Journal of Fluids and Structures 82 (2018) 258–271

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

The pressure impulse of wave slamming on an oscillating wave energy converter

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ARTICLE INFO

Article history:
Received 26 February 2018
Received in revised form 28 June 2018
Accepted 6 July 2018

ABSTRACT

Recent wave tank experiments on a flap-type wave energy converter showed the occurrence of extreme wave loads, corresponding to slamming events in highly energetic seas. In this paper, we analyse pressure-impulse values from available pressure measurements, for a series of experimental slamming tests. Then, we devise a pressure-impulse model of the slamming of a flapping plate, including the effects caused by air entrapment near the plate. Using a double conformal-mapping technique, we map the original domain into a semi-infinite channel, by means of Gauss' hypergeometric functions. This allows us to express the pressure impulse as a superimposition of orthogonal eigenfunctions in the transformed space. The mathematical model is validated against the experimental data. Parametric analysis shows that the system is much more sensitive to the impact angle than to the initial wetted portion of the flap. Furthermore, the presence of an aerated region determines the pressure-impulse values to increase significantly at all points on the flap surface.

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1. Introduction

Slamming is the violent impact between a liquid surface and a structure (Faltinsen and Timokha, 2009; Dias and Ghidaglia, 2018). Traditionally, slamming has been studied and modelled in the context of seaplane mechanics and ship hydrodynamics. Slamming has been investigated also in the context of traditional and innovative breakwaters and offshore structures, see Oumeraci et al. (1993), Cuomo et al. (2010), Vicinanza et al. (2013) and Jose et al. (2016). Recently, experiments on a flap-type wave energy converter (WEC) showed the occurrence of slamming events in highly energetic seas, which are able to exert extreme loading on the device (Henry et al., 2014, 2015; Wei et al., 2016a).

Flap-type wave energy converters, such as the Oscillating Wave Surge Converter (OWSC), are among the most effective concepts to extract energy from the ocean (Babarit et al., 2012; Babarit, 2015). The OWSC is a pitching flap which works as an inverted pendulum, driven by the surge movement of waves in the nearshore (Renzi et al., 2014b). A power take-off mechanism (PTO) linked to the device enables transformation of kinetic energy into useful electricity. One of the most popular OWSC prototypes is the Oyster wave energy converter (WEC), which was able to generate up to 1 MWh in 5 h on a single power cylinder at the European Marine Energy Centre (EMEC) in Scotland (Renzi et al., 2014b). Wave slamming has indeed been observed on the Oyster 800 prototype at EMEC, when it was operating in a rough sea of significant wave height $H_s = 5$ m (Wei et al., 2016a). During extreme slamming events, the main engineering problem shifts from generating

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https://doi.org/10.1016/j.jfluidstructs.2018.07.007
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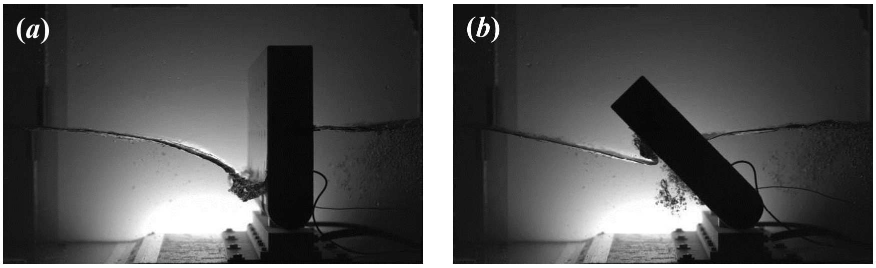

Fig. 1. Snapshots from the experiments of Wei et al. (2016a) at two different stages of a slamming event: (*a*) before slamming, the flap is vertical and the water line drops to its minimum level; (*b*) at impact the flap hits the water, creating a jet which is associated with a strong impulsive load on the structure. Waves are incoming from the left.

energy to ensuring device survival. Therefore, understanding the dynamics of flap slamming and calculating the maximum slamming loads is instrumental to inform the optimal design of OWSCs, thus increasing device reliability and reducing maintenance costs.

The slamming of an OWSC was first investigated by Henry et al. (2014) in three dimensions (3D). As the flap rotates seaward with high angular speed, it reaches a vertical position on encountering the wave trough. Then the waterline drops down the flap surface, and the flap violently hits the water, before the wave crest arrives. Later, Henry et al. (2015) and Wei et al. (2016a) performed additional experiments on a 2D model, using higher sampling rates that allowed more precise quantifications of the pressure peaks. Wei et al. (2016a) also devised a computational fluid dynamics (CFD) model, which successfully reproduced the main characteristics of the slamming event, such as flap angular speed and free-surface deformation. However, due to the very localised nature of the phenomenon and the stochastic behaviour of the experimental data, Wei et al. (2016a)'s CFD model could not capture the extreme pressure levels recorded in the experiments.

In this paper, we focus on the slamming pressure impulse, rather than on the peak pressure. Pressure impulse is defined as the integral of the pressure signal with respect to time, over the duration of the impact (Cooker and Peregrine, 1995; Faltinsen and Timokha, 2009). While slamming pressures usually have a stochastic behaviour, the pressure impulse is better behaved; therefore it is a better parameter to characterise extreme impacts (Lugni et al., 2006). This paper is organised as follows: First, we re-analyse all the experimental pressure recordings of Wei et al. (2016a) and use a local regression technique to calculate the mean curve. Then, we calculate the pressure impulse for all the experimental time series and the relevant regression data (Section 2). Second, we derive a pressure-impulse model of wave slamming on a plate, based on the seminal work of Cooker and Peregrine (1995) and Wood et al. (2000). The model includes the effect of air entrapment, which was neglected in the numerical study of Wei et al. (2016a), and is validated with the experimental data (Section 3). Finally, we perform a parametric analysis of the system, highlighting the contribution of the main engineering parameters (impact angle, contact point position, extent of the aerated region) on the maximum pressure impulse (Section 4). Our results show that the system is much more sensitive to the impact angle than to the initial wetted portion of the flap. Furthermore, in the presence of air trapping, the pressure impulse values increase significantly at all points on the flap surface.

2. Analysis of experimental data

2.1. Experimental layout

In order to develop a better understanding of the slamming of an OWSC, an experimental campaign was undertaken in the wave flume at Ecole Centrale de Marseille (ECM). The model OWSC was a 40th scale model with box-shape geometry (width × height × thickness = 0.646 m × 0.310 m × 0.0875 m), attached to a semi-circular tube under it, as shown in Fig. 1. The flap spanned the width of the wave flume, hence the experiment was two dimensional and represented a simplification of the slamming problem. A pressure sensor (Kistler 211B6, sampling rate 2000–6250 Hz) was installed at the centre of the flap near the mean water level, at a distance of 0.210 m above the hinge. In addition, a high speed camera (sample rates of 200 fps up to 2000 fps) was installed close to the glass wall of the flume, which could provide a superior view to capture images of the wave–OWSC interaction. More details about the experimental setup can be found in Henry et al. (2014).

A series of tests with various wave amplitudes A, wave periods T and water depths H were carried out in order to search for strong impacts. The case with the strongest impact was found for $A = 0.1$ m, $T = 1.9$ s and $H = 0.305$ m, with an average peak pressure of approximately 5 kPa. We emphasise that the wave conditions that resulted in strong impacts were sensitive to the distance between the wavemaker and the model OWSC, due to the re-reflection phenomenon occurring in the flume (Wei et al., 2016a).

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