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Real-time latching control strategies for the solo Duck wave energy converter in irregular waves

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HIGHLIGHTS

- Three real-time latching control strategies are defined and compared.
- Suggestions are given on how to choose the time step for predictive strategies.
- The non-predictive strategy captures the same power as the predictive ones.
- The non-predictive control strategy is most favorable for solo Duck WECs.
- Latching control does not cause additional fatigue damage to the PTO.

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ABSTRACT

As a point absorber, the solo Duck wave energy converter (WEC) shows high power capture efficiency within a narrow bandwidth around the natural period. In this paper, real-time latching control is applied to the solo Duck WEC in irregular waves to improve its performance in sea states away from the natural period. Two predictive latching control strategies, in which one is close-to-optimal and the other is sub-optimal, and one non-predictive strategy are considered. The improvement of the WEC performance due to latching control is studied. Compared to the performance under simple resistive control, the three latching control strategies show almost equivalent control effect, leading to an average increase of the maximum relative capture width by around 70% and an average decrease of the optimal power take-off (PTO) damping coefficient by around 60%. Since the non-predictive strategy requires no prediction of future excitation force and WEC motion, it can be identified as the best choice for the solo Duck WEC under latching control. Although latching control leads to significant increase of fatigue load on the WEC hull like other advanced controls, it does not cause additional fatigue damage to the PTO.

1. Introduction

Wave energy has been of interest for the academic and engineering society since the 1970s as a promising alternative to traditional fossil energy [1]. After decades of development, varieties of wave energy conversion schemes have been proposed [2]. The Edinburgh Duck [3] wave energy converter (WEC), which mainly employs the pitch mode to capture power, is acclaimed for its high efficiency [4]. In addition to the WEC farm layout in which Duck members are closely spaced and connected in series to work as terminator devices [5], the layout in which Duck members have a large separation distance and act as point absorbers has also attracted wide attention [6,7]. In the latter case, each Duck member is called a 'solo Duck'. Skyner [8] and Pizer [9] performed experimental and numerical studies on the solo Duck WEC and confirmed the benefit from the point absorber effect by a relative capture width of 1.6 and 2, respectively. An innovative solo Duck cross section, which is of circular profile but with off-centered pitch axis, was proposed by Lucas et al. [10] and Cruz et al. [11] to simplify the manufacturing process. Wu et al. [12] studied the hydrodynamic interaction among the members in solo Duck arrays to optimize the topology of a WEC farm. Currently, in an ongoing project near the south coast of Shenzhen, China, solo Ducks are integrated into a large scale offshore platform that is dedicated to convert offshore renewable energy to electricity from multiple sources, including wave, solar and wind energy.

It is well recognized that point absorbers, e.g. the solo Duck WEC,

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show high power capture efficiency only within a narrow bandwidth around the natural period and significantly lower efficiency away from it [13]. Many control strategies have been proposed to overcome this challenge and the research area is still very active. Excellent reviews of control methods can be found in [14,15]. Optimal phase control, or reactive control, was proposed already in the 1970s [16] and aims to maximize the energy absorption by matching the impedance such that the intrinsic reactance of the system is cancelled. To accomplish this, energy flow in the system is bidirectional, meaning that the system must provide energy to the primary converter during certain time intervals. Latching control, on the other hand, does not involve any bidirectional flow of energy [17]. It is one of the most extensively studied control strategies, and is implemented by locking the WEC during part of the wave cycle and releasing it when the phase is optimal relative to the excitation force from the waves, such that approximate resonance is achieved. More recent control methods involve model predictive control (MPC), which enables the optimization of energy capture in real-time under certain given constraints, such as motion limitation and device capability [18,19]. However, the performance of this control relies heavily on a variety of variables, such as the theoretical models, the optimization algorithm, the prediction horizon and the specification of the constraints [20]. Small deviations between the physical device performance and the theoretical computations may lead to significant changes in power output, and often fine-tuning is required for each simulation. Furthermore, it is found in [21] that for a generic point absorber, the captured power from latching control is comparable with MPC, and benefits from much smaller peak-to-average-power ratio and no reactive power. With the above aspects taken into consideration, latching control still provides a simple and robust method to optimize the performance of WECs, and is the topic for this paper.

