Power Conversion System Optimization for an Oscillating Wave Surge Converter in a Channel via Bang-Bang Control

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Abstract: In this work an Oscillating Wave Surge Converter (OWSC) for harvesting energy from wave motion in a channel is considered. A conversion from wave energy to electric energy is achieved through an oscillating flab gate hinged on the seabed and equipped with a directly-driven power take-off system, employing a high efficiency speed multiplier which drives a low speed alternator. Processing of the generated voltage is described by referring to a simple exemplary resistive harvesting circuit. In order to optimize the extracted energy, a semi-active control strategy based on a Bang-Bang technique is introduced. As a result, numerical solution of the corresponding dynamical problem proves the effectiveness of the adopted control strategy, highlighting an enhance up to 21% in the average harvested power when compared to the case without control.

Keywords: Oscillating Wave Surge Converters, Energy Harvesting, Bang-Bang Control, optimization

INTRODUCTION

The interest in exploiting renewable sources for power generation has rapidly grown in recent years, also due to the fact that the consumption of energy in the world has considerably risen in the last decades. In this context, the sea as a powerful and concentrated resource of energy has been an important research subject after the Second World War and in the 1970s. falnes2007 reports with an overview of the state of the art and the knowledge acquired around and before the 1980s, presenting the fundamentals in evaluating the energy amount in ocean waves and the principles of energy extraction.

As a result of different strategies conceived for extracting energy, many different typologies of Wave Energy Converters (WECs) have been developed. An useful classification of the corresponding technologies, their operating principles and mathematical modeling is reported in falcao2010. Basically, WECs working principle is generally based on the wave-induced oscillations of floating and/or submerged devices. In particular, simple floating systems are defined by referring to one degree-of-freedom oscillating devices that may essentially translate (heave) or rotate (pitch). Systems belonging to the latter typology are generally indicated as Oscillating Wave Surge Converters (OWSCs), and they have recently gained increasing interest from the scientific community. More in detail, OWSCs can be described as flap gates, namely buoyant structures hinged at the sea bed nearshore which activate, with their oscillations, an electric generator onshore. Among this class of devices, two prototypes have been developed and tested in Northern Europe: the Oyster in UK whittaker2007, spanning the whole water depth, and the totally submerged WaveRoller in Finland gunawardane2019.

A sub classification results from the typologies of the adopted power-take-off (PTO) system salter2002. It may consist in a fluid-drive generator excited by hydraulic rams hirohisa1982, hydraulic turbine budal1982, or a mechanical-drive generator. An almost exhaustive analysis of the energy conversion mechanisms, as well as of usual transmission and storage technologies for typical converter typologies, has been proposed by mccormick1981. A novel typology of PTO, that takes advantage from the advances of the Neodymium-Iron-Boron (Nd-Fe-B) magnet employed in Permanent Magnet Generators (PMGs), has been recently conceived and investigated. In this case, a PMG can be utilized for the development of a direct drive energy converter baker2001, mueller2002, mueller2007, hodgins2010, thorburn2007, capable of generating generate electric power following the heaving movement of a floating body, and without the need of mechanical or hydraulic intermediate processes.

In this contest, the present work aims to investigate the effectiveness of a semi-active control strategy, based on a Bang-Bang technique, in order to optimize the energy harvested by an OWSC placed in a channel, equipped with a PTO using a permanent magnet generator. The harvesting electric circuit is defined by a purely resistive load. The dynamic problem is formulated by describing fluid-structure interaction effects via a well-established linear approach mei2005, michele2016a, michele2016b, based on the hypotheses of an irrotational flow for an ideal fluid, small-amplitude waves, and small body oscillations.
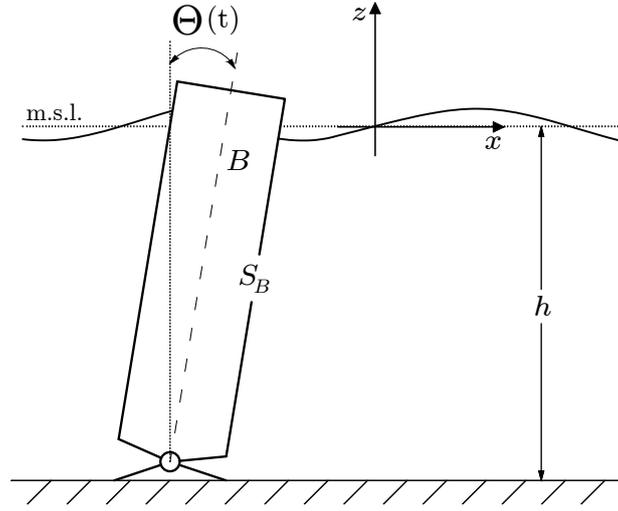
Figure 1 – Schematic sketch of a flap gate oscillating within the fluid domain. Notation.

