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Wave energy converter control by wave prediction and dynamic programming

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ABSTRACT

We demonstrate that deterministic sea wave prediction (DSWP) combined with constrained optimal control can dramatically improve the efficiency of sea wave energy converters (WECs), while maintaining their safe operation. We focus on a point absorber WEC employing a hydraulic/electric power take-off system. Maximizing energy take-off while minimizing the risk of damage is formulated as an optimal control problem with a disturbance input (the sea elevation) and with both state and input constraints. This optimal control problem is non-convex, which prevents us from using quadratic programming algorithms for the optimal solution. We demonstrate that the optimum can be achieved by bang–bang control. This paves the way to adopt a dynamic programming (DP) algorithm to resolve the on-line optimization problem efficiently. Simulation results show that this approach is very effective, yielding at least a two-fold increase in energy output as compared with control schemes which do not exploit DSWP. This level of improvement is possible even using relatively low precision DSWP over short time horizons. A key finding is that only about 1 second of prediction horizon is required, however, the technical difficulties involved in obtaining good estimates necessitate a DSWP system capable of prediction over tens of seconds.

1. Introduction

Ocean waves provide an enormous source of renewable energy [1,2]. Research into wave energy was initially stimulated by the oil crisis of the 1970s [3]. Since then many different types of sea *wave energy converters* (WECs) have been designed and tested [4,5], but this is still a relatively immature technology (compared to solar or wind energy) and is far from being commercially competitive with traditional fossil fuel or nuclear energy sources. Progress is hampered by two fundamental problems:

1. Inefficient energy extraction, often due to the fact that the WEC's dynamic parameters are not optimally tuned and their control is not optimal for most wave profiles.
2. Risk of device damage. In order to prevent WECs from being damaged by large waves, they have to be shut down, especially during winter storms. Such periods of inactivity can last for days.

Extracting the maximum possible time average power from WECs, while reducing the risk of device damage involves a combination of good fundamental engineering design of the devices and effective control of their operation. The traditional approach to these issues exploits short term statistical properties of the sea [6] but it has been shown [7,8] that doing so severely limits the average power that can be extracted. We address the above two problems by considering schemes designed to achieve optimal control. It will be shown that (as [9–11] demonstrated in the 1970s) methods for achieving the maximum power output are inevitably non-causal and require prediction of the shape of the incident waves. The recent development of *deterministic sea wave prediction* (DSWP) as a scientific discipline [12–28], particularly real time DSWP [12–19,26,28] now makes such an approach realistic. For a variety of reasons high accuracy real time DSWP is very demanding. However it will be shown that the optimal control techniques described here provide considerable improvements over traditional WEC control methods, even with modestly accurate DSWP and relatively short prediction horizons.

The dimensions of point absorbers are small compared with the wave length of incoming waves and they are potentially very efficient if their frequency response function closely matches the spectrum of the incident waves (resonance). Passive control

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methods (such as impedance matching) have been explored to improve energy extraction by tuning the dynamical parameters of the devices [9,29–31]. Most of these approaches are linear control schemes. A non-linear control method that has received some attention is latching, [32–37]. This attempts to force the phase angle between the float and the wave at the WEC to be similar to conditions at resonance. The above control strategies do not use prediction of the forces acting on the WEC and thus inevitably lead to sub-optimal energy extraction. Since the early work [5,9,11] there have been a number of authors who have recognized the importance of DSWP in the control of a variety of floating body applications [7,8,17,37,38], but these have, as yet, not been incorporated into actual control schemes.

The point absorber model used is shown in Fig. 1 and roughly corresponds to the Power Buoy device PB150 developed by OPT Inc, see [39]. On the sea surface is a float, below which hydraulic cylinders are vertically installed. These cylinders are attached at the bottom to a large area anti-heave plate whose vertical motion is designed to be negligible compared with that of the float. The heave motion of the float drives the pistons inside the hydraulic cylinders to produce a liquid flow. The liquid drives hydraulic motors attached to a synchronous generator. From here, the power reaches the grid via back-to-back AC/DC/AC converters. The mechanical circuit corresponding to this simplified model is shown in Fig. 2. Here h_w is the water level, h_v is the height of the mid-point of the float and D is the hydrodynamic damping of the float including added damping due to the damping effect of the movement of the float [1]. K is the hydrostatic stiffness giving the buoyancy force, which can be calculated from the float geometry, while m is the mass of the float including "added mass" [1]. The friction force acting on the float is $f_f = D_f \dot{h}_v$. In order to simplify the model we neglect the frequency dependence of both D and m (see, e.g., [29]). We also neglect the static component of the friction force f_f. For a more thorough investigation of the modeling issues of point absorbers, see [1,40,41].