In the field of latching control, several real-time strategies have been proposed. Babarit et al. [22] employed the optimal command theory based on the Pontryagin's maximum principle to find the optimal latching control command time series in a relatively long time interval, in which the excitation force is known ahead of time. However, in practice, the excitation force can only be accurately predicted for several seconds, making the above long term optimization process impossible in reality. Considering the time horizon limitation on predictable excitation force, Henriques et al. [23] proposed an iterative predict-ahead latching control strategy, in which the optimization process is performed at each time step within a short prediction horizon to determine the control command for the next time step. To ensure that this control strategy can be carried out in real-time, the 'repeat to convergence' iteration in the optimal command theory is removed and the code within the iteration runs only once each time step within the receding horizon framework [23]. Although this control strategy is not optimal from the algorithm point of view, the control effect is still close-to-optimal [24]. Another latching control strategy was proposed by Babarit et al. [25], in which the optimal unlatching instance is the one that maximizes the WEC displacement of the subsequent motion period. Naturally, this strategy is only locally optimal and thus sub-optimal. This latching method can also be recognized as real-time control since the unlatching command computation process only needs to be finished within the optimal latching duration. In fact, to guarantee absolute real-time implementation, some non-predictive strategies were proposed. Lopes et al. [26] studied a threshold latching control strategy in which the unlatching command is executed only when the excitation force exceeds a threshold. On the other hand, Falcão [27] employed a variant of the above non-predictive strategy, in which the variable that should exceed a threshold is the pressure in the hydraulic cylinder rather than the excitation force, because the former is easier to measure in practice.

Previous studies have been mainly focused on applying latching control to buoys such as semi-submerged spheres [28], vertical cylinders [22] and their combinations [29]. For the solo Duck investigated in this paper, its scattered and radiated wave pattern is different from those previously studied, hence the effect of latching control on improving the power capture performance of the solo Duck WEC must be specified and studied, and this is the first objective of this paper. Furthermore, although several latching control strategies have been proposed, including close-to-optimal and sub-optimal types, a synthetical comparison of the strategies has not yet be investigated in previous literature, thus this is the second objective of this paper. Lastly, it is known that latching control imposes large loads on the WEC that may have a significant impact on its mean time to failure, and a thorough study on the fatigue loads on different components of the WEC is of great significance to guide the physical design of a WEC that is dedicated to operate under latching control. However, little has been done in this field and it is the third objective of this paper. In order for the conclusions of this paper to be directly applicable in practice, we focus on real-time latching control strategies in irregular waves. The paper is organized as follows: the geometry of the solo Duck is described in Section 2; the governing equation of Duck motion is established in Section 3; the three real-time latching control strategies are introduced in Section 4; the control effect due to latching control is presented in Section 5; and the conclusions are drawn in Section 6.

2. Geometry of the Duck

The cross section of the solo Duck is shown in Fig. 1, which is proposed in [8] and introduced in [6,12]. While the paunch part complies with the trajectory of water particles to effectively interact with the incident wave, the stern part employs a circular profile with center at the pitch axis so that little leeward wave is radiated [5]. As a result, a power capture efficiency as much as 90% has been confirmed in 2D regular wave tests [4]. The dimension of the solo Duck prototype studied in this paper is the same as the one studied by Pizer [7,9], and is 100:1 scaled from [8]. The radius of the stern part is 5 m; the depth of pitch axis is 5.5 m; the width of the Duck is 29 m; and the water depth is 60 m. The global Cartesian coordinate system aligns the positive x axis with the wave propagating direction, and the positive z axis is directed upward with $z = 0$ representing the still water level. The solo Duck WEC is designed to have the pitch axis stiffly connected to a large scale offshore platform, whose motion in moderate sea states can be neglected. Therefore, in this paper, the Duck is restricted to move only in pitch. For simplicity of the analysis, the pitch axis of the solo Duck is aligned with the y axis, i.e. in head seas.

3. Governing equation

It is assumed that the fluid is incompressible and inviscid, and the fluid motion is irrotational with small amplitude. This implies that the diffraction and radiation problems can be solved based on the linear potential theory. Then, in the time domain, the Duck motion in pitch

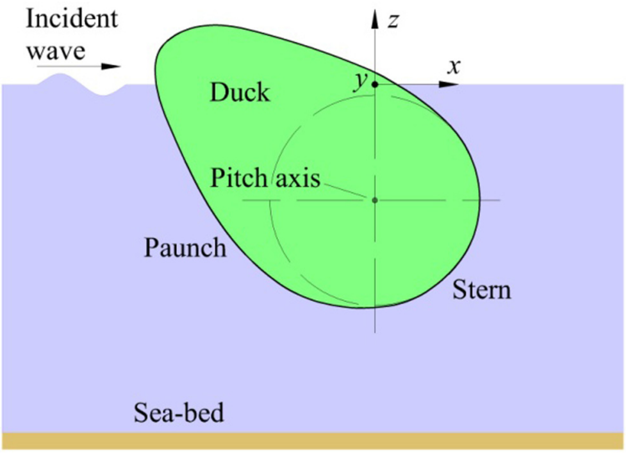

Fig. 1. A plain view of the cross section of the solo Duck.