PROBLEM STATEMENT AND MODELLING STRATEGY

In what follows reference will be made to an OWSC defined by considering the oscillating flap gate schematically depicted in Fig. 1. It consists of a floating parallelepipedic flap gate B (W: along-y width; δ: along-x thickness; h_B: along-z height) hinged on the seabed and characterized by the submerged surface S_B. With reference to the notation introduced in the figure, the flap can oscillate about the horizontal axis $z = -h$ lying on the seabed, assumed to be characterized by a constant depth h, and is excited by an incident monochromatic plane wave, whose propagation direction is opposite to the x-axis orientation. Accordingly, the gate motion, yielding the wave power extraction, is described by the rotation $\Theta(t)$ about the hinge axis parallel to the wave front, with the resting configuration, i.e. $\Theta = 0$, corresponding with B aligned with the vertical axis z. Thereby, the flap dynamics is governed by the following equation:

$$I_\theta \ddot{\Theta} = T_w + T_{PTO} \tag{1}$$

where I_θ is the moment of inertia of the device with respect to the hinge axis, T_w is torque resulting by the fluid pressure p, and T_{PTO} is the torque due to the power take-off system. By splitting p in a dynamical contribution p_d and in a hydrostatic one $\overline{p}$, T_w can be described as $T_w = T_d - T_{res}$. The first term T_d results from p_d and accounts for the dynamical part of the fluid-structure interaction between the incoming incident wave and the moving body; the second one, T_{res} is associated to $\overline{p}$, namely to the body buoyancy, and it accounts for hydrostatic effects that make the body experience a restoring torque.

By assuming that water and body densities are constant in both space and time, and that the dynamics of B undergoes a small oscillation regime, the net restoring torque T_{res} associated to the hydrostatic pressure $\overline{p}$ can be expressed by the following linear form:

$$T_{res} = C\Theta, \qquad \text{with} \qquad C = \rho g(I_{wp} + S_v) - Mg(h_B/2) \tag{2}$$

where the restoring coefficient C depends on the buoyant waterplane inertia $I_{wp} = W\delta^3/12$, the buoyant mass M, the static moment $S_v = W\delta h^2/2$ of the submerged volume with respect to rotation axis, the sea water density ρ, and the gravity acceleration g. Similarly, under the assumption of small-amplitude motions, the dynamical contribution T_d of the torque results in:

$$T_d = \int\int_{S_B} p_d(z + h_B)\,dS \tag{3}$$

A closed-form estimate of the the dynamical pressure p_d can be obtained by adopting the modelling strategy proposed by Michele et al. michele2016a, michele2016b and based on the linear wave theory falnes2002, mei2005. In detail, by assuming an ideal fluid (namely, incompressible and inviscid) and the flow is irrotational, the fluid dynamics can be described by means of the potential flow theory. As a result, there exists a velocity potential $\Phi(x,y,z,t)$ which satisfies the Laplace equation $\nabla^2\Phi = 0$ in the fluid domain, such that the fluid velocity $\mathbf{v}$ is equal to $\mathbf{v} = \nabla\Phi$. On the basis of the linearised water-wave theory mei2005 and in the limit of small-amplitude harmonic oscillations of B, the linearization of the governing problem allows to express Φ as:

$$\Phi = \Phi^I + \Phi^S + \Phi^R \tag{4}$$

where:

- Φ^I is the potential of the plane incident waves incoming from $x = +\infty$, that for an incident monochromatic plane wave is equal to:

$$\Phi^I = \mathrm{Re}\left\{ -\frac{\mathrm{i}Ag}{\omega}\frac{\mathrm{ch}k(z+h)}{\mathrm{ch}kh}\mathrm{e}^{-\mathrm{i}(kx+\omega t)} \right\} \tag{5}$$

  ω and A being the wave frequency and amplitude, respectively; k being the wavenumber, i.e. the real root of the dispersion relationship $\omega^2 = gk\tanh kh$, and i is the imaginary unit;

- Φ^S is the potential of the waves scattered by B;

- Φ^R is the potential of the radiated waves due to the motion of the flap gate.

