Ocean Engineering 126 (2016) 299–312

Contents lists available at ScienceDirect

Ocean Engineering

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

Sea-state based maximum power point tracking damping control of a fully submerged oscillating buoy

Boyin Ding[a,*], Benjamin S. Cazzolato[a], Maziar Arjomandi[a], Peter Hardy[a], Bruce Mills[b]

[a] School of Mechanical Engineering, University of Adelaide, Adelaide, SA 5005, Australia
[b] School of Mathematics and Statistics, University of Western Australia, WA, 6009, Australia

ARTICLE INFO

Keywords:
Maximum power point control
Wave energy convertor
Fully submerged buoy
Tether coupling
Hydraulic PTO
Wave variability

ABSTRACT

Optimal control has been studied for over two decades in the field of ocean wave energy extraction. However, most algorithms require not only extremely detailed models of the plant but also wave prediction, leading to difficulties when implementing these algorithms in reality. This paper investigates the use of maximum power point tracking (MPPT) control – a simple gradient-ascent algorithm well developed for solar and wind energy – on a novel wave energy converter comprising a fully submerged oscillating buoy and a tether coupled hydraulic power-take-off (PTO) unit. A study of the sensitivity of control to irregular wave fluctuations/variability was proposed to systematically determine the step size and update rate of MPPT controller. The world's first commercial scale fully submerged wave energy converter (WEC), Carnegie's CETO system, was used as a test case to assess the proposed methodology under passive damping control. Optimization was done on the CETO system based on typical Australian sea sates in order to benchmark the performance of MPPT control. Simulation results demonstrated that the MPPT damping controlled system is more effective and robust compared to the fixed-damping system with a globally optimized generator damping. The power loss of the MPPT damping controlled system due to tracking and wave/sea state variability is 1.9% of the acausal optimal damping controlled system.

1. Introduction

The ocean presents a promising yet challenging environment for energy extraction. Optimal control for energy extraction is well defined for a wave energy converter (WEC) when using simplified assumptions, such as a monochromatic wave environment, known plant dynamics and linear hydrodynamics (Falnes, 2007). However, a real wave environment, as well as physical WEC constraints such as force, velocity, and position limits, makes a classical optimal approach to WEC control difficult, which may result in suboptimal power extraction or potential damage to the system. Recent work on WEC control, motivated by the difficulty in producing accurate estimation of excitation force, has yielded novel approaches intent on avoiding the prediction problem using non-model based adaptive controllers.

Maximum Power Point Tracking (MPPT) is a non-model based adaptive control algorithm, commonly found in wind and solar energy converters (Koutroulis and Kalaitzakis, 2006; Xiao et al., 2007; van Dam et al., 2012), which uses a gradient-ascent method to optimise power. MPPT control schemes, colloquially referred to as "perturb and observe", work in the WEC power extraction sense by slightly altering an aspect of the power-take-off (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. The authors of this paper investigated the performance of MPPT adaptive approach on the latching control of oscillating water column (OWC) (Hardy et al., 2016) under regular/irregular wave conditions. Simulation results demonstrated that system nonlinearities, as well as wave variability, have the potential to result in suboptimal power output for an OWC. Amon et al. (2012) investigated MPPT control for an oscillating body WEC, where the load resistance of a linear generator was tuned by varying the duty cycle of a buck converter. They investigated the effects of varying the update rate and step size of the MPPT algorithm on the average power output of the system for a single sea state. It was concluded that MPPT can successfully find the optimal value of the control parameter and therefore significantly improve average power output of the system in irregular waves. However, there were a number limitations in their study. Firstly, the study only considered a single sea state scenario. Secondly, it was assumed that the instantaneous position of the floating oscillating body is equal to the instantaneous water surface elevation. In other words, the system dynamics are assumed to be that of a "wave follower". The authors stated that this was typical for a device with a

* Corresponding author.
E-mail address: boyin.ding@adelaide.edu.au (B. Ding).

http://dx.doi.org/10.1016/j.oceaneng.2016.09.020
Received 1 September 2015; Received in revised form 8 September 2016; Accepted 12 September 2016
0029-8018/

large-diameter float and very high buoyancy (e.g. high hydrostatic stiffness). It is well known that hydrodynamics (e.g. excitation force and radiation force) play a significant role in the absorbed power and therefore the assumption of "wave follower" limited the generality of the study. In addition, the assumption of a linear PTO and heave point absorber further simplified the MPPT control problem because the assumption inherently forced the mapping between the control parameter (e.g. generator duty cycle) and the absorbed power to be convex.

In this paper, a fully submerged oscillating buoy tethered by a hydraulic PTO unit is the system of interest under MPPT control for the following reasons. The oscillating body (buoy) is typically assumed to be partly submerged in literature (Hals et al., 2011; Babarit and Clement, 2006). However, fully submerged WECs are becoming increasingly popular due to their reduced visual impact and increased survivability of storms. The hydrodynamics of fully submerged WECs can differ significantly from partly submerged WECs and must be separately investigated for controller design. In this paper, only the fully submerged case is considered. With regards to the coupling between the oscillating body and the PTO unit, the most common approach in practice is to use a pre-tensioned flexible tether, due to its advantages over a rigid pole connection which is a typical assumption in literature (Vicente et al., 2013; Bachynski et al., 2012). Firstly, the manufacturing/maintenance cost of such a tether is much lower than a rigid pole. Secondly, a tethered coupling makes the underwater installation of the WEC much easier. Finally, a flexible tether coupling allows heave, surge and pitch motions of the oscillating body, resulting in more absorbed power compared to a rigid pole coupling that constrains the absorber to heave motion only (Falnes, 2007). For an axisymmetric body, the use of a tethered coupling leads to a system of three oscillating modes, which in theory requires three tethers to achieve optimal power absorption (Srokosz, 1979; Sergiienko et al., 2016). However, a definitive study on the number of tethers is beyond the scope of this study due to additional control complexity, and therefore, only a single tether scenario is considered. In real-life devices, the most common PTO unit is hydraulic due to their maturity, high power density and robustness. This is an obvious advantage for offshore operations, where maintenance costs can be very high (Henderson, 2006; Cargo et al., 2012; Babarit et al., 2012). However, hydraulic PTO units exhibit nonlinear behaviour. It is likely that the hydraulic nonlinearity would result in non-convex mapping between potential control parameters (e.g. generator resistance) and output power of the generator, consequently degrading the performance of MPPT control. Besides the specific design of the WEC, the variability of real wave conditions is the main factor that can reduce the efficacy of MPPT control. Although this is intuitive, to the best knowledge of the authors, there has been no systematic investigation into this matter so far.

