



A maximum capture width tracking controller for ocean wave energy converters in irregular waves



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ABSTRACT

A maximum capture width tracking (MCWT) controller for ocean wave energy converters is presented. The MCWT controller is a maximum power point tracking (MPPT) controller modified to account for incoming wave conditions as well as WEC power output. The MCWT controller will be applied to latching control of an oscillating water column with Wells turbine, optimising the latching time based on sea state. The performance of the proposed MCWT latching controller will be compared to that of an MPPT latching controller in both stationary and transitioning sea states. In stationary seas, it will be shown that both controllers can optimise capture width to within the bounds of certainty that the optimal capture width can be known for a WEC in stochastic waves. In transitioning seas, it will be shown that the MCWT controller is robust to a changing environment, whereas the MPPT controller is not.

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1. Introduction

Ocean wave energy harvesting has been a popular area of research since the 1970s oil crisis (Cruz, 2008). However, despite over 40 years of effort, wave energy remains in the research and prototype stages, with only a few pilot plants connected to grid worldwide (Hughes and Heap, 2010). The challenge preventing commercialisation of ocean wave energy harvesting is the efficient conversion of the highly variable broadband wave energy resource to grid frequency electricity. Feedback controlled oscillating systems have been a popular solution to this power conversion problem due to their versatility and ease of deployment (Lattanzio and Scruggs, 2011), with heaving buoys and oscillating water columns (OWCs) both receiving considerable attention over the years.

A feedback control strategy for oscillating wave energy converters (WECs) that has received considerable research attention over the years is latching. Latching is a passive, non-linear control method which attempts to achieve optimum phase between the excitation force and wave energy converter velocity, therefore maximising real power, by fixing the motion of the WEC during parts of the cycle (Clément and Babarit, 2012). Latching has been

used to control the natural period of a WEC heaving in regular waves (Clément and Babarit, 2012; Babarit and Clément, 2006; Babarit et al., 2004), where power absorption was found to increase for sub-resonant and post-resonant frequencies when the natural period was controlled to be equal to the incident wave period, and three times the incident wave period, respectively. Optimal latching times for the 4-DoF SEAREV device were derived using Pontryagin's maximum principle (Babarit and Clément, 2006), resulting in performance increasing by a factor of two in simulated ocean waves compared to the uncontrolled system. Small scale experiments involving an OWC with a simple threshold latching controller found that latching increased the efficiency in irregular waves by 200–350% compared to the uncontrolled case (Lopes et al., 2009).

Optimal latching of a floating spar-buoy OWC with bi-radial turbine was studied in Henriques et al. (2016) considering full scale air compressibility. The optimal latching controller was implemented using a receding horizon formulation, where the optimal latching and unlatching times over a future time-period, or horizon, were determined using Pontryagin's maximum principle considering exact knowledge of the excitation force time-series over the future horizon. Simulations of the optimally latched WEC in irregular waves found that latching could significantly increase capture width if the controller horizon exceeded the energy period of the sea state, however, for shorter horizons, the optimal latching controller was found to be less effective than a fixed passive damping. In reality, this means that for optimal latching to be

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effective, the WEC exciting force time-series must be predicted accurately over a horizon at least as long as the energy period of the sea state. In Ringwood (2012) it was found that the exciting force could be predicted accurately, quantified as less than 40% error, approximately 0.5–1 wave periods into the future depending on the bandwidth of the sea state, which is shorter than the energy period and insufficient for optimal latching control. In general, WEC controllers which maximise power on a wave-by-wave basis are not currently feasible due to the requirement for accurate prediction of incoming waves (Babarit et al., 2012). Hence, whilst latching can significantly improve the performance of a WEC, optimisation is difficult due to the need for future wave information and an optimal latching control strategy has yet to be implemented in the real world (Clément and Babarit, 2012).

Motivated by the difficulty of wave prediction, non-model based adaptive controllers have been developed which optimise WEC power take-off (PTO) parameters based on the current sea state. Adaptive control schemes of extremum seeking control and maximum power point tracking have been applied to WECs. Adaptive controllers, colloquially referred to as “perturb and observe”, work in the WEC power extraction sense by slightly altering an aspect of the PTO, such as the spring stiffness or damping, determining if the perturbation caused the extracted power to increase, and continually perturbing in an attempt to find the point of maximum power. Extremum seeking control was investigated in Hals et al. (2011) to optimise PTO damping for a heaving WEC with constrained motion in non-stationary sea states. The extremum seeking controller yielded better performance for the non-linear WEC than a gain scheduled damping controller, however, as an optimal damping profile for the non-stationary sea state was not given, it is unknown how damping produced by the controller compared to optimal. Extremum seeking control was used to maximise extracted power in a simulated heaving WEC in stationary irregular waves (Garcia-Ross et al., 2012), with the controller found to perform effectively for both linear and nonlinear PTO. The extremum seeking controller in Garcia-Ross et al. (2012) was truly model independent, unlike (Hals et al., 2011) which required estimates of the instantaneous exciting force, however, the efficacy of this model independent controller in non-stationary sea states is yet to be verified.

