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Full Length Article

Preliminary consideration of energy storage requirements for sub-optimal reactive control of axisymmetric wave energy devices[☆]

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ABSTRACT

This paper investigates sub-optimal time-domain reactive control of wave energy devices based on real-time up-wave surface elevation information. The paper first presents the overall approach required for such control, and recalls the need for future force and response information due to the causality of the radiation force and the non-causality of the exciting force (in relation to the wave profile at device centroid). The present approach constitutes a long-wave approximation, and is based on linearized wave propagation and device dynamics models. The long-wave approximation allows direct use of the instantaneous up-wave surface-elevation measurement. For predominantly heaving axisymmetric primary energy converters in an approximately uni-directional irregular incident wave field, the amount of cumulative reactive energy is compared with the cumulative absorbed energy. Calculations are carried out for a heaving axisymmetric buoy, when floating and when fully submerged. Oscillations are assumed to be unconstrained, so as to obtain a basic understanding of the best performance improvements and the implementation challenges associated with the present control approach. Although the net reactive energy is zero in the absence of actuator losses, it is concluded, that the reactive force magnitudes and reactive energy requirements should be an important design-level consideration. Time-domain calculations show that the reactive energy requirements for the submerged buoy may be significantly greater (compared with the floating buoy) in spectra with energy periods ≥ 13 s.

1. Introduction

Active control of the hydrodynamic response of wave energy converters can enable over 2–5 fold increase in the overall efficiency depending on the device (Eidsmoen, 1996; Hansen & Kramer, 2011; Korde, 2014b; Salter, 1993), (i) allowing fewer, structurally efficient smaller units to meet the required power generation targets, and (ii) improving the overall annual productivity of the device. For many devices, the economic benefits thus resulting may significantly offset the added expense of providing control.

It was shown some decades ago, that hydrodynamic control for greatest energy conversion efficiency ("optimal") in irregular waves requires oscillation/exiting force information (Falnes, 1995; Naito & Nakamura, 1985) upto some duration into the future. Compromise solutions using velocity estimation based on time-series analysis of past velocities were reported some years ago (Korde, 1999; Korde, Schoen, & Lin, 2002).

A non-reactive time-domain switching control approach ('latching', later extended to declutching) using coordinated real-time application of intermittent braking forces was first tested in the seventies (Budal & Falnes, 1980), and later investigated by many authors (Babarit & Clement, 2006; Falcao & Justino, 1999; Hoskin, Count, Nichols, & Nicol, 1985; Korde, 2001; Perdigao & Sarmento, 1989, etc). The use of a high-pressure hydraulic power take-off was studied for a heaving buoy type device to optimize the converted hydraulic power in the time domain (Falcao, 2008). For a small, tubular oscillating water column device, a 'non-predictive' phase control strategy was also considered (Lopes et al., 2009), with the understanding that the radiation impedance was small. Frequency domain 'complex-conjugate control' approaches comprising adjustable reactive loading for selective tuning to changing wave spectra have been studied since the mid-seventies (Korde, 1991; Nebel, 1992; Salter, 1978), etc. Such an approach was tested recently on the Wavestar device in Denmark (Hansen & Kramer, 2011).

A coupled fuzzy logic-robust controller was used recently for short term tuning with incoming-wave prediction in Schoen, Hals, and Moan (2011). Some recently proposed time-domain control

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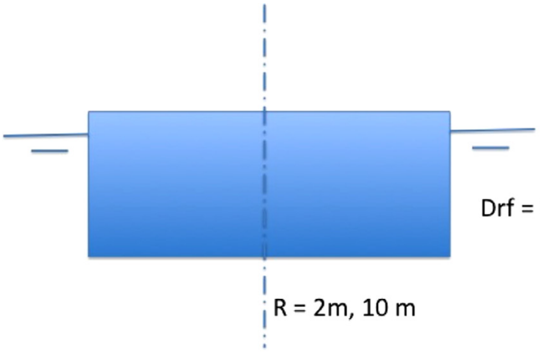
approaches were evaluated in Hals, Falnes, and Moan (2011a). A stochastic control approach based on past information only was recently investigated and found to produce good performance (Scruggs, Lattanzio, Taflanidis, & Cassidy, 2013). Constrained optimal control under 'hard' displacement and force constraints on the primary converter was reported recently in Hals, Falnes, and Moan (2011b), Bacelli and Ringwood (2013). The effect of device geometry on the 'prediction horizon' for real-time control was studied with a view to velocity/exciting force prediction (Fusco & Ringwood, 2012), and a technique for short-term wave forecasting for use in real-time control was examined in Fusco and Ringwood (2010).

