Ocean Engineering 113 (2016) 319–334

Contents lists available at ScienceDirect

Ocean Engineering

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

Wave interaction with an Oscillating Wave Surge Converter. Part II: Slamming ☆

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ARTICLE INFO

Article history:
Received 19 May 2015
Accepted 21 December 2015

Keywords:
Oscillating Wave Surge Converter
Slamming
Impact pressure
Re-flection effects

ABSTRACT

In Part I, viscous effects on bottom hinged Oscillating Wave Surge Converters (OWSCs) were investigated numerically. In the present paper (Part II), the slamming on an OWSC is studied both experimentally and numerically. Numerical simulations are performed with the Volume of Fluid (VOF) approach for capturing the interface between air and water and the dynamic mesh method for modelling the motion of the oscillating flap. Comparisons between experiments and simulations validate the numerical model. Sequences of frames from a high speed camera and from numerical results are investigated to understand the physics of the slamming process. The spatial and temporal distribution of the slam pressure on the flap is presented. The free oscillating flap and the wavemaker with prescribed motion create a multiple reflection system. The re-reflection effects on the wave field, the flap dynamics and the slamming event are discussed by comparing a series of cases from experiments and simulations.

1. Introduction

OWSCs are large buoyant flaps, hinged at the bottom of the ocean, which oscillate back and forth under the action of incident waves. They are intermediate water depth devices and hence the interacting waves have an amplified horizontal motion, resulting in large amplitudes of flap rotation and thus increased power output. In an earlier paper (Wei et al., 2015), hereafter referred to as Part I, we investigated the viscous effects on OWSCs under normal operating conditions, and concluded that the viscous effects are not important for OWSCs with wide flaps. However, in extreme sea states, as the flap pitches seaward and reaches a vertical position in the wave trough, the water line suddenly drops in front of the flap, the flap hits the water surface with a high angular velocity, leading to a short duration but high magnitude load on the device. Wave slamming on an OWSC was first investigated by Henry et al. (2014b), using experimental and numerical methods. The slamming event was identified using images recorded by high speed cameras. A sequence of images explicitly shows that it is the flap which impacts the water free surface rather than a wave hitting an object like in classical wave impact problems, therefore this is characterized as slamming. Measurements by a finite number of pressure sensors indicate that the maximum peak value of the pressure is located at the center of the flap. But the low spatial resolution was not sufficient to describe the impact pressure distribution. In Part I, we have observed that the slamming phenomenon as well as a sharp spike in the time history of the pressure can be captured by our numerical model. However, the mesh resolution is still too low to capture the thin water jet and the local sharp pressure peaks accurately. Wave slamming phenomena have also been observed with the full-scale prototype of an OWSC (*Oyster*800), when it was operating in a rough sea state with a significant wave height greater than 5.0 m (see Aquamarine Power, 2013).

Wave impact on a rigid wall is a common but complex phenomenon, which has already been examined extensively (see Takahashi, 1996; Bullock et al., 2007; Bredmose et al., 2009; Lafeber et al., 2012). It is thought that the front shape of the wave has a significant influence on the local impact pressure. Lafeber et al. (2012) performed an experimental study on the sloshing impact loads on the tanks inside LNG carriers. Depending on the characteristics of the pressure time series, the interactions between the different parts of the waves and a flat wall can be categorized into three types of impact: slosh impact, flip-through impact and air pocket impact. In complex wave impacts, i.e., a breaking wave impacting on a corrugated wall, the pressure signal or the force recorded on the wall can be considered as the result of one or a combination of three Elementary Loading Processes

☆http://dx.doi.org/10.1016/j.oceaneng.2015.05.002
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http://dx.doi.org/10.1016/j.oceaneng.2015.12.041
0029-8018/

(ELPs): the direct impact (ELP1), the building jet along the wall (ELP2) and the pulsating entrapped or escaping gas (ELP3). The wave slamming on an OWSC shares some analogy with the impacts observed during sloshing experiments. In our paper we categorize the impact type and the ELPs.

The slamming on an OWSC is also similar to the water entry problem of a wedge. The earliest model for dealing with the water entry problem was proposed by von Karman (1929). Von Karman's theory is based on a momentum formulation and neglects the water pile-up profile. Wagner (1932) developed the theory by taking into account the deformation of the free surface elevation. The theoretical models are based on a rigorous mathematical derivation, which can only solve simplified problems involving bodies with a simple geometry. Numerical models must be used for more complex applications. The Boundary Element Method (BEM) was first used for the slamming problem by Greenhow (1985), but difficulties were met when dealing with jet flows. Later Zhao and Faltinsen (1993) presented a numerical tool based on BEM for studying the water entry of a two-dimensional (2D) body of arbitrary cross-section. They used exact non-linear free surface boundary conditions to deal with the jet flow. In the aforementioned studies, the entry velocity of the body is constant, which means that the body motion and the fluid flow are decoupled. Wu et al. (2004) considered the water entry problem of a symmetric wedge through free fall, using fully non-linear potential flow theory together with an auxiliary function to obtain the body acceleration. As a result, the body motion and the flow are fully coupled. Xu et al. (2010) extended the model and studied the water entry problem of a free falling wedge in three degrees of freedom, including body rotation. Xu et al.'s (2010) method might be applicable to study an OWSC with prescribed motion impacting on an initially still water surface, but the method cannot deal with the strong coupling between the wave and the OWSC under extreme wave conditions.

