtion compared with the uncontrolled device. The decrease in energy absorbtion was caused by the need of supplying energy to the turbine for it to work as a compressor during certain phases of the energy production. Ideally, this energy should have been recovered when the turbine produces power.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the constant support given by the Wave Energy Centre, and in particular by Marco Alves and Prof. António Sarmento. Research for this paper was partially supported by grant PTDC/EME-CRO/70341/2006 of FCT, funded by POCI 2010, POS C, FSE and MCTES; and by the Portuguese Government and FEDER under program "Programa de Financiamento Plurianual das Unidades de I&D da FCT" (POCTI-SFA-10-46-IDMEC).

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