Applied Ocean Research 69 (2017) 126–137

Contents lists available at ScienceDirect

Applied Ocean Research

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

Constrained near-optimal control of a wave energy converter in three oscillation modes☆

Umesh A. Korde[a,*], Jianyang Lyu[a], Rush D. Robinett III[a], David G. Wilson[b], Giorgio Bacelli[b], Ossama O. Abdelkhalik[c]

[a] Michigan Technological University, Houghton, MI, USA
[b] Sandia National Laboratories, Albuquerque, NM, USA
[c] Michigan Technological University, Houghton, MI, USA

ARTICLE INFO

Article history:
Received 30 May 2017
Received in revised form
17 September 2017
Accepted 17 October 2017
Available online 5 November 2017

Keywords:
Wave energy
Wave-by-wave control
Irregular waves
Wave prediction
Multiple modes

ABSTRACT

This paper investigates the performance of a small axisymmetric buoy under wave-by-wave near optimal control in surge, heave, and pitch modes in long-crested irregular waves. Wave prediction is obtained using a deterministic propagation model. The paper describes the overall formulation leading up to the derivation of the feedforward control forces in surge and heave, and the control moment in pitch. The radiation coupling between surge and pitch modes is accounted for in the model. Actuation is relative to deeply submerged reaction masses. Heave oscillations are constrained by the swept-volume limit. Oscillation constraints are also applied on the surge and pitch oscillations. The paper discusses time-domain simulations for an irregular wave input with and without the present control. Also discussed are results obtained over a range of irregular wave conditions derived for energy periods from 7 s to 17 s, and a significant wave height of 1 m. It is found that, while the gains in power capture enabled by the present control are significant, the actuation forces are also very large, given the small size of the buoy. Further, due to the small size, heave is found to be the dominant contributor to power capture, with relatively modest contributions from surge and pitch.

1. Introduction

Many wave energy devices developed over the last few decades utilize the oscillations of a floating body relative to a reference (e.g. submerged body, sea-floor, etc.) for energy conversion [1]. One way to improve the cost effectiveness of wave energy converters is to use small devices whose oscillations are actively controlled to enhance the energy capture in a range of wave conditions (see, for instance, [2]). Efforts to increase response bandwidth by controlling the phase of the force applied by the power take-off were first reported in the seventies [3,4]. For the Salter duck, active control was accomplished by including a reactive component, in addition to a resistive part, in the torque opposing the duck oscillation, and by independently adjusting the magnitudes of the resistive and reactive parts. Independently developed for small heaving point-absorber devices with short resonant periods was the 'latching' concept [5], where device oscillations would be alternately locked and released so that device velocity when unlocked would be synchronous with force. An extension of single-mode reactive control was a multiple-mode impedance matching approach termed 'complex-conjugate control' [6,7], etc., which could be applied in the frequency-domain for peak-frequency tuning in changing wave spectra. At-sea tests on reactive + resistive loading were performed a few years ago on prototypes of the Wave Star device [8], and a 2–3 fold improvement in annual power production was reported.

Latching control does not require reactive forces, and has received considerable attention in the literature (e.g. see [9–14], etc.). The latching sequence leading to best power capture was first determined using an optimal control framework in [9] with the device dynamic model providing a dynamic constraint. The optimum switching sequence was determined with the help of the Pontryagin Max/Min Principle (often following an iterative

☆ This work was carried out under a grant from the U.S. Defense Advanced Research Projects Agency (DARPA) under contract D16PC00143. The views, opinions and/or findings expressed are those of the authors and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

* Corresponding author.
E-mail address: uakorde@mtu.edu (U.A. Korde).

https://doi.org/10.1016/j.apor.2017.10.004
0141-1187/

Nomenclature

g	acceleration of gravity
ω	angular frequency
k	wave number
$\eta(x;i\omega)$	frequency-domain expression for wave surface elevation
$\mathbf{Z}_{ij}$	impedance in i-direction oscillation and i–j coupled oscillation
X_j, j = 1, 3, 5	frequency-domain displacements in the surge, heave, and pitch modes respectively
U_1, U_3, Ω_5	frequency domain velocity response of surge, heave and pitch, respectively
F_{L1}, F_{L3}, M_{L5}	near-optimal control forces and moment of surge, heave and pitch, respectively
M	in-air mass of vertical cylinder buoy
I_p	in-air moment of intertia of buoy in pitch mode
K_h	hydrostatic stiffness in heave mode
K_s	stiffness due to moorings, etc., in surge mode
K_p	hydrostatic stiffness in pitch mode
$\bar{a}_{ij}(\omega)$	frequency-dependent added mass; i = 1, 3, 5
$\bar{a}_{ij}(\infty)$	infinite-frequency added mass; i = 1, 3, 5
$a_{ij}(\omega)$	frequency-variable part of $\bar{a}_{ij}(\omega)$; i.e. $\bar{a}_{ij}(\omega)-\bar{a}_{ij}(\infty)$
R	radius of vertical cylinder buoy
D_r	draft of vertical cylinder buoy
F_1, F_3, M_5	exciting forces and moment of surge, heave and pitch
v_{so}, v_{ho}, v_{po}	frequency domain optimal velocity in surge, heave and pitch modes respectively
v_{so}, v_{ho}, v_{po}	frequency domain optimal velocity in surge, heave and pitch modes respectively
$\Lambda_{ii}(\omega)$	frequency domain constraint damping; i = 1, 3, 5.
c_{dii}	viscous damping coefficient; i = 1, 3, 5.
$u_{1o}\, u_{3o}\, \mho_{5o}$	time domain optimal velocity in surge, heave, pitch modes, respectively
$\Re(\cdot)\ \Im(\cdot)$	real and imaginary parts of complex arguments
P_{wr}	time-averaged converted power
$P_{rc}(t)$	instantaneous reactive power
ω_p	peak frequency in the incoming spectrum
H_s	significant wave height
T_e	energy period

