Renewable Energy 69 (2014) 453–463

Contents lists available at ScienceDirect

Renewable Energy

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

Model predictive control of sea wave energy converters – Part I: A convex approach for the case of a single device

Guang Li [a,*], Michael R. Belmont [b]

[a] School of Engineering and Material Sciences, Queen Mary, University of London, Mile End Road, London E1 4NS, UK
[b] College of Engineering, Mathematics and Physical Sciences, University of Exeter, Harrison Building, North Park Road, Exeter EX4 4QF, UK

ARTICLE INFO

Article history:
Received 14 February 2013
Accepted 26 March 2014
Available online

Keywords:
Wave energy
Model predictive control
Quadratic programming

ABSTRACT

This paper investigates model predictive control (MPC) of a single sea wave energy converter (WEC). By using control schemes which constrain certain quantities, such as the maximum size of the feedback force, the energy storage for actuators and relative heave motion, it is possible for control to not only improve performance but to directly impact strongly on design and cost. Motivated by this fact, a novel objective function is adopted in the MPC design, which brings obvious benefits: First, the quadratic program (QP) derived from this objective function can be easily convexified, which facilitates the employment of existing efficient optimization algorithms. Second, this novel design can trade off the energy extraction, the energy consumed by the actuator and safe operation. Moreover, an alternative QP is also formulated with the input slew rate as optimization variable, so that the slew rate limit of an actuator can be explicitly incorporated into optimization. All these benefits promote the real-time application of MPC on a WEC and reduced cost of hardware.

1. Introduction

A sea wave energy converter (WEC) is a device used to harvest sea wave energy. Extracting the maximum possible time average power from WECs, while reducing the risk of device damage and at the same time minimizing the device cost, involves a combination of good fundamental engineering design of a device and effective control of its operation. The linking of control and basic design is not the conventional approach because control schemes are typically overlaid upon existing designs. However, minimizing certain quantities such as feedback force, stored energy for actuators and the relative heave motion using some control strategy has very marked direct effects upon design/cost.

In this paper, we investigate the control aspect of WECs. In particular, we focus on a typical type of WECs, called point absorbers, whose dimensions are small compared with the wave length of incoming waves.

Various control methods have been explored to improve energy extraction, such as impedance matching by tuning the dynamical parameters of the devices [1–4], and latching control by locking the body at some moments to keep the velocity in phase with the excitation force [5–10]. There are also some optimization based control strategies developed for WECs. Eidsmoen [5] uses Lagrange multipliers to determine the optimal velocity profile. In Ref. [11] an linear quadratic Gaussian (LQG) control problem is formulated, with the assumption that no constraints are present. However, all these control methods are only suboptimal. More recent works [12–17] show that maximizing energy extraction while maintaining the safe operation of WEC is essentially a constrained optimization problem and the concept of model predictive control (MPC) can be potentially employed as the WEC control strategy. Fusco and Ringwood [18] use an MPC as a benchmark for comparative evaluation of the performance of a simple controller. MPC is an online optimization technique. It resolves an optimization problem at each sampling instant to yield an optimal control sequence, the first of which is applied to the plant as the control input. This online optimization feature requires a fast optimization algorithm, especially when it is applied to mechanical systems, e.g. Ref. [19]. Conventionally, the optimization is formulated as a convex quadratic program (QP) [16], so that efficient optimization algorithms such as the interior point method and the active set method can be employed. However, the optimization associated with the WEC control may not be guaranteed to be convex as shown later in this paper. This problem impedes the implementation of these

* Corresponding author.
E-mail addresses: g.li@qmul.ac.uk (G. Li), M.R.Belmont@exeter.ac.uk (M.R. Belmont).

http://dx.doi.org/10.1016/j.renene.2014.03.070
0960-1481/

efficient algorithms. In this paper we show how to overcome this problem by adopting a novel cost function.

