Ocean Engineering 38 (2011) 436–443

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Modeling and control of a 75 kW class variable liquid-column oscillator for highly efficient wave energy converter

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ARTICLE INFO

Article history:
Received 23 July 2010
Accepted 14 November 2010
Editor-in-Chief: A.I. Incecik
Available online 22 December 2010

Keywords:
Ocean wave
High efficiency
Oscillating body
Wave energy converter

ABSTRACT

The modeling and control of a variable liquid-column oscillator having a liquid filled U-tube with air chambers at its vertical columns are presented. As an ocean wave energy extracting device, the structure of the variable liquid-column oscillator (VLCO) is analogous to that of the tuned liquid-column damper used to suppress oscillatory motion in large structures like tall buildings and cargo ships. However, owing to an air spring effect caused by the dynamic pressure of air chambers, the amplitude of response of the VLCO becomes significantly amplified for a desired wave period. The governing equations for the motion of VLCO structure under wave excitation and the motion of liquid with an air spring effect caused by an air–liquid interaction are described by a series of nonlinear differential equations. A set of control parameters for extracting maximum power from various wave conditions is determined for the efficient operation of the VLCO. It is found that the effect of the air spring has an important role to play in making the oscillation of the VLCO match with the ocean wave. In this way, the VLCO provides the most effective mode for extracting energy from the ocean wave.

1. Introduction

Ocean wave energy is a renewable energy source with a large potential that may contribute to the worldwide increasing demand for power. The global wave power potential is estimated to be 8000–80,000 TWh/y or 1–10 TW (Boud, 2003). There are several different types of wave energy converters (WECs) depending on their energy extracting principles. The major WECs can be classified into overtopping, oscillating water column and oscillating body converters (Khan et al., 2008; Rodrigues, 2008; Falcão, 2008). Among them, the oscillating body type converter is believed to be the most efficient one because the structure of the converter directly absorbs energy from the wave. However, for various reasons, it is estimated that only 10–15% of wave energy is converted into electric power (Rodrigues, 2008), which is an incredibly small magnitude compared with that of wind energy converters having 30–40% efficiency. On the other hand, a considerable amount of waves having heights shorter than 1 m, which is the lower operating limit for the majority of present WECs, is widely distributed in the real ocean (Cruz, 2008). So, a highly efficient wave energy converter extracting more energy from the shorter wave heights is also necessary to increase the capacity factor, which is an important measure for the commercialization of the WECs.

Since the ocean waves have oscillating property in nature, the energy extracting device of a WEC needs to be an oscillatory device, which can match its oscillation with the wave oscillation, to provide the most effective mode for energy extraction. One of the good examples is an oscillatory device equipped with a mechanical mass and a spring designed for a point absorbing type WEC (Temeev et al., 2006). The mass and spring make the device match with the wave oscillation to provide an effective mode for energy extraction. Another example is the Pelamis developed by Pelamis Wave Power Ltd. The Pelamis is tuned to make its stiffness (buoyancy) couple with its mass (weight), providing a natural oscillation period that matches with the waves where the most power is found (Cruz, 2008; Retzler, 2006).

In this study, we propose a variable liquid-column oscillator (VLCO) as an oscillatory device. The configuration of a VLCO is analogous to that of the tuned liquid-column damper (TLCD) used to suppress oscillatory motion in large structures like tall buildings and cargo ships. The TLCD comprises two vertical columns of liquid that are joined at the base by a horizontal column to form the shape of a U-tube. The TLCD is designed to counteract the oscillatory motion of the building or cargo ship with the dynamic momentum of its internal liquid to reduce the amplitude of response (Moaleji and Grei, 2007; Taflanidis et al., 2005; Wu et al., 2008). However, the VLCO acts in a completely opposite way to the TLCD by amplifying its amplitude of response in the interested range of

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0029-8018/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.oceaneng.2010.11.017

wave periods. In this paper, the results of a simulation study of the VLCO with a control law are presented. The motion of VLCO is described by a series of nonlinear differential equations, and a set of control parameters for extracting maximum power is determined for the control law. Finally, the performance of the VLCO is compared with the VLCO in a frozen state, which belongs to the wave energy extracting device of conventional oscillating body type WECs.

2. Theoretical background

The possible configurations of the oscillating body type WECs equipped with the VLCO units as their wave energy extracting devices are shown in Fig. 1. In the configuration shown in Fig. 1(a) and (b), the energy conversion process is based on the relative motion of VLCO and the heavy pendulum (Falcão, 2010), or the gyroscopic system (Kanki and Furusawa, 2010). The WEC shown in Fig. 1(c) comprises a number of semi-submerged VLCO units connected together with the power takeoff units to form an articulated chain-like structure. The wave-induced motion of the VLCO gives bending moment to the power takeoff units as energy for generating electricity.

