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A novel control method to maximize the energy-harvesting capability of an adjustable slope angle wave energy converter

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ABSTRACT

This paper introduces a novel control approach to maximizing the output energy of an adjustable slope angle wave energy converter (ASAWEC) with oil-hydraulic power take-off. Different from typical floating-buoy WECs, the ASAWEC is capable of capturing wave energy from both heave and surge modes of wave motions. For different waves, online determination of the titling angle plays a significant role in optimizing the overall efficiency of the ASAWEC. To enhance this task, the proposed method was developed based on a learning vector quantitative neural network (LVQNN) algorithm. First, the LVQNN-based supervisor controller detects wave conditions and directly produces the optimal titling angles. Second, a so-called efficiency optimization mechanism (EOM) with a secondary controller was designed to regulate automatically the ASAWEC slope angle to the desired value sent from the supervisor controller. A prototype of the ASAWEC was fabricated and a series of simulations and experiments was performed to train the supervisor controller and validate the effectiveness of the proposed control approach with regular waves. The results indicated that the system could reach the optimal angle within 2s and subsequently, the output energy could be maximized. Compared to the performance of a system with a vertically fixed slope angle, an increase of 5% in the overall efficiency was achieved. In addition, simulations of the controlled system were performed with irregular waves to confirm the applicability of the proposed approach in practice.

1. Introduction

Among various sources of renewable energy, ocean wave energy is important, as it has significant potential in many locations, due to its relatively high power density and predictability [1]. Therefore, wave energy conversion technologies have gained more attention to meet the increasing demand for electrical power.

To harvest energy from waves, floating-buoy type wave energy converter (WEC) is the simplest and most popular design, and has been a focus of research. To maximize energy extraction from waves, the WEC must reach two optimal conditions, amplitude and phase, for each sinusoidal incident wave [2]. To satisfy the amplitude condition, the amplitudes of the radiated waves must be exactly half that of the incident waves [2,3]. To satisfy the phase condition, the oscillating velocity of the body must be in phase with the excitation force on the body. This can be achieved using phase control to obtain the resonance condition in which the wave frequency equals the natural frequency of the body. Here, two main control strategies, reactive control and latching control, are applied to WEC devices. Several interesting works have been reported [4–8]. Although phase control is capable of substantially increasing the amount of absorbed energy, implementation of this technique in real irregular waves has met both theoretical and practical difficulties that have not been satisfactorily overcome [9]. In addition, a phase control strategy requires governing equations for the body oscillations that are difficult to derive under real-world conditions. Modeling the highly non-linear behavior of both friction and wave characteristics is problematic.

To overcome the difficulty in regulating the power flow of WECs, neural networks (NNs) can be used to adaptively control the power-take-off (PTO) mechanisms [10]. As reported in Refs. [11,12], NNs were used to forecast the wave information in the near future to adjust in advance the PTO force. In another study [13], NN was

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utilized to derive the heuristic relationship between the system inputs and the control parameters. Although remarkable results were obtained using these approaches, the development and use of the control logic is complex, which restricts their applicability. Therefore, a simple and efficient way of maximizing WEC productivity without information on system dynamics is required.

To meet that requirement, this study focuses on a particular type of floating-buoy WEC, which was recently introduced: the adjustable slope angle wave energy converter (ASAWEC) [14]. The ASAWEC comprises mainly a sliding-buoy structure and a hydrostatic transmission-based PTO system. Different from typical floating-buoy designs, which are normally fixed vertically, an efficiency optimization mechanism (EOM) was integrated in the ASAWEC to enable adjustment of the system slope (or tilting angle) to increase the capture ratio from waves in both heave and surge modes. An analytical study of the interaction between waves and a buoy in the horizontal and vertical directions was carried out by Heikkinen et al. [15]. The results indicated that by combining the two modes to create the cylinder movement, the amount of absorbed energy could be increased. In the study by Thinh et al. [14], the effect of non-vertical linear motion of a hemispherical-float wave energy converter was evaluated by both numerical simulations and experiments. The sliding angle exerted a significant impact on the energy capture ratio. Therefore, this paper aims to develop a simple control approach to maximize energy harvesting capability of the ASAWEC by regulating its slope angle. A control scheme that includes a supervisor controller and a secondary controller for the EOM mechanism is designed. The supervisor controller is constructed using a learning vector quantitative neural network (LVQNN) algorithm to classify wave conditions based on limited wave information, and so produces the optimal titling angles. The secondary controller with a simple control algorithm is used to drive the EOM mechanism to regulate automatically the ASAWEC slope angle to reach the value determined by the supervisor controller. In this way, the energy capture ratio is improved.

