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Time-domain modeling of a fixed detached oscillating water column towards a floating multi-chamber device

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ABSTRACT

A simplified time-domain model for a fixed detached Oscillating Water Column (OWC) device is presented as a first step towards modeling a floating multi-chamber OWC device. The motion of a floating body in the time-domain is expressed by Cummins integro-differential equation, and based on it, water mass motion inside the chamber has been modeled here as a piston-like motion. Radiation, hydrostatic, excitation and viscous forces have been considered, as well as the added mass of the water in the chamber and the effect of the air pressure inside it. The equation of the floating body in the time domain has been approximated by a state-space method, which comes from the extension of the state-space system corresponding to the convolution integral of the radiation force. Experimental data have been used for model calibration and validation. Furthermore, the model has also been validated with a widely used Computational Fluid Dynamics (CFD) model (IH-2VOF). These show that the model presented is reliable and computationally efficient allowing for massive simulations for a statistical design or economic feasibility studies.

1. Introduction

Wave energy is one of the most promising renewable energy resources nowadays and research is being carried out worldwide. OWC is a wave energy extraction technology based on wave to air energy conversion driven by an oscillating column or water trapped in a chamber connected to the sea. The air energy is extracted by means of self-rectifying air turbines placed on top of the chamber. Due to water level oscillations in the chamber, the air inside it is compressed and decompressed making a reversible flow towards the atmosphere and to the chamber through a self-rectifying air turbine that rotates in the same direction regardless of the direction of the air flow, and generating mechanical energy. Compared to other Wave Energy Converters (WEC) the main advantage of OWC devices is that they do not have any moving parts in the water, leading to easier maintenance works.

Since the first OWC column was built in 1910 by Bochaux-Praceique attached to a cliff next to Bordeaux (France), a wide typology of devices have been developed. Different designs have reached prototype stage. For instance, the single chamber Pico plant in Azores (Portugal) and the multi-chamber Mutriku plant (Spain) are two fixed plants nowadays tested. There are also floating devices that have been tested in field such as the 1:4 scale OEbuoy prototype in Galway bay (Scotland) or Kaimei (1978–1986, Japan). However, OWC technology has not reached yet a fully commercial stage. Many of this full scale prototypes are testing sites for OWC turbines under development, as is the case of Limpet in Islay (Scotland), which is a clue issue for the optimization of the OWC technology. Weber (2007) addressed the problem of simultaneous scaling of hydrodynamics and compressibility effects in small scale experiments and stated that air compressibility cannot be accurately represented by geometrical scaling of the device (Lopes et al., 2009). Despite it, some experimental analyses have been developed in OWC. Whittaker and McPeake (1986) presented the first experimental testing on an axisymmetric floating OWC based on a navigation buoy geometry and Sarmento (1992) experimentally tested a 2D bottom-standing OWC. Later experimental studies analyzed the front wall shape influence on the flow (Morris-Thomas et al., 2007) and the air flow in the chamber (Ram et al., 2010). Experimental testing of a fixed cylindrical OWC has been used for hydrodynamic model validation (Sykes et al., 2011) and a floating cylindrical OWC was tested by Sheng et al. (2012) and Sykes et al. (2011) (Gomes et al., 2012). Overall, there is not enough experimental and field data and the existing data is in general inaccessible (Alves et al., 2011). Since there is no experimental data available of fixed detached OWC devices, experimental testing was carried out in this work in order to calibrate and validate the simplified numerical model developed.

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A successful design and optimization of WECs must be strongly based on numerical modeling, due to the high economic and time costs which physical modeling entails. CFD models that approximate Navier–Stokes equations are widely accepted as being the best way of solving the dynamics involved in WEC analysis. However, their complexity leads to high computational costs. There is therefore a need to develop sufficiently accurate but computationally less demanding models. In general, the hydrodynamic interaction between WECs and ocean waves is a complex high order non-linear process, which, under some particular conditions, might be simplified. In the case of waves and device oscillations described by low amplitude motions this hydrodynamic problem is well characterized by a linear approach. Therefore, in the framework of an entirely hydrodynamic linear approach and under linear forces imposed by both the PTO and the anchoring system, the first step to model the WEC dynamics is, traditionally, carried out in the frequency domain. However, besides the interest of the frequency domain approach, in practice WEC dynamics have some parts which are strongly non-linear. Therefore, the superposition principle is not any longer applicable. Those parts include, for instance, the non-linear forces induced by the mooring system and the PTO (the main cause of the PTO non-linearities is typically the complexity of the control strategies). Thus, to account for the non-linear parts of the problem the WEC dynamics have to be analyzed in time domain. However, as currently there are no available tools to model fixed detached OWC, the objective of this work was to fulfil this gap by developing and experimentally validating a numerical tool for that purpose.