Accordingly, by introducing $\Phi^D = \Phi^I + \Phi^S$ as the diffraction potential, and considering the linearized Bernoulli's equation, the dynamical pressure p_d results in

$$p_d = -\rho\frac{\partial}{\partial t}\left(\Phi^D + \Phi^R\right) \tag{6}$$

so that the dynamical contribution T_d of the torque (see Eq. (3)) can be recast as

$$T_d = \int\int_{S_B} p_d(z+h_p)\,dS = T_D - \rho\frac{\partial}{\partial t}\int\int_{S_B}\Phi^R(z+h_B)\,dS \tag{7}$$

where T_D identifies the exciting torque, induced by the diffraction potential Φ^D, whereas the second term on the right hand side of Eq. (7) represents the torque exerted on the flap gate by the radiating waves. By considering the harmonic motion $\Theta(t) = \theta\mathrm{e}^{-\mathrm{i}\omega t}$ induced by the harmonic incident wave characterized by the same frequency ω, the problem linearity allows to enforce that $\Phi^{R,D}(x,y,z,t) = \varphi^{R,D}(x,y,z)\mathrm{e}^{-\mathrm{i}\omega t}$. As a consequence, the exciting torque and the radiating contribution in Eq. (7) can be respectively written as

$$T_D = \overline{T}_D(\omega)\mathrm{e}^{-\mathrm{i}\omega t} \tag{8}$$

$$-\rho\frac{\partial}{\partial t}\int\int_{S_B}\Phi^R(z+h_B)\,dS = \left[-\mathrm{i}\omega\theta\nu(\omega) - \omega^2\theta\mu(\omega)\right]\mathrm{e}^{-\mathrm{i}\omega t} = \nu(\omega)\dot{\Theta} + \mu(\omega)\ddot{\Theta} \tag{9}$$

where $\overline{T}_D(\omega)$ is the frequency-dependent amplitude of the exciting torque, $\nu(\omega)$ is the radiation damping (namely, the frequency-dependent coefficient modulating a damping-like term proportional to the flap velocity) and $\mu(\omega)$ is the added inertia (the frequency-dependent coefficient modulating an inertial-like term proportional to the flap acceleration).

Therefore, the motion equation (1) associated to the excitation of a monochromatic wave with frequency ω results in:

$$[I_\theta + \mu(\omega)]\ddot{\Theta} + \nu(\omega)\dot{\Theta} + C\Theta + T_{PTO} = \overline{T}_D(\omega)e^{-\mathrm{i}\omega t} \tag{10}$$

Following falnes2002,mei2005, the terms associated to radiation damping and added inertia can be rearranged considering a convolution integral derived by introducing the inverse-transform function of $\nu(\omega)$. In detail, Eq. (10) may be written in the form:

$$(I_\theta + \mu_\infty)\ddot{\Theta} + C\Theta + \int_{-\infty}^{t}L(t-\tau)\ddot{\Theta}d\tau + T_{PTO} = \overline{T}_D(\omega)e^{-\mathrm{i}\omega t}, \tag{11}$$

where μ_∞ is the limiting value of the added inertia attained for $\omega \to \infty$, and the memory function $L(t)$ is expressed as:

$$L(t) = \frac{2}{\pi}\int_0^\infty \frac{\nu(\omega)}{\omega}\sin\omega t\,d\omega \tag{12}$$

For a parallelepipedic oscillating flap gate as the one depicted in Fig. 1 approached by an incident monochromatic plane wave, the hydrodynamical quantities $\mu(\omega)$, $\nu(\omega)$ and $\overline{T}_D(\omega)$ have been derived in a closed form by michele2016a, michele2016b, whether it is located in the open sea or in a channel.

The conversion from kinetic to electric energy is assumed to be made at the axis of rotation of the body by means of a directly driven power take-off system. In detail, the electro-magnetic system is assumed to be composed of: a low speed three-phase permanent-magnet generator salter2002 driven by a high-efficiency speed multiplier; a simple harvesting electrical circuit. It is worth observing that the rotational velocity of a floating gate is proportional to the wave amplitude and the wave frequency, hence resulting in too low values for an efficient direct connection between the generator and the oscillating flap. Thereby, the mediation of a power transmission system is needed to increase the generator rotor speed. In what follows, the speed multiplication ratio associated to the mechanical speed multiplier will be denoted as r.