approach). A declutching approach was later introduced mainly for devices with longer resonance periods than the prevailing energy periods [15,16]. With either latching or declutching the sudden application or release of large forces/moments can lead to transient vibrations through the entire system, which, in addition to the force/moment load magnitudes, should be considered early in the design process. In addition, the suitability of switching control to multiple-mode conversion also needs to be examined further.

Power conversion through a particular oscillation mode is maximized when oscillations occur at the hydrodynamically optimum velocity. In regular waves, as discovered in the tests on the duck, this is not possible without exchanging reactive power with the device, except at resonance. Application of reactive and resistive loads to produce correct impedance matching conditions on a wave-by-wave basis presents a fundamental challenge in irregular waves. As has been known since the mid-eighties, wave-by-wave control of a wave energy converter for maximum power conversion requires knowledge or prediction of the incoming wave field [17,18].

Use of multiple modes for energy conversion has been considered since the seventies, when controlled oscillation in the surge and heave modes for a submerged cylinder in terminator configuration was analyzed and tested as a way to provide nearly complete absorption of a long-crested incoming wave [19]. Favorable interaction between the diffracted (in two dimensions, generally both reflected and transmitted), and radiated waves made all of the incident wave energy available for conversion. The surge and heave oscillations of the submerged cylinder were controlled such that the cylinder centroid traced a circular orbit in the direction along the propagation direction of the incident wave (i.e., clockwise for a wave approaching from the left). A similar principle was adopted for power conversion in terminator configuration using the duck and spine oscillations in heave and surge modes (in addition to the duck pitch mode) [20].

Advantageous interaction among the incident, diffracted, and radiated wave fields could also be extended to three-dimensional devices, particularly, for axisymmetric omni-directional devices (see, e.g. [21]). In particular, it was shown that an axisymmetric buoy in unconstrained heave oscillation could convert all energy incident over a width $\lambda/(2\pi)$ under impedance matching conditions (λ being the wave length), thanks to the favorable interaction between the incident wave field with the diffracted wave field and symmetric, omni-directional radiated wave field. Unconstrained surge oscillation of an axisymmetric buoy under optimal conditions could enable twice as much energy capture as heave, because its radiated wave field was anti-symmetric and directional. Combined use of unconstrained surge and heave oscillations thus could allow three-times as much energy capture as heave alone [21]. Because of the radiation coupling between pitch and surge for axisymmetric converters (and the singularity of their combined radiation impedance matrix[1]), the maximum energy conversion enabled by unconstrained oscillations of an axisymmetric converted in surge, heave, and pitch modes was also three times that enabled by heave alone.

Practical oscillation constraints limit the actual increase possible, however, since (i) heave oscillations are subject to the swept volume limit (converter can neither fully submerge nor fully emerge), (ii) surge oscillations are limited by the mooring-line watch circle and impending dominance of viscous effects [22,23], and (iii) pitch oscillations could also be subject to the limit that no part of the deck should submerge nor no part of the keel should emerge. In addition, as oscillation amplitudes get large, the small-amplitude linearity assumption breaks down, as do many of the expectations based on linear theory.

This work investigates gains in power capture under wave-by-wave constrained control of heave, surge, and pitch oscillations. As pointed out above, hydrodynamically optimum velocity (as enabled when impedance matching conditions are achieved) requires a non-causal force at each instant, which cannot fully be evaluated without knowledge or prediction of information from the future. The approach attempts constrained impedance matching using prediction of incident wave elevation at the device centroid. A number of prediction approaches have been considered in the literature. For instance, surface elevation was predicted using a Kalman-filter as described by Budal and Falnes [5]. Fosberg [24] used an autoregressive moving average model to predict the wave surface elevation. Naito and Nakamura [17] used an up-wave surface elevation model and a deterministic propagation model [17]. Similar approaches were used by Belmont [25] and later by one of the authors [26]. In [26] the up-wave distance and length of the moving time-series were determined based on the range of group velocities included in an approaching sea state and the prediction duration as required by the radiation impulse response function for the converter. However, because the asymptotically decreasing device impulse response function was truncated at finite time

[1] The two oscillations can be driven such that their radiated wave fields cancel.