Applied Ocean Research 48 (2014) 236–243

Contents lists available at ScienceDirect

Applied Ocean Research

journal homepage: www.elsevier.com/locate/apor

Effect of non-ideal power take-off on the energy absorption of a reactively controlled one degree of freedom wave energy converter

Romain Genest, Félicien Bonnefoy, Alain H. Clément, Aurélien Babarit*

Ecole Centrale de Nantes – CNRS, 1 Rue de la Noë, Nantes 44000, France

ARTICLE INFO

Article history:
Received 5 March 2014
Received in revised form 16 July 2014
Accepted 7 September 2014
Available online 30 September 2014

Keywords:
Wave energy converter
Reactive control
Efficiency

ABSTRACT

In this paper, the effect of non-ideal actuators on the performance of reactive control for a heaving wave energy converter is studied. The concept of the control is to cancel all or part of the reactive terms in the equation of motion. The proposed control is causal, thus it may be applied in practice. Actuators efficiencies from 50 to 100% are considered.

The methodology used in the study relies on mathematical and numerical modeling. Control performance is investigated in regular waves and in irregular waves, and also from the perspective of the annual mean absorbed power at a typical Western Atlantic site. Motion constraints are not taken into account in the analysis for sake of simplicity.

As already shown in previous work, it is found that reactive control can increase the mean annual power absorption at the considered site by a factor 10 in case of ideal actuators. However, it is shown that actuators efficiency is critical to control performance, because of the large amount of reactive power involved in the control strategy. Thus, for low efficiencies actuators (<80%), control performance is a fraction of what it can be with ideal actuators (approximately 10%). Even with 90% efficiency, control performance is less than 30% of the ideal case. In the range 90–100%, every percent of increase in efficiency leads to significant increase in control performance.

1. Introduction

During the last decades, control strategies have been developed in order to increase the energy performance of wave energy converters (WECs) [1,2]. Model predictive control [3,4], latching [5,6], declutching [7], phase and amplitude control [8], and reactive control [9] are examples of the diversity of control strategies which have been studied.

In theory, reactive control is the best control as it allows reaching the theoretical maximum energy absorption [10–12] by bringing artificially the buoy to resonance [2]. However, it comes with difficult issues and drawbacks: the optimal reactive control is known to be anti-causal (meaning that it requires prediction of the future of the incident wave and wave excitation force [13]); its practical implementation goes with stability problems; last but not least, it involves to deal with large reactive power flux (as bringing the system to resonance requires canceling the reactive terms in the equation of motion). It was shown in [9] that the maximum of reactive power could be larger than ten times the average power. This is a difficult issue when implementing this control strategy to non-ideal actuators, as energy losses in these components might be equivalent or even larger than the energy gain obtained thanks to control.

In [14], a two-dimensional oscillating water column with optimal reactive control was considered. It was shown that optimal reactive control provides maximum energy absorption, but not maximum energy production due to power take-off losses. A 'phase-lag reduction' technique was proposed in order to maximize energy production. However, it cannot be applied in practice because of causality and stability issues. More recently, it was shown in [15] that a trade-off can be obtained between high average power absorption and actuators limitations by applying power saturation techniques. In [16], results for absorbed energy and produced energy are shown for the Wavestar WEC prototype in Denmark. Reactive control consists of applying a force proportional to the motion with a coefficient optimized for each sea state. It is shown that greater power generation is achieved when the coefficient is optimized with respect to the energy production instead of wave energy absorption. In [17], a heaving WEC with reactive control is considered with 90% energy efficiency for the control actuators. It is shown that reactive control still allows an increase in the performance of the WEC. However, the optimal control with taking into account 90% efficiency is different from the optimal control with ideal actuators (100% efficient). In [18], it is shown how

---

* Corresponding author. Tel.: +33 240371623.
E-mail address: aurelien.babarit@ec-nantes.fr (A. Babarit).

0141-1187/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2014.09.001

ϵ	reactive part of equation of motion at ω frequency (Ns/m)
ϵ_0	reactive part of equation of motion at ω_0 frequency (Ns/m)
η	actuator efficiency [0; 1]
κ	control coefficient [0; 1]
λ	efficiency coefficient ($\mathbb{R}^+$)
μ_∞	added mass for infinite frequency (N/m)
ω_0	natural frequency (rad/s)
A	added mass (Ns/m)
A_s, B_s	coefficients of the Bretschneider energy spectrum ($\mathbb{R}^+$)
A_W	water plane area (m^2)
B	radiation damping coefficient (Ns/m)
B_{PTO}	power take-off damping coefficient (Ns/m)
$F_{control}$	control force (N)
F_{ex}	wave excitation force (N)
F_{PTO}	power take-off force (N)
$H_{1/3}$	significant wave height (m)
J	wave energy flux per unit wave crest (kW/m)
K	impulse response function of radiation force (N/m)
k	wave-number (m^{-1})
K_H	hydrostatic stiffness (N/m)
M	physical mass (kg)
$P_{control}$	control power (W)
P_{grid}	power flow at grid connection point (W)
P_{PTO}	PTO absorbed power (W)
S	energy spectrum (m^{2}s)
V	velocity of the buoy (m/s)
$X, \dot{X}, \ddot{X}$	position, velocity and acceleration (m, m/s, m/s^2)

the force and amplitude limitations affect the energy absorption under a reactive causal control.

