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Review

Nonlinear control of flap-type wave energy converter with a non-ideal power take-off system☆

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ABSTRACT

Wave energy converters (WECs) require active control to maximise energy capture over a wide range of sea conditions, which is generally achieved by making the device resonate. The exaggerated device motion arising at resonance, however, may result in nonlinear effects that are ignored by the linear models that are typically employed. In particular, nonlinear viscous forces are significant for particular device types, such as hinged flaps, which we take as a case study in this paper. The paper develops a general nonlinear WEC control methodology based on pseudospectral methods. The continuous time energy maximisation problem is fully discretised (both state and control), and the optimal solution is obtained by solving the resulting finite dimensional optimisation problem. By way of example, the nonlinear viscous damping for a hinged flap WEC is incorporated into the control model which also considers non-ideal power take-off efficiency. It is shown that the ratio of energy captured to energy dissipated is significantly increased with the nonlinear controller, compared to the linear case.

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1. Introduction

Wave energy conversion is the process of transforming energy carried by water waves in the sea into a usable form of energy, e.g. electricity. Devices designed to fulfil this task are known as Wave Energy Converters (WECs), and this paper concerns the control of a particular type of device, where the objective of the control system is to maximise the amount of energy absorbed. The device considered in this paper is a bottom-hinged vertical plate (Fig. 1) which exploits the same conversion principle as the *Oyster* WEC being developed by *Aquamarine Power Ltd.* (Folley, Whittaker, & van't Hoff, 2007). The force exerted by the incident waves (excitation force) induces a pitching motion on the plate. Part of the mechanical work done by the excitation force is converted into a usable form of energy by means of the Power Take Off (PTO), a component of the WEC capable of doing mechanical work on the oscillating plate by exerting a force, which is the control variable.

Most studies, academic and commercial, focus on the use of linear models; their appeal is mainly due to the possibility of developing analytical solutions for the control problems and analysis of performance (Falnes, 2002). A variety of sources introduce nonlinearities in the model of WECs, from the PTO (Bacelli, Gilloteaux, & Ringwood, 2008; Engja & Hals, 2007) to the fluid–body interactions. While it is often reasonable to assume a linear approximation for the radiation (Gilloteaux, 2007), some studies have shown the wide disparity between linear and nonlinear models of excitation forces (Merigaud, Gilloteaux, & Ringwood, 2012), viscous forces (Folley et al., 2007) and hydrostatic restoring forces (Zurkinden & Kramer, 2012). This paper focusses on viscous drag applied to a hinged flap WEC as an example to illustrate the application of the pseudospectral methods for the nonlinear control of wave energy converters. In addition, nonlinearities coming from non-ideal PTO losses are studied and modelled via an efficiency curve. An investigation is carried out on a generic hinged flap device to illustrate how PTO losses can be taken into account during the optimal trajectory generation using pseudospectral methods. However, the nonlinear control framework is general and can be applied to other nonlinearities and WEC device types. An initial exposure of the nonlinear control of a flap-type WEC using pseudo-spectral methods was presented in (Bacelli & Ringwood, 2014), though a non-ideal PTO was not considered.

The control problem is an optimal control problem because the objective is to find the control (PTO force) which maximises the amount of absorbed energy. In this paper, the solution to the nonlinear optimal control of a WEC is obtained by means of pseudospectral methods, which are a subset of the class of techniques used for the discretisation of integral and partial differential equations, known

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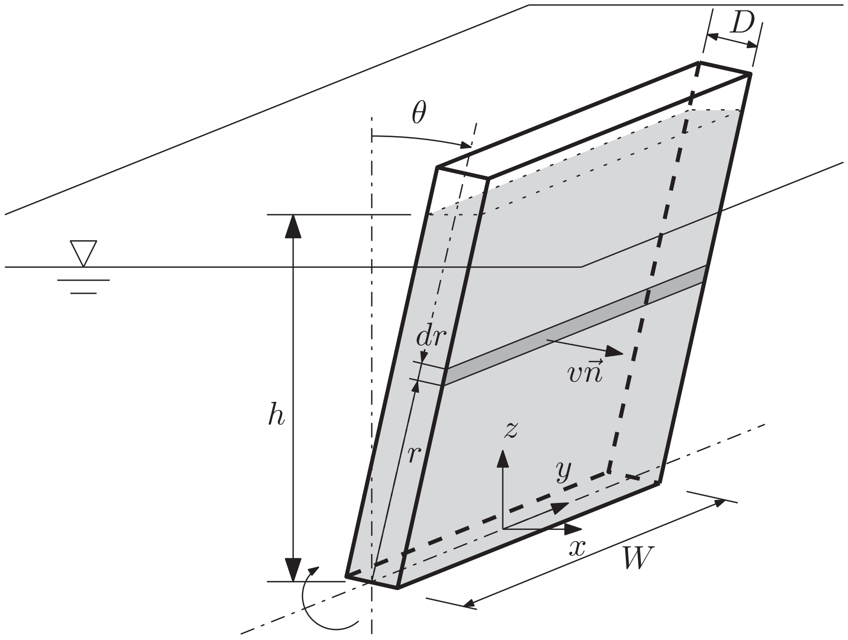

