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Effects of non-vertical linear motions of a hemispherical-float wave energy converter

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ABSTRACT

The hydraulic power-take-off mechanism (HPTO) is one of the most popular methods in wave energy converter (WECs). However, the conventional HPTO with only one direction motion has some drawbacks which limit its power capture capability. This paper proposes an *adjustable slope angle wave energy converter* (ASAWEC) and investigates the effect of slope angle on the performance of the proposed wave energy converter to find the optimal slope angle with the purpose to increase the power capture capability as well as energy efficiency. A mathematical model of components from a floating buoy to a hydraulic motor was modeled. A small scale WEC test rig was fabricated to verify the power capture capability and efficiency of the proposed system throughout experiments.

1. Introduction

Nowadays, the demand for energy is rapidly increasing, fossil resource get scarcer and scarcer. Many studies in the field of wave energy and various technologies of wave energy conversion systems, or wave energy converters (WECs) are currently being developed, such as overtopping devices (for example, the Wave Dragon), attenuators (Pelamis) and point absorbers (WaveBob, OPT PowerBuoy), as noted in Nielsen et al. (2006). The prior principle of WEC is that the wave motion is used to create a high-pressure fluid, which is used to drive a hydraulic motor coaxially connected to an electric generator. The mechanism by which energy is transferred from waves to the WEC, and subsequently or directly into useful form is called a hydraulic power take-off mechanism, generally known as the power take-off (PTO). The Pelamis WEC, using an active control of PTO to maximize absorbed power throughout a range of sea-states was presented in Henderson (2006). A seabed-mounted bottom-hinged *flap-type* wave energy converter, which increases the capture factor width and wave frequency was proposed and designed as in Folley et al. (2007). This design is good but when it is mounted on the sea bottom, several problems will appear, such as: difficulty in maintenance; corrosion by sea water; and oil leakage pollution. In Anbarsooz et al. (2014), a flap-type wave maker and the submerged cylinder WEC are proposed and modeled based on the complete solution of the Navier–Stokes equations to predict the behavior of the submerged cylinder WEC subjected to highly nonlinear incident waves. The numerical results and the analytics are observed in a good agreement, and the maximum efficiency point moves toward higher wave frequencies with increasing the wave height. One of the simplest and most popular wave energy converters is *point absorber* type, mentioned in Oskamp and Özkan-Haller (2012) and Zurkinden et al. (2014). However, wave energy is absorbed in only one direction: either vertical or horizontal. Therefore, this limits the total efficiency of the converter. Evans (1976) proposed a wave-power absorption device which can absorb both the horizontal and vertical force components. It is shown that theoretically 100% efficiency is possible in some cases. Heikkinen et al. (2013) proposed a new structure of cylindrical wave energy converters oscillating in two modes. This approach can absorb energy in two directions to improve the total efficiency. However, similar to the seabed-mounted bottom-hinged wave energy converter in Folley et al. (2007), it still has some drawbacks, such as difficulty in maintenance, corrosion, and oil leakage. To determine the cylindrical wave coefficients of any wave field from a known circular-cylindrical section, four types of WECs were used: a heaving point absorber, a surging point absorber, a terminator, and an attenuator in McNatt and Venugopal (2013). According to Folley and Whittaker (2009), there exists a significant direction or sector in which wave energy is the most energetic.

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Therefore, a wave energy converter with a predefined direction is more effective than the conventional WEC, such as a vertical linear motion WEC. Moreover, to overcome the drawbacks of the above wave energy converters and enhance the total efficiency, an *adjustable slope angle wave energy converter* (ASAWEC) is proposed in this paper. Besides, the experiment was done in three conditions corresponding to weak, normal and strong wave conditions; and, slope angle is varied from 0 (vertical) to 20° to investigate an optimal slope angle of each wave condition.

The remainder of this paper is organized as follows. Section 2 describes the wave making tank and the test rig of ASAWEC, Section 3 presents the mathematical model of ASAWEC, and Section 4 shows the experiments and analysis of the experimental results. Finally, conclusions and future works are presented in Section 5.

2. Description of wave simulator and adjustable slope angle wave energy converter

2.1. Wave making tank

To carry out the experiment, a wave making tank with adjustable amplitude and frequency is employed, as in Fig. 1. The wave making tank includes a wave making wall moved by propulsion hydraulic cylinders, placed in a water tank. A slope damping net attached at the opposite side of the wave making wall eliminates the reflex wave to avoid inexpectant noise. The motion of the wave making wall and cylinders is set up and controlled by a computer and sensors to achieve the exact wave amplitude and wave frequency or wave height and wave period. Before starting each wave condition, we must ensure that the water of the tank stands still. The working principle of the wave making tank in this research is similar to the *wave maker* described in Anbarsooz et al. (2013). The main parameters of the wave making tank are presented in Table 1.