The control input is the q-axis current in the generator-side power converter, to control the electric torque of the generator [42]. The generator torque is proportional to the force f acting on the pistons from the fluid in the cylinders. Since the motion of the float imposes a velocity v on the piston, the extracted power $P(t)$ at time t is expressed as

$$P(t) = f(t)v(t). \tag{1}$$

This power is smoothed by the capacitors on the DC link of the converters. In our model the modest power losses in the hydraulic transmission, the generator and the converters will be neglected.

To avoid damage, and for overall performance reasons, two constraints have to be considered in any real WEC. One concerns the relative motion of the float to the sea surface (it should neither

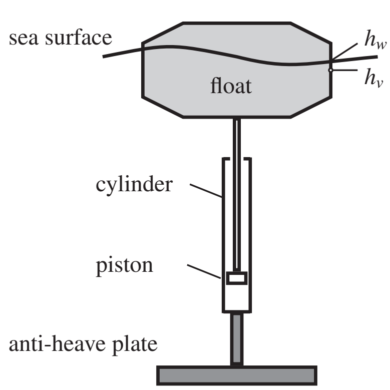

Fig. 1. Schematic diagram of the point absorber.

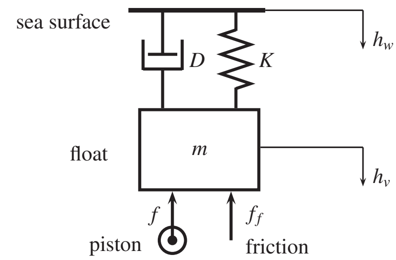

Fig. 2. A mechanical circuit representation of the point absorber.

sink nor raise above the water and then slam), which can be expressed as

$$|h_w - h_v| \leq \Phi_{\max}. \tag{2}$$

The other constraint is on the control signal set by limitations on the allowable converter current. This constraint can be expressed as

$$|f| \leq \gamma. \tag{3}$$

The control objective is to maximize the extracted energy subject to the constraints (2) and (3). We remark that there is a further constraint on the motion of the float because of the limited excursion of the piston with respect to the cylinder (see Fig. 1). This constraint has the form $|h_v| \leq \lambda$. However, we shall not consider this constraint, since we assume that λ is large enough compared with the expected excursion.

The constraints imposed on WECs significantly affect the power that can be extracted. It has been shown that by using control strategies that incorporate these constraints, considerable increases in the energy output can be obtained without increasing the risk of damage [7,8]. The ability to handle constraints combined with the development of real time wave prediction methods has recently led to an interest in the use of *model predictive control* (MPC) for wave energy devices [43–45]. The work published to date has used standard MPC techniques and they rely on the formulation of a convex *quadratic programming* (QP) problem. The underlying problem formulations and the cost function representations in [43–45] differ from our case. We leave the question open if the convexity assumption holds for a broad class of constrained optimal control problems for WECs. However, we find that this assumption does not hold for the problem formulated in this paper and many other similar optimal control problems [46,47].

In this paper, the constrained optimal control problem is solved using fundamental principles from optimal control theory [48–50], see Section 3, and real time deterministic sea wave prediction [12–19,26,28]. We demonstrate that a nearly optimal control is of bang–bang type, meaning that the control input f is always at one edge of the allowed range, see Subsection 3.2. As will be shown, for an arbitrary sea wave input known over an interval of time (not a sine wave), direct numerical computation of the optimal control scheme is not realistic. Consequently, we employ *dynamic programming* (DP) [46], which is well suited for constrained optimal control problems [51]. We have sacrificed some detail in the hydrodynamic modeling, leading to a model of manageable complexity for on-line DP.

The implementation of DP on a WEC control system is based on the assumption that the sea surface shape can be predicted for a short time period. This requirement has been a bottleneck for the development of suitable optimal control strategies for WECs. However, the developments in deterministic sea wave modeling techniques have made real time sea wave prediction for a short time period realizable, [12–19,26,28]. A key finding from this work is that the prediction horizons required are considerably smaller than those resulting from the previous studies [43–45].