The approach used in the present paper is based on hydrodynamics-driven modeling of wave propagation and device response and known results (Falnes, 1995; Korde, 2014b; Naito & Nakamura, 1985). Further, it is noted that over distances approaching 1–2 km, a deterministic linear-system type understanding of wave propagation may be valid for primarily uni-directional waves (Belmont, Horwood, Thurley, & Baker, 2006; Dannenberg, Naaijen, Hessner, den Boom, & Reichert, 2010), etc. X-band radar technology has been used in recent years for real-time prediction of ship motions using wave profile measurements 500–1500 m in the up-wave direction (Dannenberg et al., 2010) and could be employed in the present application.

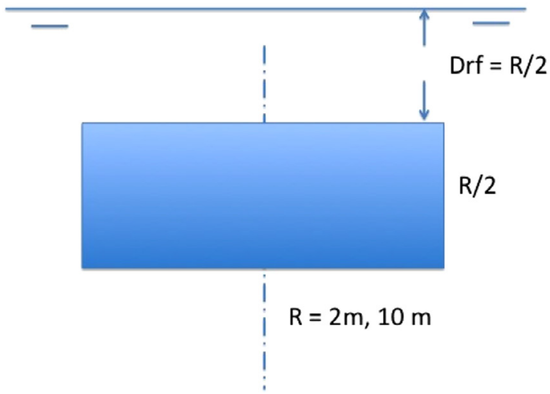
A wave-by-wave impedance matching control approach was investigated recently in Korde (2015), where the incident wave field at the device was predicted using a linear, deterministic wave-propagation model. Up-wave surface elevation time history over several seconds was used to predict the wave elevation at the device, at the required time duration into the future (∼15−30 s). In contrast to that work, the present paper concerns a sub-optimal strategy that only requires instantaneous up-wave surface-elevation measurements. Such an approximation may be justified in wave spectra dominated by long-period swells. In addition, it can be argued that the use of instantaneous (as opposed to time-histories of) up-wave measurements could be easier to implement in practice as it saves the measurement/computational effort associated with wave prediction, and/or exciting force prediction. This sub-optimal control strategy was discussed in Korde (2014b), though the long-wave approximation was not explicitly stated in that paper. Uni-directional waves are assumed here, although the present approach can be extended to multi-directional waves, in part, by incorporating additional directionally separated instantaneous measurements. It could be interesting to compare, in a more systematic study, the results of the present approach with results based on a time-series analysis and prediction approach that does not impose the present restrictions on the wave field.

The question addressed in this work concerns the cost of providing the type of control just discussed, in terms of the associated force and energy requirements. Fig. 1 shows the two primary converters considered in this paper. The power conversion characteristics for these devices under control were examined in Korde and Ertekin (2015). Although the time-averaged power absorption under control was found to be comparable for the two conditions, the improvement resulting from control was greater for the submerged buoy. The present paper briefly compares the reactive energy requirements for the two devices, and finds that control of the submerged buoy to provide the expected improvement requires greater reactive energy flow in swell-dominated spectra. Secondary conversion is by means of a double-acting hydraulic cylinder. The same cylinder is also used for control. A deeply submerged disc or the sea floor provides the reference for energy conversion.

Earlier work showed that the exciting force and radiation damping functions become flatter in the frequency domain with submergence depth, leading to narrower impulse response functions in the time domain (Korde & Ertekin, 2013). The impulse-response narrowing in turn enables shorter up-wave distances for wave profile measurement (Korde, 2014b). However, radiation damping decreases with submergence depth while the frequency-independent reactive terms such as rest mass and stiffness remain constant. Thus, though large reactive forces are probably to be expected for most small devices operating in swell-rich wave climates, these are likely to pose a greater challenge for submerged devices. Implications of this situation are studied here, and preliminary reasoning under some simplifying assumption indicates, that in spectra dominated by long-period swells, the device may need to draw from and pump into an on-board energy storage system and/or the grid or another device.



(a) Floating Buoy



(b) Submerged Buoy

Fig. 1. A schematic view of the floating and submerged cylindrical buoy devices studied in this work (see Korde & Ertekin, 2015). The goal here is to compare the reactive energy requirements for the two cases.

2. Real time approximate near-optimal control using up-wave surface elevation

For the axisymmetric body in predominant heave and operating in primarily uni-directional irregular waves propagating from left to right along the positive x axis, the linear equation of motion is Falnes (1995),

$$[m+\overline{\mu}(\infty)]\dot{v}+c_d v+\int_0^{\infty} h_r(\tau)v(t-\tau)d\tau + k_h\int_{-\infty}^{t} v(\tau)d\tau = F_f+F_r \tag{1}$$

Here m is the in-air mass of the body, $\overline{\mu}(\infty)$ the infinite-frequency added mass in heave, k_h is the hydrostatic stiffness, or stiffness offered by the hydraulic power take-off, c_d the constant damping in the system to approximate viscous losses, and $h_r(t)$ the radiation [without the contribution of $\overline{\mu}(\infty)$] impulse response kernel. The goal is to apply an instantaneous control force $F_r(t)$ such that the

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