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# On improving wave energy conversion, part I: Optimal and control technologies

Wanan Sheng*, Raymond Alcorn, Anthony Lewis

*Beaufort Research-Hydraulics and Maritime Research Centre, University College Cork, Cork, Ireland*

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ABSTRACT

Extracting wave energy from seas has been proven to be very difficult although various technologies have been developed since 1970s. Among the proposed technologies, only few of them have been actually progressed to the advanced stages such as sea trials or pre-commercial sea trial and engineering. One critical question may be how we can design an efficient wave energy converter or how the efficiency of a wave energy converter can be improved using optimal and control technologies, because higher energy conversion efficiency for a wave energy converter is always pursued and it mainly decides the cost of the wave energy production.

In the first part of the investigation, some conventional optimal and control technologies for improving wave energy conversion are examined in a form of more physical meanings, rather than the purely complex mathematical expressions, in which it is hoped to clarify some confusions in the development and the terminologies of the technologies and to help to understand the physics behind the optimal and control technologies. And as a result of the understanding of the physics and the principles of the optima, a new latching technology is proposed, in which the latching duration is simply calculated from the wave period, rather than that based on future information/prediction, hence the technology could remove one of the technical barriers in implementing latching control technology. From the examples given in the context, this new latching control technology can achieve a phase optimum in regular waves, and hence significantly improve wave energy conversion. Further development on these latching control technologies in irregular waves can be found in the second part of the investigation.



## 1. Introduction

Wave energy is a type of well-concentrated and predictable renewable energy, and its resources are huge (IEA's estimation of the total wave energy is up to 80,000 TWh a year [1], compared to the worldwide electricity production 17,400 TWh in the year of 2004). Extracting wave energy from seas may significantly contribute to the green target of sustainable development around the world. In the past three decades, it has been shown that the wave energy conversions are practically difficult, although the principles of wave energy conversion have been proven, and different technologies can be used for extracting wave energy from seas. One question is how expensive we can convert wave energy into useful energy, and this question must be answered by researchers and developers before any commercial wave energy farm is built.

Although difficulties, wave energy conversions have been seen some successful stories. It is reported a few hundred navigational buoys (oscillating water columns) have been deployed in the remote and harsh areas where the access for frequently changing batteries is not viable (see Chozas [2] and Falcao [3]). Also, the breakthroughs in wave energy conversion in 1970–1980s on some prototype devices once convinced people that massive wave energy production would soon become a reality. For example, 2 GW wave power plant producing power at a rate of 1.3 p/kWh has been described in Whittaker et al. [4]. So far, more than 1000 patents of wave energy conversion techniques have been granted in Europe, Japan, and North America (McCormick [5]), but only few technologies have actually progressed to large practical devices which could produce useful energy, and some of them even achieve full-scale or pre-commercial sea-trial stages (see Refs. [3,6,7]).

In the path to make wave energy production comparative to other conventional or renewable energy resources, researchers and developers have made their efforts to improve the wave energy conversion efficiencies, either by designing efficient wave energy converters, such as the famous Salter Duck; or employing the

* Corresponding author.
*E-mail addresses:* w.sheng@ucc.ie, wanan93@gmail.com (W. Sheng).

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advanced control technologies to improve wave energy capture capacity, such as the full reactive/phase control; or the less effective but yet more practical latching/de-latching control (see Salter et al. [8]); or both. In this research, the popular optimal and control technologies for improving wave energy conversions are discussed, with an emphasis on how practically these control technologies can be used for improving wave energy conversion.

Optimal and control technologies for improving wave energy conversion have been proposed and developed since 1970s (see Falnes [9]) and the developed optimal theories have shown if an ideal power take-off (PTO) can provide the required performance, the wave energy capture by the device can be made to or close to the theoretical maximum. However, such as ideal PTO can not be achievable in practice due to the very high demands for the control optima and the mechanical limitation for the PTO device and some other issues. As a result of the difficulties in realizing the full optimal/control strategy, more practical control technologies have been proposed and developed by partially fulfilling the optimal conditions, thus they are often called the sub-optimal controls ([10–18]).