Although there are similarities between the slamming on an OWSC and the wave impact on a wall or the water entry of a wedge, the former has some unique features. It is different from wave impacting on a stationary wall, where the pressure distribution on the wall is dominated by the front shape of the wave only. It is also different from the water entry problem, for which the initial contact angle and the relative motion are known in advance. The slamming on an OWSC is significantly affected by the strong coupling between the incident wave and the flap motion. In practice, the slamming pressure on a vessel can be determined by an empirical pressure–velocity relationship, which is based on a suitable theory such as Wagner's theory, as suggested by the American Bureau of Shipping (ABS, 2011). Although a strong correlation between the jet root velocity and the maximum pressure on the flap is found in the experiment via Wagner's theory (Henry et al., 2015), the jet root velocity used for the calculation is not straightforwardly obtained, but only estimated by the sequence of images. Therefore, there are no available analytical solutions nor empirical data that can be employed directly to predict the pressure and the resultant loads to be used in the design of the structure.

Computational Fluid Dynamics (CFD) methods are a good option to study slamming on an OWSC. With CFD methods the entire flow field can be computed. In particular the generation of the jet flow and the local pressure distribution can be visually presented. The compressibility of the fluid and the elasticity of the body can be taken into account to estimate the cushioning effects on the impulse pressure. Complicated geometries can be handled. Many applications have proved that CFD is a useful tool for studying wave impact and slamming problems. Rafiee et al. (2015) simulated a wave impact on a rigid wall with a large entrained air pocket using a two phase compressible SPH method. Zhao and Hu (2012) applied a constrained interpolation profile based Cartesian grid method to model the non-linear interactions between extreme waves and a floating body. A good agreement with experiments was obtained for large amplitude body motions and water-on-deck. Guilcher et al. (2014) numerically investigated the influence of the wave shape on the breaking wave impacts against a flat rigid wall, using a bi-fluid compressible SPH solver. The continuous time-space distribution of the load on the wall obtained through the numerical simulations greatly helps understanding the scarce information obtained from a finite number of sensors used during the tests. Therefore, CFD simulations can extend our understanding on slamming on an OWSC.

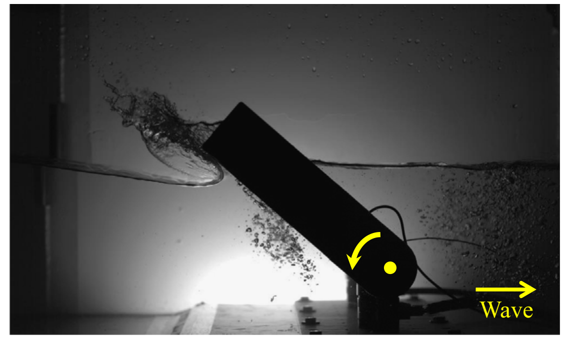

Fig. 1. Snapshot showing slamming on an OWSC in a 2D experiment. The wave travels from left to right, the slamming occurs when the OWSC pitches seaward before the wave crest arrives.

In this paper, we investigate the slamming on an OWSC using 2D experimental and numerical models. The flap dynamics in the 2D model is different from that in the three-dimensional (3D) model, because diffraction effects are omitted in the 2D model. The spatial and temporal distributions of the impact pressure on the flap might be different due to the 3D effects (in the 3D model, the impact pressure will be enhanced towards the center of the flap). However, according to our observations, the slamming process in the 2D model is very similar to that in the 3D model. As opposed to 3D experiments which are difficult to visualize, 2D experiments provide a better view to capture images of the slamming process. Moreover, 2D experiments are easier for mapping the pressure on the flap. This pressure map is quite helpful to gain insight into the slamming phenomenon. From the numerical point of view, the computational cost of 2D simulations is much lower than that of 3D simulations. Hence, 2D experiments can also provide a benchmark for the development of numerical models which is less computationally demanding than a 3D one. The OWSC is a relatively novel marine device, in which the slamming process is still not fully understood. As a preliminary study of slamming on such devices, the major goal is to develop our understanding of the slamming process. Therefore, it is decided to carry out 2D experimental and numerical studies. Fig. 1 provides a snapshot of a typical slamming event captured in a 2D experiment.

This paper is organized as follows: In Section 2, we briefly introduce the 2D experiments that were undertaken at Ecole Centrale Marseille (ECM) in 2013 and 2014. In Section 3, we describe the numerical model based on the commercial CFD package ANSYS FLUENT. In Section 4, we validate the numerical model by comparing with experimental results. We then investigate in Section 5 the flow field, the water surface evolution during a slamming event as well as the spatial and temporal distribution of the pressure on the flap. It is found both in the experiments and the simulations that the re-reflection influences the wave field, the flap motion and the slamming event (see Section 6). Finally, conclusions are given in Section 7.