In this paper, we address the effect of energy efficiency on the performance of a heaving WEC with *partial* reactive control [15]. The aim is to investigate what is the actual benefit of partial reactive control as a function of the energy efficiency of the actuators. Partial reactive control is considered because it has a high potential for performance improvement and because it is a practical option at present since it does not require prediction of the incident wave elevation or wave excitation force. It is shown that optimal power take-off and control coefficients are highly dependent on the energy efficiency of the control system and the control performance (defined as the ratio of averaged power delivered to the grid to the grid averaged power with ideal actuators) decreases rapidly with decreasing efficiency.

Firstly, a partial sub-optimal reactive control is applied on a floating heaving WEC under regular wave excitation. Theoretical optimal values are derived for the maximization of the energy absorption from a WEC with non-ideal actuators. Eventually, irregular waves are considered in order to determine the impact of the conversion efficiency on the energy absorption in a more realistic environment.

2. Methods

2.1. Equation of motion of a heaving wave energy converter with ideal control

The wave energy converter under consideration is a floating buoy restrained to move in the heave degree of freedom only. The buoy has a cylindrical shape of 10 m diameter and 10 m draft. The water depth is supposed to be infinite. The control elements are split in two parts: a passive power take-off (PTO) modeled by a linear damper and an active actuator used to bring the system close to resonance; modeled as a motor.

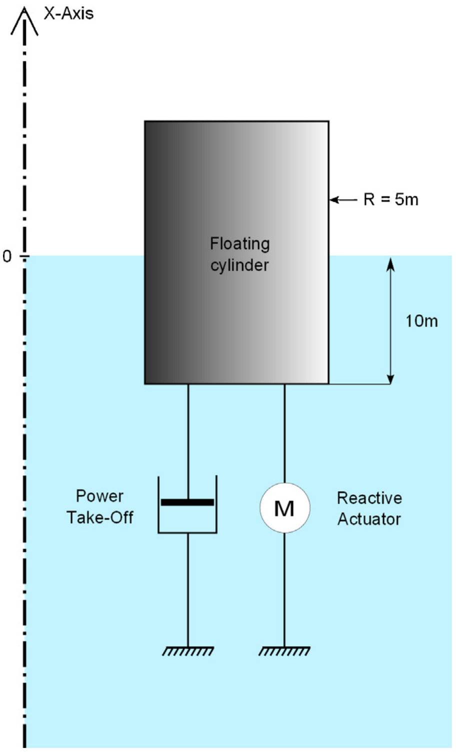

Fig. 1. Schematic of the considered heaving wave energy converter.

Let us assume the fluid to be incompressible, inviscid and the flow to be irrotationnal. The amplitude of motion and waves are considered small enough so that linearized potential theory may be used. Thus, the equation of motion of the wave energy converter can be written as follow (Fig. 1):

$$(M + \mu_\infty)\ddot{X}(t) + \int_0^t K(t-\tau)\dot{X}(\tau)d\tau + K_H X(t) = F_{ex}(t) + F_{PTO}(t) + F_{control}(t) \qquad (1)$$

with

- $X, \dot{X}, \ddot{X}$ are respectively the heave motion, velocity and acceleration of the buoy.
- M is the physical mass.
- $-\mu_\infty\ddot{X} - \int_0^t K(t-\tau)\dot{X}(\tau)d\tau$ corresponds to the radiation force in which μ_∞ is the infinite frequency added mass and K is the radiation velocity impulse response. According to the classical Cummins' decomposition [19], these two terms correspond to the effect of wave radiated by the body after an impulsive velocity at $t = 0$. One can further approximate this function by a sum of N complex functions such as $K \simeq \sum_{j=1}^{N} \alpha_j e^{i\beta_j t}$ whose complex coefficients (α_j, β_j) can be obtained by using Prony's method [20]. Thus, after this approximation, one can show that the convolution product can be replaced by a sum of N additional radiative complex states $\int_0^t K(t-\tau)\dot{X}(\tau)d\tau = \sum_{j=1}^{N} I_j$, each I_j given by a simple ordinary differential equation $\dot{I}_j = \beta_j I_j + \alpha_j \dot{X}$. More details on the method can be found in [6].
- $K_H = \rho g A_W$ is the hydrostatic stiffness with A_W the water plane area.