To present the point absorber control problem, we use the Power Buoy device similar to PB150 developed by OPT Inc, see Ref. [20], as a concrete example, which is illustrated in Fig. 1 and is studied in Ref. [16]. On the sea surface is a float, below which a hydraulic cylinder is vertically installed. This cylinder is attached at the bottom to a large area anti-heave plate whose vertical motion is designed to be negligible compared to that of the float. In this paper the cylinder is assumed to be anchored to the seabed directly. 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; see Ref. [21] for more details related to the power electronics. Here z_w is the water level and z_v is the height of the mid-point of the float. The control input is the q-axis current in the generator-side power converter, to control the electric torque of the generator [22]. The generator torque is proportional to the force f_u acting on the pistons from the fluid in the cylinders. Since the motion of the float imposes a velocity $v = \dot{z}_v$ on the piston, the extracted power $P(t)$ at time t is expressed as

$$P = -f_u v \tag{1}$$

Note that, different from Ref. [16], it is assumed here the directions of f_u and v are the same, so that a minus sign in Eq. (1) is needed. This is merely a matter of expression for the formulation of the QP. The extracted energy over a period [0,T] is therefore

$$-\int_0^T f_u v \mathrm{d}t \tag{2}$$

MPC aims to maximize the energy in its discrete time version, which amounts to minimize the cost function

$$J = \sum_{k=0}^{N} f_u(k)v(k) \tag{3}$$

where $f_u(k)$ and $v(k)$ are the discrete time values of $f_u(t)$ and $v(t)$ sampled with a sampling period T_s. 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 sink nor raise above the water and then slam), which can be expressed as

$$|z_w - z_v| \leq \Phi_{max}. \tag{4}$$

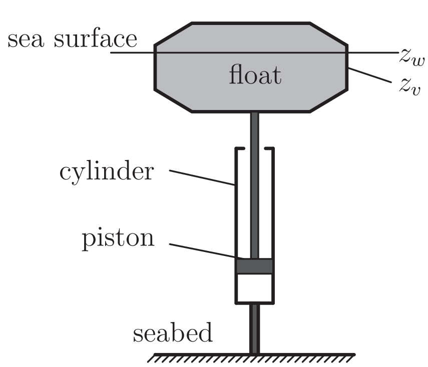

Fig. 1. Schematic diagram of the point absorber.

Since $z_w - z_v$ is proportional to the buoyancy force f_s, Eq. (4) can be equivalently represented as

$$|f_s| \leq z_{max}. \tag{5}$$

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

$$|f_u| \leq \gamma. \tag{6}$$

The control objective is to maximize the extracted energy subject to the constraints (5) and (6).

However, this constrained optimization problem leads to a non-convex QP, which prevents us from using efficient optimization algorithms to resolve it efficiently online. Some methods have been proposed to overcome this problem. In Ref. [23], the WEC control is formulated as a constrained optimization problem which is approximated by a resulting concave quadratic function. In Ref. [16], we aim to resolve this non-convex optimization problem directly. This constrained optimal control problem is analyzed using Pontryagin's minimum principle, and the analysis result facilitates the employment of dynamic programming (DP) for the online optimization. This is because the resulting control takes a bang–bang type of control, that is, only the maximum or minimum of the allowed control signal is used as input at each sampling instant. This allows the cost function to be evaluated only along two trajectories generated by the two boundary input values, so that the computational burden is significantly reduced. However, there are two drawbacks related to this control method. Firstly, although simulations show that the computational speed is fast enough to guarantee the real time implementation of DP for a second order model, the exponentially increased computational burden for a higher order model, namely "the curse of dimensionality of DP", can invalidate its application. Secondly, since the control input only takes the maximum and minimum values, this has two impacts on the actuator: on the one hand, the physical design of the actuator may not allow the switch between the two boundary values at a very high frequency; on the other hand, the energy consumed by the actuator can be very large.

An alternative approach is to use a modified objective function to approximate the original one (3). This modified objective function takes the form of

$$J = \sum_{k=0}^{N} f_u(k)v(k+1) \tag{7}$$

which contains one sampling instant delay from input to output. In Refs. [13,14], similar approaches are used, and the QP resulting from this approximated objective function is assumed convex, which enables the application of the conventional MPC. It is noticed that, possibly by mistake, the power expression in the objective function in Ref. [14] does not involve the delay term. We acknowledge the efficacy of this approximation method for many cases. However, in this paper, we show by examples that the assumption on the QP's convexity associated with the modified cost function may not always hold for all the possible parameter selections. Moreover, we demonstrate by simulations that the MPC based on this modified cost function can cause significant loss of extracted energy for a WEC in some cases.

Motivated by the existing results, the present paper aims to propose an efficient MPC control strategy to directly optimize the energy output and control signal. The MPC employs the following objective function