The primary goal of this study is to investigate the capacity of MPPT control on a fully submerged WEC tethered by a generic hydraulic PTO unit under real wave conditions. This will facilitate the applications of MPPT control in common WECs. As part of the work, a high fidelity wave-to-wire model was developed for the simulation study based on the well-known Cummins model with additional non-linear damping (Morison's formula). The nonlinear behaviour of the hydraulic system was considered in modelling. A sea-state based MPPT damping control strategy was formulated for a generic hydraulic PTO system. The proposed control strategy is fully passive, and therefore can be easily applied to a generic hydraulic PTO unit that can only operate in power generator mode (Hals). The world's first commercial-scale fully submerged WEC, Carnegie's CETO, was used as an example to present the simulation results.

2. Wave-to-wire model

A simplified WEC model consisting of a fully submerged cylindrical buoy and a hydraulic PTO unit is shown in Fig. 1. A pre-tensioned tether (2) connects the buoy to a single-acting hydraulic pump (3) that is part of the hydraulic PTO unit. Universal joints are placed at the mooring point of the hydraulic pump (C) and at the attachment point on the buoy (A), allowing the buoy (1) to move freely in the plane of the incoming wave. The motion of the buoy drives the hydraulic pump. The resulting motion of the pump piston relative to the pump cylinder drives fluid through a set of two check valves (4) to rectify the flow so that fluid always passes through the hydraulic motor in the same direction (independent of the direction of the buoy motion). A high pressure accumulator (5) is placed on the inlet to the hydraulic motor and a low pressure one (6) on the outlet of the hydraulic motor. The pressure difference between the two accumulators drives the hydraulic motor (7), which is connected to an electrical generator. The accumulators are included in the hydraulic PTO unit to keep an approximately constant pressure differential across the motor so it rotates at an approximately constant speed, and therefore, energy is transmitted at approximately a constant rate.

2.1. Dynamics model of the WEC

Assuming an incompressible fluid with zero viscous losses, linear wave theory can be used to solve the governing hydrodynamic equations. It is well known that linear wave theory is not capable of modelling the higher order dynamics of buoy-fluid interaction and may result in overestimation of the power absorption capacity of the WEC, particularly at high sea states (Falnes, 2007). Nevertheless, it is an effective computational tool for the study of control methods applied to WECs and is sufficient to analyse control systems. The dynamic equation for the buoy motion is (Falnes, 2007)

$$\mathbf{M}\ddot{\boldsymbol{x}} + \boldsymbol{F}_{\mathrm{r}} + \boldsymbol{F}_{\mathrm{hs}} = \boldsymbol{F}_{\mathrm{e}} + \boldsymbol{F}_{\mathrm{drag}} + \boldsymbol{F}_{\mathrm{m}}, \tag{1}$$

where $\boldsymbol{x}$ is a displacement vector that represents the surge x, heave z, and pitch θ motions of the buoy at the centre of gravity (COG),

$$\boldsymbol{x} = [x \quad z \quad \theta]^{\mathrm{T}}; \tag{2}$$

$\mathbf{M}$ represents the buoy mass matrix with the buoy mass m, and moment inertia I, at its diagonal axis

$$\mathbf{M} = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & I \end{bmatrix}; \tag{3}$$

$\boldsymbol{F}_{\mathrm{e}}$, the excitation force, is the force produced by the incident waves on an otherwise fixed body; The radiation force, $\boldsymbol{F}_{\mathrm{r}}$, is the force produced by an oscillating body creating waves on an otherwise calm sea; $\boldsymbol{F}_{\mathrm{hs}}$ is the hydrostatic fore; $\boldsymbol{F}_{\mathrm{drag}}$ is the form drag force; $\boldsymbol{F}_{\mathrm{m}}$ represents the PTO force acting at the buoy COG. Based on the schematics shown in Fig. 1, $\boldsymbol{F}_{\mathrm{m}}$ can be written as

$$\boldsymbol{F}_{\mathrm{m}} = \mathbf{T}\boldsymbol{F}_{\mathrm{PTO}}, \tag{4}$$

where $\boldsymbol{F}_{\mathrm{PTO}}$ is a vector denoting the PTO force along the tether and $\mathbf{T}$ represents the matrix which transports the PTO force applied at the attachment point to the buoy COG

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -d\cos(\theta) & d\sin(\theta) & 1 \end{bmatrix}, \tag{5}$$

where, d is the distance between the attachment point (A) and the buoy COG (G). It is worth noting that $\boldsymbol{F}_{\mathrm{m}}$ is a nonlinear function due to both tether attachment and hydraulic PTO behaviour (e.g. valve switching, pressure losses). Therefore, analysis of the system must be conducted in the time domain. Cummins (Cummins, 1962) developed a time-domain approach for investigating ship response to sea waves, which has been widely applied and accepted when investigating WECs. With this approach, the equation of motion takes the following form (Cummins, 1962)