The three-phase generator is assumed to be a star-star (Y-Y) connected one, with purely resistive balanced loads characterized by the electric resistance R (see Fig. 2). By disregarding any inductance effect and by introducing the total resistance for each phase as $R_t = R + R_c$, with R_c being the the phase winding resistance, the three-phase circuit currents I_i (with $i = 1, 2, 3$) result in chapman2005

$$I_i = \frac{e_i}{R_t} \qquad \text{with} \qquad e_i = Kr\dot{\Theta}\sin\left\{\frac{n_p}{2}\left[r\Theta - (i-1)\frac{2}{3}\pi\right]\right\} \qquad (i = 1, 2, 3) \tag{13}$$

where e_i is the generated voltage for the i-th phase, n_p is the number of poles in the generator, and K is a constitutive parameter of the permanent magnet generator equal to $K = n_p\Psi/2$, with Ψ being the magnetic flux amplitude, proportional to the magnetic flux density in the air gap and to the number of winding in each phase coil. Thereby, under the constraint $n_p/3 \notin \mathbb{N}$ ($\mathbb{N}$ being the natural number set), the electric power for the considered case can be simply expressed as:

$$P_{YY}(t) = \frac{3}{2}\frac{K^2 r^2}{R_t^2}\dot{\Theta}^2 \tag{14}$$

Accordingly, the conversion torque T_{PTO} in Eq. (11) can be written in the form:

$$T_{PTO}(t) = u_c(t)\,\eta\,\dot{\Theta}(t) \qquad \text{with} \qquad \eta = \frac{3}{2}\frac{K^2 r^2}{R_t^2} \tag{15}$$

where η is the power take-off coefficient (with the physical meaning of a viscous damping) and $u_c(t)$ a suitable control function that allows to control the engagement of the power take-off system. In detail, in the framework of a bang-bang control strategy, $u_c(t)$ is such that $u_c \in \{0, 1\}$, with $u_c = 1$ (respectively, $u_c = 0$) corresponding to the case in which the oscillating flap gate is connected (respectively, disconnected) to the harvesting circuit.

The average harvested electric power over a period T can be written in the form

$$\overline{P} = \frac{1}{T}\int_0^T u_c(t)P_{YY}(t)\,dt = \frac{1}{T}\int_0^T u_c(t)R_t I^2 dt \qquad \text{with} \qquad I = \sqrt{\frac{3}{2}}\frac{Kr}{R_t}\dot{\Theta} \tag{16}$$

I being XXX ??? (what kind of current??? of phase? effective? of line?).

RESULTS

The previously-introduced system for wave energy conversion has been analyzed in order to investigate the effectiveness of a bang-bang control strategy. In detail, the system dynamics described by Eq. (11) has been numerically simulated by referring to a parallelepipedic oscillating flap gate as in Fig. 1 approached by an incident monochromatic plane wave and located in a channel. The gate is characterized by a mass $M = 850$ kg, a moment of inertia $I_\theta = 1.2927 \times 10^3$ kg m^2, the along-y width equal to 3 m, the along-x thickness equal to 1.5 m, and oscillating in a water channel with a depth equal to $h = 2$ m. Correspondingly, the restoring coefficient C has been set equal to $C = 8.8229 \times 10^4$ kg m^{2}s^{-2}. Available closed-form solutions michele2016a, michele2016b for the scattering and radiating potentials are employed to compute the frequency-dependent amplitude of the exciting torque $\overline{T}_D$, as well as the terms in Eq. (11) associated to radiation damping and added inertia.

The power take-off system is assumed to be characterized by $r = 300$, $K = 15$ Wb and $R_t = 211.5\,\Omega$.

The bang-bang control strategy has been applied by turning on the connection between the flap gate and the PTO (namely, $u_c = 1$) for time intervals centered about the time values where the gate velocity is expected to attain maximum values. Such a condition is estimated by referring to the phase shift between the excitation and the gate response in the case of a null power take-off torque (namely, by referring to the scenario in which the gate and the PTO system are not connected). The optimization problem consist to find a control law $u_c(\cdot) : \mathbb{R}^2 \to [0, 1]$ which minimizes the cost

$$J = -\overline{P} = -\frac{3K^2 r^2}{2TR_t}\int_0^T u_c(t)\dot{\Theta}(t)dt. \tag{17}$$

By referring to a time interval equal to one period of the exciting condition, Fig. 3 depicts the electrical power extracted on average as a function of the percentage of the time interval in which the control is active (namely, the flap gate is connected to the PTO system). It is worth observing that the case of 100% control (namely, PTO system always engaged) must be intended to be representative of the harvesting scenario without control and is used as a benchmark in order to evaluate the control performance. As it clearly appears, the proposed numerical results show that the optimal condition occurs when the control percentage is about 18%, corresponding to an enhancement of approximately 21% in the average extracted power in comparison to the case without control.