2.2. Adjustable slope angle wave energy converter

The test rig of ASAWEC, as shown in Fig. 2a, includes two components: the PTO and hydraulic transmission. In the PTO, a floating buoy attached to a moving shaft can be moved by a wave. The moving shaft is ensured to move in a linear direction and with low friction by rollers. The moving shaft connects to a hydraulic cylinder which functions as a hydraulic pump to generate pressurized fluid. The slope angle adjustment is carried out by a rotation mechanism with electric actuator and potential meter. The control signal is given by a PID closed-loop controller from a computer. The schematic diagram of ASAWEC is shown in Fig. 2b.

Initially, we estimate that the optimal angles of the wave conditions which the wave-making tank can generate are less than 25°. The ASAWEC was fabricated so as to be able to rotate from 0° (vertical) to 25°. In experiment, the optimal sliding angles in three wave condition are is less than 20°. Therefore, the experimental result is shown from 0° to 20°.

The PTO and hydraulic transmission are supported by a frame and conjoined via hydraulic hoses. A low pressure hose carries low pressure fluid from the tank to the hydraulic cylinder, while a high pressure hose lets pressurized fluid from the cylinder to the high pressure accumulator and hydraulic motor of the hydraulic transmission.

The hydraulic circuit of ASAWEC is shown in Fig. 3. When the cylinder is extended, fluid is sucked from the tank to the full bore chamber of the cylinder. The CVI check valve allows low-pressure fluid from the low-pressure hose to enter the cylinder but prohibits entry of the fluid in the opposite direction. When the cylinder is compressed, fluid in the full bore chamber is pressurized and pumped to the high-pressure accumulator (HPA). The CVO check valve transfers the high-pressure fluid from the cylinder to the high-pressure hose to charge the HPA, but prohibits transfer of the fluid in the opposite direction. The hydraulic motor is driven by high-pressure fluid from the HPA. By employing HPA, the operation pressure is smoothened and the fluctuation of the hydraulic motor velocity is reduced. The relief valve RLV_1 releases pressure in the HPA to protect the hydraulic circuit if the operating pressure becomes too high. A Magnetorheological (MR) brake is used to simulate the load of a generator. A torque and speed sensor are placed between the hydraulic motor and the “generator” (herein MR brake) for output power calculation. The parameters of components of ASAWEC are shown in Table 2.

Data of the wave, floating buoy motion, buoyant force, pressure of cylinder and accumulator, flow rate of the hydraulic motor, output torque and speed are collected from the corresponding sensors and sent to the computer via a data acquisition card. A Matlab Simulink program is built for slope angle control and data processing.

Table 1
Parameters of wave making tank.

Parameters		**Symbol**	**Value**
Water tank	Length	L_T	50 m
	Width	W_T	20 m
	Height	H_T	2 m
Damping length		L_d	5 m
Water depth		h	1 m
Max. stroke of wave making wall		S_{max}	0.5 m
Propulsion cylinder	Bore diameter	D_p	50 mm
	Rod diameter	d_p	28 mm
	Length	l_p	0.7 m
	Number of cylinders	q	10
Wave generation capacity	Wave period	T_w	1–5 s
	Wave height	H_w	0.1–0.4 m

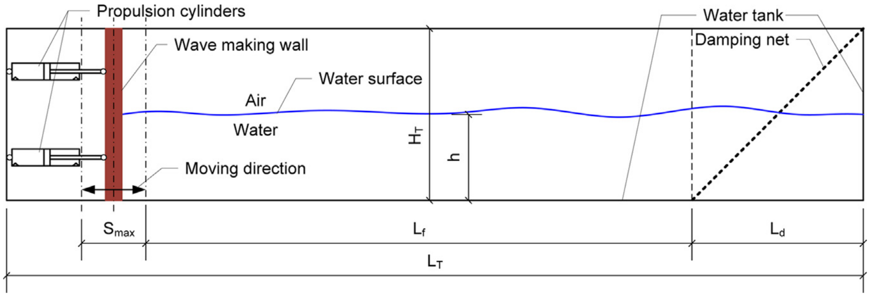

Fig. 1. Schematic diagram of wave making tank.