Fig. 1. Flap-type wave energy converter. The shaded area indicates the submerged region.

as mean weighted residuals (Canuto, Hussaini, Quarteroni, & Zang, 2006; Fornberg, 1996). The first applications of pseudospectral optimal control were presented more than 15 years ago (Elnagar, Kazemi, & Razzaghi, 1995; Vlassenbroeck & Van Dooren, 1988); however, only in recent years has it received increasing attention (Garg et al., 2010; Ross & Karpenko, 2012) and found application, mostly in flight control.

Adopting an optimal numerical framework gives the opportunity to deal with the full complexity of the device model (possibly including nonlinear terms and non-ideal PTO), device constraints and optimising the device for the a panchromatic wave spectrum, where multiple frequencies are simultaneously present.

Previous approaches to nonlinear control of WECs include the application of Pontryagin's maximum principle to the continuous time optimal control problem (Babarit & Clément, 2006; Nielsen, Zhou, Kramer, Basu, & Zhang, 2013) and its discretisation (Richter, Magana, Sawodny, & Brekken, 2013; Tom & Yeung, 2013). However, discretisation using pseudospectral methods generally gives a faster convergence rate (Benson, 2005), which results in a smaller nonlinear program and reduced computing time, thus suitable for real-time applications. Additionally, discretisation by means of the pseudospectral method presented in this paper allows the convolution integral that models the radiation force to be simplified analytically, instead of the classical approach of using system identification to build a state space model (Tom & Yeung, 2013) or being completely neglected (Richter et al., 2013).

Since more and more new devices and prototypes are being tested in wave tanks or under real sea conditions, WECs dealing with non-ideal PTO systems becomes a new issue and a contemporary technological challenge. Solutions have been proposed by Hansen, Pedersen, and Andersen (2014) for hydraulic PTO systems, replacing on/off valves by bidirectional check valves in order to reduce switching losses. Other recent studies, such as Tedeschi, Carraro, Molinas, and Mattavelli (2011), Kovaltchouk et al. (2013) and Genest, Bonnefoy, Clément, and Babarit (2014), evaluate the impact of power take-off losses on the absorbed power of generic wave energy converters using efficiency curves or a constant efficiency rate for electrical or hydraulic PTO systems. Such studies illustrate how essential it is to take into account PTO losses in the control strategy since, even with a high efficiency PTO, the absorbed grid power significantly drops in comparison to the ideal case.

The remainder of the paper is organised as follows: the dynamical model of the flap-type WEC is described in Section 2, and a brief overview of pseudospectral optimal control is provided in Section. 3, while Section 4 shows a case study for the flap-type device. Inclusion of a nonideal PTO in the pseudospectral optimal control is introduced in Section 5 and simulation results are illustrated and discussed in Section 6, with conclusions drawn in Section. 7.

2. WEC model

2.1. Dynamical model

The device considered in this paper is depicted in Fig. 1. It is a flap-type WEC hinged on the y-axis at a depth h =15 m, with a width $W = 30$ m, thickness D =1 m and a uniform density $\rho_b = 250$ kg/m^3.

The equation of motion is derived from Euler's second law, which says that the rate of change of the angular momentum is equal to the sum of the external moments of force about the axis y:

$$I_y\ddot{\theta} = \gamma_w(t) + \gamma_p(t). \tag{1}$$

I_y is the moment of inertia of the body with respect to the axis y, γ_p is the torque applied by the PTO, and γ_w is the resultant of the moments due to the interaction between water and the oscillating body, which is composed of four terms, as described by Folley et al. (2007):

$$\gamma_w(t) = \gamma_h(t) + \gamma_d(t) + \gamma_r(t) + \gamma_e(t). \tag{2}$$

The hydrostatic restoring moment γ_h is assumed to be linearly proportional to the pitch angle ($\gamma_h = S_h\theta$), where S_h is the hydrostatic restoring coefficient. The excitation torque γ_e is due to the effect of the incident waves, and is calculated as $\gamma_e(t) = h_e * \zeta$, where ζ is the wave elevation and $*$ denotes the convolution operator, defined by

$$f * g = \int_{-\infty}^{-\infty} f(t-\tau)g(\tau)d\tau.$$

The radiation torque γ_r is due to the motion of the body which causes waves to be radiated away, and depends on the velocity and acceleration of the oscillating body as (Cummins, 1962):

$$\gamma_r = -I_\infty\ddot{\theta} - h_r * \dot{\theta} \tag{3}$$

The functions h_e and h_r are the impulse responses of the excitation and radiation respectively, while I_∞ is the asymptotic value of the

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