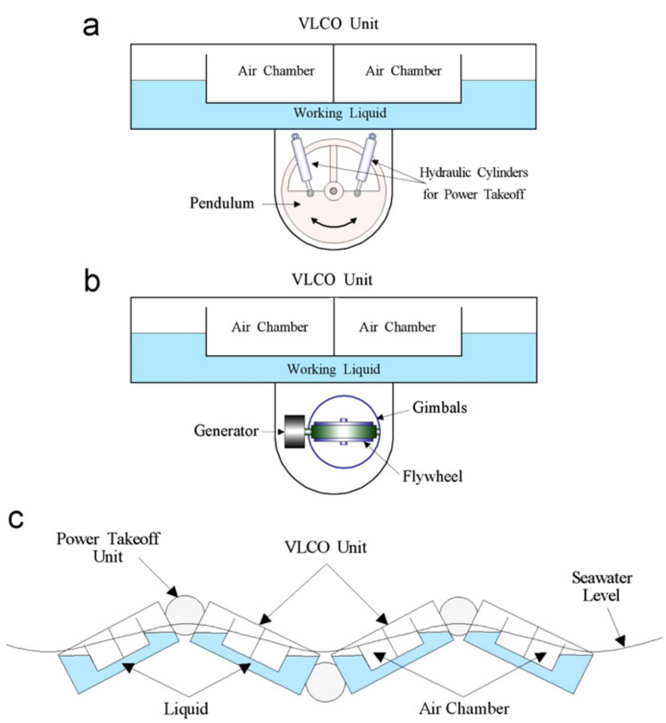

Fig. 1. Configuration of WECs equipped with VLCO unit: (a) VLCO with pendulum, (b) VLCO with gyroscopic system and (c) VLCOs joined with PTOs.

A simplified VLCO shown in Fig. 2 is investigated in this study. In the VLCO configuration, air chambers are added at the vertical columns of the U-tube, and a certain amount of liquid is contained in the U-tube. The motion of the liquid, acting as a fluid piston, causes an air spring effect by compressing and expanding the air in the air chambers. If the stiffness of the air spring is chosen properly, the stiffness and the mass of the liquid can provide a natural oscillation frequency that matches with the waves. In order to make the stiffness of the air spring adjustable by changing the air chamber volume, the control valves $SV_{01}(SV_{11})$ through $SV_{0n}(SV_{1n})$ are included in the configuration. The control valves CV_0, CV_1 and CV_2 have the role of initializing or balancing the VLCO system.

2.1. Governing equations

The fundamental assumption that is made in formulating the governing equations is that the rotational center is located at the geometric center of the VLCO, with the moment components causing the displacement of the VLCO being neglected. The governing equations of the motion of the VLCO are derived from Lagrange's equation as Taflanidis et al. (2005) and Wu et al. (2008) proposed for the TLCD analysis. Lagrange's equation can be expressed as

$$\frac{d}{dt}\left\{\frac{\partial(T-V)}{\partial \dot{z}_w}\right\}-\frac{\partial(T-V)}{\partial z_w}=Q_{int} \tag{1}$$

and

$$\frac{d}{dt}\left\{\frac{\partial(T-V)}{\partial \dot{\alpha}}\right\}-\frac{\partial(T-V)}{\partial \alpha}=Q_{ext} \tag{2}$$

for the motion of working liquid in the VLCO and the rotational motion of the VLCO structure, respectively. In Eqs. (1) and (2), T and V are the kinetic and potential energies, respectively, and Q_{int} and Q_{ext} denote the non-conservative forces. The kinetic energy of the VLCO shown in Fig. 2 is composed of following terms:

$$T_S=(J_S+J_A)\dot{\alpha}^2 \tag{3}$$

$$T_L=\frac{1}{2}\rho(L_v-z_w)A_v\left(\dot{z}_w+\frac{L_h}{2}\dot{\alpha}\right)^2 \tag{4}$$

$$T_R=\frac{1}{2}\rho(L_v+z_w)A_v\left(\dot{z}_w+\frac{L_h}{2}\dot{\alpha}\right)^2 \tag{5}$$

$$T_H=\tfrac{1}{2}\rho A_h L_h(r\dot{z}_w+R_h\dot{\alpha})^2 \tag{6}$$

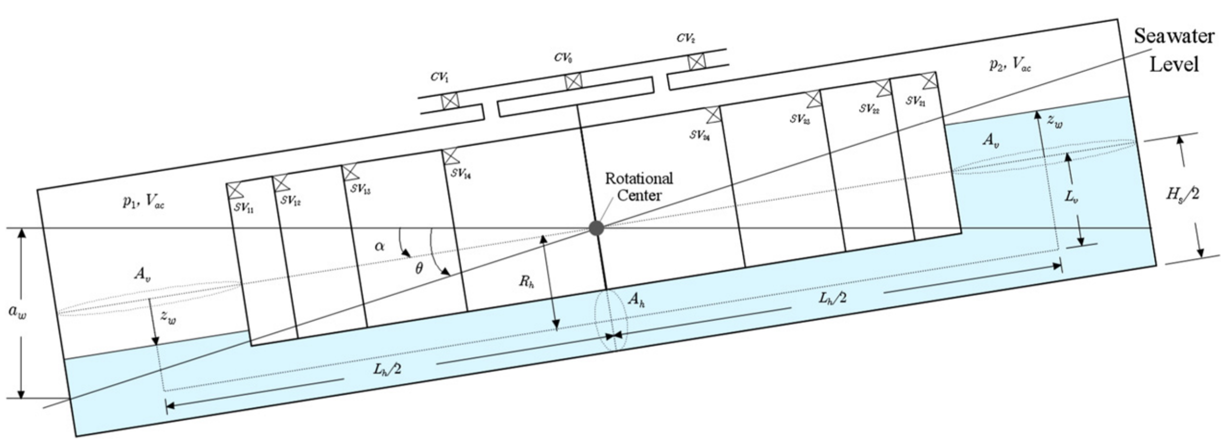

Fig. 2. Schematic diagram of a VLCO unit.