Figure 4 shows the system behavior with (in blue) and without (in orange) control. In the case without control, when the device is subject to higher damping as it is always connected to the circuit, the maximum displacement and velocity amplitudes are smaller, and there is always current flowing in the electric circuit. For the case with control, it is noticeable when the control is on, and the device is connected to the circuit, as the phase space presents a sharp decrease in the absolute value of the velocity, and there is current running through the circuit.

CONCLUSIONS

In this paper the effectiveness of a bang-bang control strategy applied to an Oscillating Wave Surge Converter, conceived for harvesting energy from the wave motion in a channel, has been addressed. The harvesting system has been defined by an oscillating flap gate connected to a power take-off system comprising a permanent magnet generator and a simple resistive harvesting circuit. The proposed numerical results, obtained by describing the system dynamics in the framework of a linearized approach based on the potential flow theory and on the assumptions of small-amplitude waves and small gate oscillations, prove that the adopted control strategy allows to enhance the extracted electric power in comparison to the case of the control absence. In detail, by referring to optimal conditions, proposed results highlight an increment up to 21% in the average harvested power when the control is applied.

ACKNOWLEDGMENTS

REFERENCES

[Baker and Mueller(2001)] Baker, N.J., Mueller, M.A., 2001. "Direct drive wave energy converters". *Renewable and Sustainable Energy Reviews*, Vol. 1, pp. 1–7.

[Budal *et al.*(1982)] Budal, K., Falnes, J., Iversen, L.C., Lillebekken, P.M., Oltedal, G., Hals, T., Onshus, T., Høy, A.S., 1982. "The Norwegian wave-power buoy project". In *Proceedings of the 2nd International Symposium on Wave Energy Utilization*. Trondheim, Norway.

[Chapman(2005)] Chapman S.J., 2005. *Electric machinery fundamentals - 5th edition*. Mc-Graw-Hill.

[Falcão(2010)] Falcão, A.F. de O., 2010. "Wave energy utilization: A review of the technologies". *Renewable and Sustainable Energy Reviews*, Vol. 14, pp. 899–918.

[Falnes(2002)] Falnes, J., 2002. *Ocean waves and oscillating systems: linear interactions including wave-energy extraction*. Cambridge University Press.

[Falnes(2007)] Falnes, J., 2007. "A review of wave-energy extraction". *Marine Structures*, Vol. 20, pp. 185–201.

[Gunawardane *et al.*(2019)] Gunawardane, S., Folley, M., Kankanamge, C.J., 2019. "Analysis of the hydrodynamics of four different oscillating wave surge converter concepts". *Renewable Energy*, Vol. 130, pp. 843–852.

[Hirohisa(1982)] Hirohisa, T., 1982. "Sea trial of a heaving buoy wave power absorber" In *Proceedings of the 2nd International Symposium on Wave Energy Utilization*. Trondheim, Norway.

[Hodgins *et al.*(2010)] Hodgins, N., Keysan, O., McDonald, A., Mueller, M.A., 2010. "Linear generator for direct drive wave energy applications". In *Proceedings of the XIX International Conference on Electrical Machines - ICEM 2020*. Rome, Italy.

[McCormick(1981)] McCormick, M.E., 1981. *Ocean wave energy conversion*. Wiley-Interscience.

