Latching Control of an Oscillating Water Column Spar-Buoy Wave Energy Converter in Regular Waves

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The present paper concerns an oscillating water column (OWC) spar-buoy, possibly the simplest concept for a floating OWC wave energy converter. It is an axisymmetric device (and so insensitive to wave direction) consisting basically of a (relatively long) submerged vertical tail tube open at both ends and fixed to a floater that moves essentially in heave. The length of the tube determines the resonance frequency of the inner water column. The oscillating motion of the internal free surface relative to the buoy, produced by the incident waves, makes the air flow through a turbine that drives an electrical generator. It is well known that the frequency response of point absorbers like the spar buoy is relatively narrow, which implies that their performance in irregular waves is relatively poor. Phase control has been proposed to improve this situation. The present paper presents a theoretical investigation of phase control through the latching of an OWC spar-buoy in which the compressibility of air in the chamber plays an important role (the latching is performed by fast closing and opening an air valve in series with the turbine). In particular, such compressibility may remove the constraint of the latching threshold having to coincide with an instant of zero relative velocity between the two bodies (in the case under consideration, between the floater and the OWC). The modeling is performed in the time domain for a given device geometry and includes the numerical optimization of the air turbine rotational speed, chamber volume, and latching parameters. Results are obtained for regular waves. [DOI: 10.1115/1.4007595]

1 Introduction

The oscillating water column wave energy converter equipped with an air turbine has been the object, possibly more than any other type of wave energy device, of extensive research and development effort dating back to the navigation buoys of pioneer Y. Masuda and to the first large prototype Kaimei [1]. The OWC device comprises a partly submerged (floating or sea-bottom-fixed) structure, open below the water surface, inside which air is trapped above the water free surface. The oscillating motion of the internal free surface produced by the incident waves makes the air flow through a turbine that drives an electrical generator. In most cases, a self-rectifying air turbine (i.e., a turbine that does not need rectifying air valves) is used, the best known being the Wells turbine patented in 1976 by Alan A. Wells [2]. If the structure is fixed (shoreline or bottom-standing OWC), then the energy absorption results solely from the interaction between the water column motion and the surrounding wave field. In the case of a floating device, the motions of both the water column and the structure (by interacting with the incident wave field) contribute to the energy absorption from the waves. This is namely the case of the backward bent duct buoy (BBDB) [3].

An OWC spar-buoy is possibly the simplest concept for a floating OWC. It is an axisymmetric device (and so insensitive to wave direction) consisting basically of a (relatively long) submerged vertical tail tube open at both ends and fixed to a floater that moves essentially in heave. The length of the tube determines the resonance frequency of the inner water column. The air flow displaced by the motion of the OWC inner free-surface, relative to the buoy, drives an air turbine. Several types of wave-powered navigation buoys have been based on this concept [4,5], which has also been considered for larger scale energy production [6]. The sloped buoy [7] has some similarities with the spar buoy and consists of a buoy with three sloped immersed tail tubes such that the buoy-tube set is made to oscillate at an angle intermediate between the heave and surge directions. A report prepared for the British Department of Trade and Industry [7] compared three types of floating OWCs for electricity generation in an Atlantic environment: BBDB, sloped buoy, and spar buoy. If the vertical tail tube of the spar buoy is long enough (say larger than about 40 m), then the distance from its open bottom to the sea surface is such that the interaction between the motion of the inner water column and the surrounding surface wave field becomes very small. In such a case, the energy absorption from the waves is due essentially to the motions of the floater-tube set; the water inside the tube acts essentially as an inertial frame of reference.

The OWC spar buoy with a tube of uniform cross section was the object of two of the earliest published theoretical studies on wave energy converters [8,9]. An analytical solution by the method of separation of variables was obtained by Korde [10] for the diffraction problem concerning an axisymmetric tail tube buoy consisting of a cylindrical tube of negligible wall thickness attached to a cylindrical floater.

The advantages of using a tube of nonuniform inner cross section were discussed in detail in Ref. [11], where a procedure was presented for the optimization of the tube and buoy geometry and of the air turbine characteristics for maximum energy production in a given wave climate.

Like other axisymmetric absorbers oscillating in heave, the spar buoy can theoretically attain a capture width equal to $\lambda/2\pi$ in regular waves of wavelength λ if optimally designed and tuned for that. However, it is well known that the resonance bandwidth of such devices is relatively narrow, which implies that their performance in irregular waves is relatively poor. Phase control has been proposed to improve this situation [12]. In particular, control

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by latching, initially proposed by Budal and Falnes [13,14], can be quite effective and relatively easy to implement in the case of single-degree of freedom devices. However, control by latching has been found to be much less effective when applied to two-body devices like the SEAREV [15] and the IPS Buoy [16]. It has been found, for a generic two-body system, that the inertia ratio between the two bodies plays a major role in the effectiveness of the latching control for the increase of energy absorption [17]. Theoretically, reactive control can give better results on what concerns energy absorption, but its practical implementation in real power takeoff systems (PTOs) is much more problematic.

The present paper presents a numerical investigation of phase control through the latching of an OWC spar-buoy in which the compressibility of air in the chamber plays an important role. In particular, such compressibility may remove the constraint of the latching threshold having to coincide with an instant of zero relative velocity between the two bodies (in the case under consideration, between the floater and the OWC). The device is equipped with the new biradial self-rectifying air turbine described in Ref. [18]. The configuration of the turbine allows a fast-acting axially-sliding valve to be inserted close to the turbine rotor that enables latching control to be implemented. The modeling is performed in the time domain for given device geometry. The characteristic curves of the new biradial turbine, obtained from computational fluid dynamic (CFD) simulations, were used in the numerical computations. Optimal phase control (including optimal latching control) in irregular random waves is known to raise difficult problems, namely, the requirement of predicting the incoming waves and the need to perform relatively heavy computing in real time (see Refs. [12,15,19]). For this reason, suboptimal control strategies have been proposed and investigated by several teams. In the present paper, latching control optimization is addressed only in regular waves. This may be regarded as a first step in an effort to study the control of a floating OWC converter in which air compressibility and a realistic air turbine are modeled. The more difficult problem of (suboptimal) latching control in irregular waves is not considered here. All the results presented in this paper are from numerical simulations.