Principally, optimization of wave energy devices can be obtained either by an optimum phase and/or an optimum amplitude (Falnes [9]). The full optimal/control technologies have required both phase and amplitude optima completely, in which the PTO system is assumed as an ideal control device, and can perform as an additional inertia or a spring as required so to fully counteract the intrinsic reactance of the wave energy converter, that is, the mass and spring terms cancels each other in the mass-spring-dashpot system of the wave energy conversion. Under the assumptions of a full control, the wave energy converter is resonant with the wave excitation, and hence the phase optimum is fulfilled, and if the PTO damping is further optimized, the amplitude optimum can be fulfilled. As a result of the full optima, the device could extract wave energy to (or close to) the theoretical maximum. Terminologically, the full optimal control (hereafter 'full optimum') can be also called the full complex-conjugate control (Nebel [19]) or the full reactive/phase control (Salter et al. [8]). Examples given by Falnes [20] have shown in the full optimal control, a part of the extracted energy must be effectively fed back into the waves through the PTO. By extracting wave energy from and releasing partial energy back to waves, the control system can significantly improve wave energy production. This implies that the full control requires the PTO must have both very high energy conversion efficiencies in extracting energy from and feeding energy back to waves. This has been proven to be too difficult for a practical PTO if it is not impossible.

To develop more realistic optimum and control technologies, different technologies are proposed, and the most popular control technology would be the latching control technologies [10,12,16,17,21–23]. Among the latching control technologies, different control strategies have been proposed on how the latching control can help to reach a sub-optimal condition. For instance, the phase control by latching has been achieved by implementing different control strategies. Babarit et al. [21] have compared three different latching control strategies, and concluded all three technologies can help to improve wave energy conversion significantly. However, in implementing these latching control technologies, some future information must be predicted or forecasted (the method of Falcao [12] is an exception), and they are often named as the 'predictive method'. The requirement of the future information applies a challenge to practical applications.

In this research, the optimal methods are first examined and studied in a manner that the complex control theory is replaced with the method of more evident physical meaning and implementation, and based on the understanding and the principle of the phase optimum, a new latching control method is then proposed, for which the latching duration is simply calculated based on the wave period (further development of the technology can be found in the second part of the research [24]). To illustrate the optimal and control technologies, a generic point absorber, which may be similar to some practical point absorbers, is used for the investigation. Hence the numerical results can be sensible and realistic in terms of the hydrodynamic parameters and energy conversion. It has been shown that the generic wave energy converter with optimal or control technologies could extract more energy from waves, and among them, the full optimum technology could improve to extract energy close to the theoretical maximum.

## 2. A simple wave energy converter

In studying wave energy conversion and control technologies for how to improve power conversion, a simple wave energy converter is used as an example through all the applications in this research. The wave energy converter is a generic point absorber of a cylinder with a radius $R = 3.0$ m and a draft $D = 1.5$ m. The point absorber is a single body device with a reference to a fixed point, for example, the seabed. To improve wave energy production by the point absorber, a PTO with a control is applied (see Fig. 1). The idealized PTO is capable of providing the required inertia, damping and spring effects, and it will be shown that how the PTO can possibly maximize wave energy production.

The same cylinder point absorber has been analysed in Sheng et al. [25], and the panels for WAMIT analysis are for the wetted surfaces, shown in Fig. 2.

For wave energy conversion, the single motion mode, heave, is considered as the motion for power take-off. And we will show the improvements of wave energy conversion by the inclusions of inertia and spring effects from the power take-off system.

To illustrate the hydrodynamic performances of the cylinder in waves, Figs. 3–5 show the responses of the heave motion for the cylinder freely floating in waves. Fig. 3 shows the added mass and the hydrodynamic damping coefficient. It can be seen that the cylinder has a minimum added-mass at $\omega = 2.18$ rad/s, and its added-mass approaches a constant value at large frequencies; while the hydrodynamic damping has a maximum value at $\omega = 1.47$ rad/s, and becomes zero when the frequencies become large.

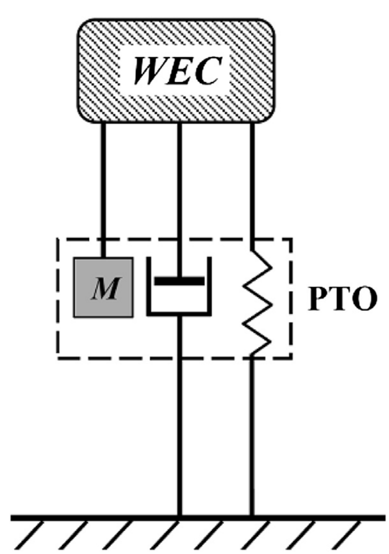


**Fig. 1.** A point absorber with a full PTO referencing to the seabed.