[Mei *et al.*(2005)] Mei, C.C., Stiassnie, M., Yue, D. K.-P., 2005. *Theory and applications of ocean surface waves*. World Scientific.
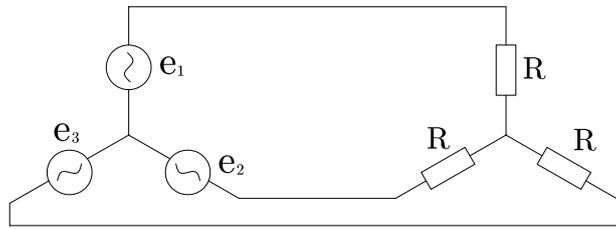
Figure 2 – PTO system: Y-Y connection between the three-phase generator and balanced purely resistive loads.
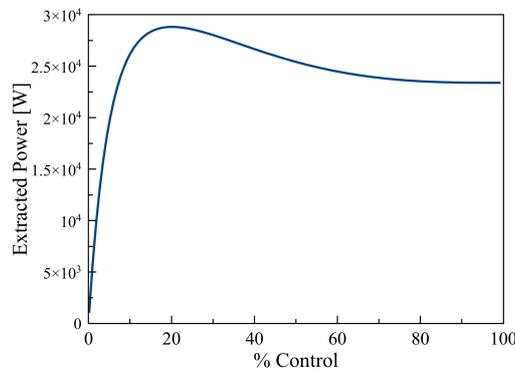

Figure 3 – Average extracted power vs. the control percentage (i.e., control duration percentage with respect to the observation interval). The case of 100% control corresponds to the harvesting scenario without control.
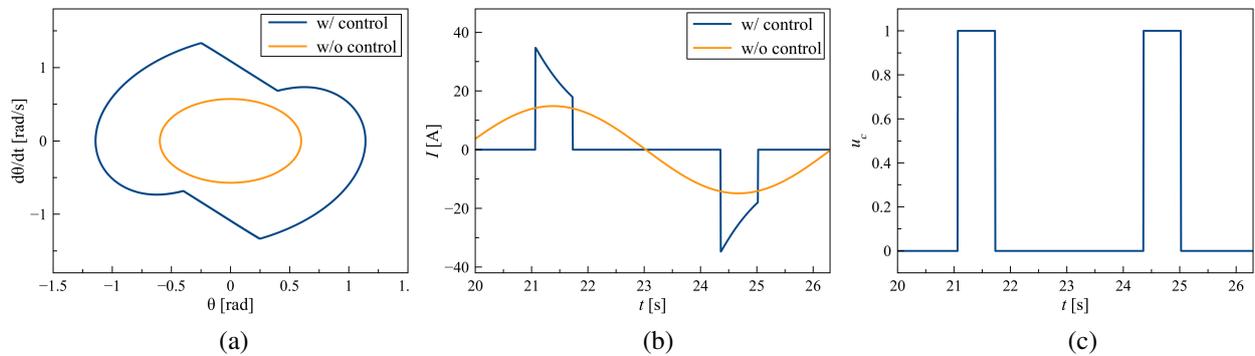

Figure 4 – System response with optimal control and without control. (a) Phase space. (b) Current I vs. time. (c) Control function u_c vs. time at the optimal state.

[Michele *et al.*(2016a)] Michele, S., Sammarco, P., d'Errico, M., 2016. "The optimal design of a flap gate array in front of a straight vertical wall: Resonance of the natural modes and enhancement of the exciting torque". *Ocean Engineering*, Vol. 118, pp. 152–164

[Michele *et al.*(2016b)] Michele, S., Sammarco, P., d'Errico, M., 2016. "Theory of the synchronous motion of an array of floating flap gates oscillating wave surge converter". *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 472, p. 20160174.

[Mueller(2002)] Mueller, M.A., 2002. "Electrical generators for direct drive wave energy converters". *IEE Proceedings - Generation, Transmission and Distribution*, Vol. 149, pp. 446–456.

[Mueller *et al.*(2007)] Mueller, M.A., McDonald, A., Ochije, K., Jeffrey, J., 2007. "A novel lightweight permanent magnet generator for direct drive power take off in marine renewable energy converters". In *Proceedings of the 7th European Wave and Tidal Energy Conference - EWTEC 2007*. Porto, Portugal.

[Salter *et al.*(2002)] Salter, S.H., Taylor, J.R.M., Caldwell, N.J., 2002. "Power conversion mechanisms for wave energy". *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, Vol. 216, pp. 1–27.

[Thorburn and Leijon(2007)] Thorburn, K., Leijon, M., 2007. "Farm size comparison with analytical model of linear generator wave energy converters". *Ocean Engineering*, Vol. 34, pp. 908–916.

[Whittaker *et al.*(2007)] Whittaker, T., Collier, D., Folley, M., Osterried, M., Henry, A., Crowley, M., 2007. "The development of Oyster - a shallow water surging wave energy converter" In *Proceedings of the 7th European Wave and Tidal Energy Conference - EWTEC 2007*. Porto, Portugal.

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