This paper presents a time-domain numerical model to assess the performance of a fixed detached OWC, opened at the bottom and with the PTO simulated by a rectangular slot in the ceiling of the chamber. The model is based on the floating body motion equation in the time-domain. The presence of the convolution integral in Cummins (1962) equation difficults its solution in the time domain (Kashiwagi et al., 2005). To avoid this problem, one method proposed within the literature is to approximate the convolution integral by a state-space system (Jefferys, 1980; Yu and Falnes, 1995). Kurniawan et al. (2011) presented a comparison between time-domain models using different ways to face the convolution integral for some WEC concepts. In the case of an OWC device, they concluded that for an accurate direct convolution integration an extremely small integration time step was needed, since the model dynamics are stiff due to fluid (air) compressibility. They stated that a state-space approximation is an efficient and accurate alternative to avoid the direct calculation of the convolution integral. Taghipour et al. (2008) showed that using state-space models is approximately 8 times faster than solving convolution integrals. The problem has therefore moved from solving the convolution integral to finding the elements of the state-space system which approximates that convolution integral. This state-space receives as input the velocity of the body and produces an approximation to the convolution integral as an output. Several approaches have been used in the literature, such as Duclos et al. (2001), Kristiansen et al. (2005), McCabe et al. (2005) and Yu and Falnes (1995). A description of the different methods can be found in Taghipour et al. (2008). These techniques share a starting point, as all of them require the use of information taken from a 3D Boundary Element Method (BEM) such as WAMIT/WADAM (WAMIT, 2012; DNV, 2008). A novel alternative, proposed by Armesto et al. (under review), does not require BEM codes, as it directly identifies the state-space which solves Cummins equation from other sources of information such as laboratory tests or CFD simulations. The present work uses a frequency domain identification method based on Perez and Fossen (2008, 2009, 2011) and Taghipour et al. (2008) to determine the coefficients of the state-space system which approximates the convolution integral. A frequency-domain identification method (which consists of approximating the transfer function by a complex rational function) was chosen because it uses frequency-domain data directly and avoids the additional error caused by the inverse Fourier transform required to compute the impulse response function in the time-domain identification (Alves et al., 2011). This model uses the BEM to compute the added mass and damping coefficients for a given set of frequencies, and then the transfer functions associated with these frequencies are calculated. Finally, the state-space system that approximates the convolution integral can be extended to a new state-space system which completely replaces Cummins equation (Alves et al., 2011; Alves, 2012; Yu and Falnes, 1995). The new state-space receives as input the excitation force and produces the movement of the body as output.

Most of the works already available in the literature are mainly focused on independent numerical or experimental approaches. In this paper both approximations are considered and a detached OWC is experimentally tested and numerically simulated. The main objective is to develop a reliable and efficient numerical model experimentally calibrated and validated. The model presented has also been validated with IH-2VOF (Losada et al., 2008) numerical model results. In Section 2, the physics are modeled and the equations to be solved are described. The experimental testing carried out is explained in Section 3. Validation and calibration of the new model with experimental and numerical results is shown in Section 4. Final conclusions are presented in Section 5.

2. Numerical model implementation

In this section the physics underlying the model are described as well as the model resolution.

2.1. Physics in the model

The time domain motion of a floating body is described by Cummins (1962) equation. This equation can be adapted to a single degree of freedom to represent the heave motion of the water mass inside a fixed OWC chamber:

$$(m+A_\infty)\ddot{z}(t)=\int_0^t K(t-\tau)\dot{z}(\tau)\,d\tau+F_{excitation}(t)+F_{hydrost}(t)-F_{friction}(t)-F_{air}(t) \tag{1}$$

where in Eq. (1) $(\dot{})$ represents the time derivative of the function, m is the water mass inside the chamber at Still Water Level (SWL), A_∞ is the added mass of the body at infinite frequency ($A_\infty=\lim_{\omega\to\infty}A(\omega)$), $z(t)$ is the heave displacement of OWC with respect to the SWL, $F_{excitation}(t)$ is the force due to incident waves acting on the OWC bottom, $F_{hydrost}(t)$ is the restoring hydrostatic force, $F_{friction}(t)$ is the friction force that takes into account the viscous and turbulent losses at the chamber entrance, $F_{air}(t)$ represents the air forces acting on top of the OWC and the integral term represents the diffraction and radiation forces. $K(t)$ is the Impulse Response Function and represents the memory of the fluid. Table 1 contains the nomenclature used throughout the mathematics in the paper.

In the following paragraphs, exact or approximate expressions of the different terms in Eq. (1) are presented. The hydrostatic force can be expressed as $F_{hydrost}(t)=\rho gSz(t)$, being ρ the water density, g the gravity acceleration and S the chamber interior area. The friction force at the chamber entrance will be modeled as a function of the water mass heave velocity. Babarit et al. (2012) considered viscous losses as a quadratic function of the heave velocity. In this work, the following combination of linear and non