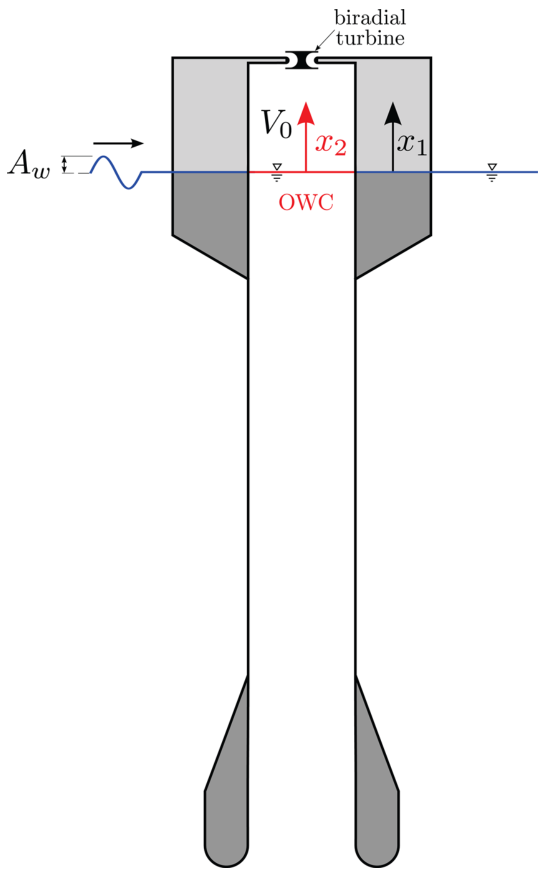

Fig. 1 Cross-section view of the axisymmetic floating OWC

2 Device Modelling

2.1 Governing Equations of the Spar-Buoy and OWC. The spar buoy (floater and tail tube) is named here as body 1. We neglect the warping of the inner water free surface, which is reasonable taking into account the large length of tube and the effect that only heave motions are considered, and define body 2 as an imaginary piston floating on the OWC surface, whose length is assumed small and density equal to water density. Let x_i be the coordinates of body i for the heaving motion, with $x_i = 0$ at equilibrium position and x_i increasing upwards, as seen in Fig. 1. The motion equations for the two-body system are

$$\begin{aligned}(m_1 + A_{11}^{\infty})\ddot{x}_1 + \rho_w g S_1 x_1 + A_{12}^{\infty}\ddot{x}_2 - p_{\text{ref}} S_2 p^* &= F_{d1} - R_{11} - R_{12} \\ (m_2 + A_{22}^{\infty})\ddot{x}_2 + \rho_w g S_2 x_2 + A_{21}^{\infty}\ddot{x}_1 + p_{\text{ref}} S_2 p^* &= F_{d2} - R_{22} - R_{21}\end{aligned} \tag{1}$$

Here ρ_w is the water density, g is the acceleration of gravity, m_i is the mass of body i, S_1 is the annular cross-sectional area of body 1 defined by the undisturbed free-surface plane, S_2 is the area of the piston flat top, F_{di} is the hydrodynamic excitation force on body i, and R_{ij} is the hydrodynamic radiation force concerning the motion of one of the bodies as affected by the motion of the other body. The air pressure inside the chamber is $p + p_{\text{atm}}$, where p_{atm} is the atmospheric pressure. The dimensionless relative pressure oscillation inside the chamber is defined as $p^* = p/p_{\text{ref}}$ with $p_{\text{ref}} = \rho_w g H$, and H is the incident wave height.

The radiation force is computed in the time domain as

$$R_{ij} = \int_{-\infty}^{t} K_{ij}(t-s)\dot{x}_j(s)\,\mathrm{d}s \tag{2}$$

where K_{ij} is the impulse response function. The added masses are given by $A_{ij}^{\infty} = \lim_{\omega\to\infty} A_{ij}(\omega)$, where $A_{ij}(\omega)$ are the frequency-dependent added mass coefficients for the set of bodies spar-buoy/piston. Similar relations are applied to radiation forces on the piston. Since we are assuming linear water wave theory, the diffraction force in regular waves of frequency ω may be written as

$$F_{di}(t) = \Gamma_i(\omega) A_w \cos(\omega t + \phi_i) \tag{3}$$

where $\Gamma_i(\omega)$ is an excitation force coefficient, $A = H/2$ is the wave amplitude, and ϕ_i is the phase response of body i.

2.2 Governing Equations for the Turbine. The mass flow rate of air $\dot{m}_t$ through the turbine (positive for outward flow) is

$$\rho\dot{V} + \dot{\rho}V = -\dot{m}_t \tag{4}$$

where ρ is the air density and V the volume of air inside the chamber. The time-dependent volume of air is

$$V = (h_0 + x_1 - x_2)S_2 \tag{5}$$

with

$$h_0 = \frac{V_0}{S_2} \tag{6}$$

where V_0 is the volume of air inside the chamber in calm water. It should be noted that it must be $h_0 \geq x_2 - x_1$ since the volume of air cannot be negative.