Maximum power point tracking (MPPT), a gradient-ascent type method commonly used in wind and solar energy converters, has been investigated for adaptive PTO control in a WEC (Amon et al., 2009, 2012), where the load resistance of a linear generator was tuned by varying the duty cycle of a buck converter. The investigation considered a surface following WEC, effectively neglecting hydrodynamics, and focused on the effects of varying the update rate and step size of the MPPT algorithm on the average power output for a single sea state. It was concluded that MPPT could significantly improve average power output in stationary irregular waves. Real ocean waves, however, are not stationary, and MPPT algorithms are known to become confused in changing environmental conditions as the controller cannot determine the cause of a change in measured output power (Abdullah et al., 2012; Kazmi et al., 2010, 2011). MPPT controllers which are robust to environmental changes have been developed for wind turbines (Kazmi et al., 2011) by combining wind speed measurements, to detect changes in the environment, with output power measurements to determine if the maximum power point had been reached.

A similar control algorithm to Kazmi et al. (2011) has been applied to a WEC by measuring incoming wave power in addition to WEC power to track the maximum capture width (Ding et al., 2015). The maximum capture width tracking algorithm (MCWT) was used to control PTO damping for a heaving, submerged WEC in irregular waves. MCWT was found to drive PTO damping

towards optimal in both stationary and transitioning sea states, however, the damping was then found to oscillate randomly about optimal. It was explained that the gradient-ascent type controller became ineffective when the sensitivity of the capture width to damping change was less than the variance of the capture width estimate, which occurred when the slope of the power vs. damping characteristic was shallow. Hence, it was shown that MCWT could optimise damping to within some bounds dependent on WEC dynamics.

This work will expand on Ding et al. (2015) by investigating the performance of MPPT and MCWT latching control of an OWC in irregular waves. MPPT/MCWT latching controllers will be used to optimise the latching time of an OWC with Wells turbine in both stationary and transitioning sea states. A mathematical model of an OWC with Wells turbine will be presented in Section 2, followed by details of the MPPT/MCWT algorithms in Section 3, and simulation methods in Section 4. Results of Monte-Carlo simulations will be used in Section 5.1 to determine confidence intervals for the capture width estimate and optimisation bounds for the latching time, before results of MPPT/MCWT latching control simulations are presented in Section 5.3. The MPPT/MCWT latching control results will show that in stationary sea states both latching controllers can optimise capture width to within the confidence bounds that the optimal capture width can be known. In transitioning sea states it will be shown that MCWT control is superior to MPPT. Finally, a brief investigation into OWC performance in bi-modal waves will be performed, where it will be concluded that MCWT latching control can be effective in bi-modal seas.

2. Mathematical model

Hydrodynamic models of wave energy converters (WECs) are typically estimated based on linear wave theory, which is a good approximation for WECs operating in waves of moderate amplitude. The assumption of linearity allows for the net flux through the turbine to be considered as the sum of separate scattering and radiation fluxes (Evans, 1982);

$$\begin{aligned} Q^T(\omega) &= Q^S(\omega) - Q^R(\omega) \\ &= \eta(\omega)q^S(\omega) - \frac{i\omega p_c}{\rho g}q^R(\omega) \end{aligned} \quad (2.1)$$

where $Q^T(\omega)$ is the net flow of water into the OWC chamber, $Q^S(\omega)$ and $Q^R(\omega)$ the net scattering and radiation fluxes respectively, η the incoming wave amplitude, ω the wave frequency, ρ is the water density, g is gravitational acceleration, p_c is the air pressure inside the OWC chamber, $q^S(\omega)$ is the scattering flux induced by a wave of unity amplitude and $q^R(\omega)$ the radiation flux induced by unity amplitude air pressure oscillation. Furthermore, the radiation can be decomposed into real and imaginary parts (Evans, 1982);

$$-\frac{i\omega p_c}{\rho g}q^R(\omega) = [B(\omega) - iA(\omega)]p_c \quad (2.2)$$

where $B(\omega)$ and $A(\omega)$, defined as the radiation conductance and susceptance respectively (Falnes, 2002), are real, frequency dependent quantities analogous to damping and added mass respectively in a rigid body system (Evans and Porter, 1995).

A two-dimensional OWC was considered, a schematic of which is shown in Fig. 1. The scattering and radiation flux problems for the OWC were solved at discrete frequencies using a Galerkin approximation (Evans and Porter, 1995), considering 500 evanescent modes and five Chebyshev polynomial test functions to represent the velocity of each mode. The radiation flux transfer function, $H^R(\omega) = B(\omega) - iA(\omega)$, was identified using a least

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