The remainder of this paper is organized as follows: in Section 2, the ASAWEC configuration is briefly introduced and, a mathematical model is developed for further investigation; in Section 3, a prototype of the suggested ASAWEC is fabricated and the experimental apparatus is discussed; the LVQNN-based on EOM control scheme is constructed and optimized using training data in Section 4; the proposed approach is evaluated by both numerical simulations and real-time experiments in Section 5; and concluding remarks are provided in Section 6.

2. EOM-based ASAWEC design and modeling

2.1. EOM-based ASAWEC configuration

To maximize the ability to harvest energy from waves, an ASAWEC device design is suggested in Fig. 1.

The ASAWEC includes the following two modules:

- PTO module: converts wave energy into electric energy. This consists of a hydrostatic transmission (HST) and an electrical generator. The system interacts with waves through a sub-buoy jointed with a sliding shaft. This shaft can slide along sliding bearings or through rollers fixed on the device frame. The sliding shaft is then linked in parallel to a non-symmetric hydraulic cylinder. To convert mechanical energy into hydraulic energy, the HST is a simple hydraulic circuit with a one-directional hydraulic motor, a high-pressure accumulator (HPA), check valves and a small oil sump. The mechanical energy of the PTO is transmitted to the HST through the large chamber of the cylinder, while the small chamber is connected to the oil sump. For safety, a pressure relief valve is used to protect the system from damage due to extremely high power waves. Next, a generator block is employed to generate electric energy from hydraulic energy. This block comprises an electrical generator, a converter and an electricity storage device, such as battery. The output shaft of the hydraulic motor is coupled to the generator shaft to generate electricity.
- EOM module: designed based on the ASAWEC configuration. A linear actuator with an appropriate driver is selected as the power source for the EOM. A controller is designed for this mechanism in order to adjust automatically the tilting angle of the PTO according to wave conditions in such a way that the device can absorb most of the energy from waves.

During operation, waves force the sub-buoy to move up and down based on the floating-buoy concept. Here, only upward motion of the sub-buoy is utilized for energy harvesting. During upward motion, the cylinder is retracted and a high-pressure flow is created in the large cylinder chamber. This pressurized flow enters the hydraulic circuit through the first check valve (CV1) and reaches the inlet of the hydraulic motor. Consequently, in this case the electric generator operates to generate electricity. In contrast, during downward motion of the cylinder, the low-pressure flow is supplied from the oil sump to fill the large cylinder chamber through the second check valve (CV2). The pressure at the hydraulic motor side is not affected in this case. To store redundant energy generated by large waves and to facilitate smooth performance of the electric generator between upward and downward motion of the sub-buoy, an HPA accumulator is employed. Using this HPA, the generator speed does not decrease to zero when the cylinder extends, and so, the system performance is improved.

2.2. Modeling of the ASAWEC device

2.2.1. Equations of motion

Generally, real ocean wave evaluation can be represented as [16]:

$$x = \sum_{n=-\infty}^{+\infty} Z_n \exp^{i2\pi nft} dt \tag{1}$$

where $Z_n = (1/T)\int_{-T/2}^{T/2} x(t)\exp^{-i2\pi nft} dt$, $(n = 0, 1, 2, \ldots)$, $f = 2\pi/T$ is the fundamental frequency.

The mean wave power (P_{wave}) can be described as a function of the mean wave energy density and the group velocity [2]:

$$P_{wave} = Ec_g \tag{2}$$

where E is the mean wave energy density per horizontal unit area and is computed as:

$$E = E_k + E_p = \frac{1}{8}\rho g^2 H^2 \tag{3}$$

and c_g is the group velocity. For a constant water depth h at near shore locations (neither deep nor shallow water), the group velocity is obtained as follows:

$$c_g = \frac{D(kh)}{2\tanh(kh)} \quad c_p = \frac{g}{2\omega}D(kh) \tag{4}$$

where $D(kh)$ is the depth function: