Applied Ocean Research 39 (2013) 137–145

Contents lists available at SciVerse ScienceDirect

Applied Ocean Research

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

# Experimental measurements of the complex motion of a suspended axisymmetric floating body in regular and near-focused waves

S.D. Weller*, T.J. Stallard, P.K. Stansby

*School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, UK*

ARTICLE INFO

*Article history:*
Received 22 July 2011
Received in revised form 3 October 2012
Accepted 4 October 2012

*Keywords:*
Wave energy converter
Regular wave
Near-focused wave
Two-dimensional motions
Steady-state
Experimental

ABSTRACT

Numerical models which account for the multiple response modes of floating wave energy converters (WECs) in operating conditions require experimental data for validation. Measurement and observation of complex hydrodynamic mechanisms are also required to inform the development of modelling tools suitable for the simulation of response to extreme waves. Experimental measurements are reported of the motion of an axisymmetric float to regular and near-focused waves. The mechanical system, incident wave conditions and response in a 2D vertical plane are detailed to facilitate comparison to numerical simulations. The system comprises a heaving float connected to a counterweight by an inextensible cable over two pulleys to provide a simplified representation of the slowly varying surge constraint of a mooring system. Translation of the float is measured using an optical encoder. Motion in heave, surge and pitch are also determined by a position identification method based on analysis of video footage. For low frequency regular waves, the float prescribes an elliptical trajectory and the variation of response amplitude with wave amplitude is linear. At higher frequencies, drift of up to one-third of the float radius is observed and the float oscillates along an arc. More complex motions are observed due to the three large amplitude waves of a near-focused wave group. During these waves the upper surfaces of the float are partly immersed and motion occurs in heave, surge and pitch.



## 1. Introduction

Certain wave energy converters (WECs) are based on the heaving motion of axisymmetric floats, e.g. Wave Star [1], Buldra [2] and Manchester Bobber [3]. Accurate modelling of such body motions is necessary for determining power output in operating conditions and response in extreme conditions, the latter of which is crucial for device survivability. It is perhaps surprising that detailed experimental data of float responses is not yet available for validating response to extreme conditions that are typically non-linear. Approaches for modelling time-varying response include linearised [4] or partially linearised approximations [5,6], conventional computational fluid dynamics (CFD; [7]) and smoothed particle hydrodynamics (SPH; [8]). It is the intention of this study to provide experimental data on multi-mode float motions in well defined wave conditions including extreme sea-states, for the purpose of evaluating the accuracy of hydrodynamic models. Specifically the response of a float that is primarily intended to oscillate in heave but is only weakly constrained in surge is studied. So that the response of the float is maximised and to facilitate comparison to numerical models, only cases without a power take-off (PTO) system are considered.

Quantifying horizontal excursion from the equilibrium position is particularly important in the case of an array of floating wave energy converters, which comprise a flexible connection between the power-take off system and float, as both the excitation force and radiation damping will change with the array separation distance [9,10]. A method of device station keeping is crucial to avoid damage to adjacent floats in the case of an array of closely spaced devices. Mooring systems must be designed to minimise fatigue loading and, if large horizontal motions occur; abrasion loading [11]. A strut-supported design would eliminate horizontal motion but would be subject to large horizontal forces during extreme conditions that are unlikely to be tolerated by practical designs [12]. Friction on the supporting shaft may also degrade power capture during operating conditions [13]. Earlier studies by the authors have provided experimental measurements of the heave response amplitude of arrays of floats in regular waves [14,15] and the time-varying vertical response of a float in near-focused waves [16]. Each float is supported by a counterweight which provides a slowly varying horizontal constraint to the float representing a simplified mooring system. The float draft can be varied by changing the counterweight mass. For the regular wave tests reported herein, a Shallow draft float is considered which is a possible configuration for operating wave conditions.

The responses of two deeper draft floats are also studied in extreme wave conditions. During large amplitude waves, response in multiple modes was observed. An extended dataset is presented here

* Corresponding author at: IFREMER, France.
*E-mail address:* samuel.weller@ifremer.fr (S.D. Weller).

0141-1187/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apor.2012.10.008

to facilitate the evaluation of numerical models for predicting the extreme response of a moored heaving float. Detailed measurements of the float position are obtained by analysis of video footage. The experimental arrangement and the two methods used to determine the position of the float are presented in Section 2. Float motions due to a range of regular wave frequencies and amplitudes are presented in Section 3 and motions due to two near-focused wave groups are presented in Section 4.

## 2. Experimental equipment

A small-scale (approx. 1:70th based on the float geometry; Fig. 1(a)) model of a heaving wave energy device is subjected to regular and near-focused wave-fields in a 15 m long and 5 m wide wave flume. The mechanical system comprises an axisymmetric float of radius $a = 0.072$ m, which is cable supported by two pulleys and a counterweight (Fig. 1(b)). With reference to Fig. 1(a) the lower part of the float is constructed of 2.5 mm thick acrylic and the conical upper surface (black) from PTFE, with a polypropylene tube of thickness 2 mm (indicated grey). The dry mass of the empty float is 0.54 kg with steel ballast placed at the base of the float to obtain the drafts used in this study. The float mass ($m_f$) and counterweight mass ($m_c$) can be altered to change the equilibrium draft ($z_{eq}$) and the heave ($f_3$) and surge ($f_1$) natural frequencies of the system (Table 1). A dynamometer system (not shown in Fig. 1(b)) is used to specify the magnitude of torque applied by the drivetrain to one of the support pulleys and subsequently the magnitude of mechanical damping applied to the float. The dynamometer system is calibrated to account for static friction in the rotating drivetrain components ensuring that the mechanically undamped responses reported in this study are repeatable. Further details regarding the dynamometer system and its operation are not given here but can be found in [15,17].

### 2.1. Wave specification

Regular and near-focused wave-fields are generated in a water depth $d = 0.46$ m by eight Edinburgh Designs position-controlled wave paddles located at a distance 3.6 m upwave of the float equilibrium position. The surface elevations of waves propagating towards the test area and energy-absorbing beach (located at a distance 14.7 m downwave of the float) are recorded by capacitance-type wave gauges. Three wave gauges are used and located 0.34 m upwave of the float (WG1), in-line with the float (WG4) and 0.5 m downwave of the float (WG5). Herein, incident conditions are those measured in the absence of the float by WG4 aligned with the float position. Angular displacement measurements from an optical encoder and surface elevations from each wave gauge are recorded at a sample rate of 256 Hz using a Labview interface installed on a National Instruments data logging PC. The regular wave conditions tested include 33 wave frequencies in the range 0.5 Hz $\leq f \leq$ 1.5 Hz and nominal wave amplitudes 0.007 m $\leq a_{nom} \leq$ 0.025 m. These are equivalent to full-scale wave periods between 16.7 s $\geq T \geq$ 5.6 s and wave heights 0.98 m $\leq H \leq$ 3.48 m.

For the near-focused wave groups, the Edinburgh Designs Ocean software is used to define the relative phase of a set of regular wave components such that a near-focused crest is developed at a specified position in the flume. The component amplitudes are defined according to a Bretschneider spectrum which has been found to be reasonable approximation to wave spectra measured at several wave energy sites [18]. The resultant wave group comprises three large wave crests only. Simulating such short duration events should incur lower computational cost than the longer duration wave groups that correspond to JONSWAP spectra with peak enhancement factors greater than unity. The resulting wave groups are classed as 'near-focused' instead of 'focused' as the measured wave profiles do not possess the same characteristics as theoretical focused wave groups,

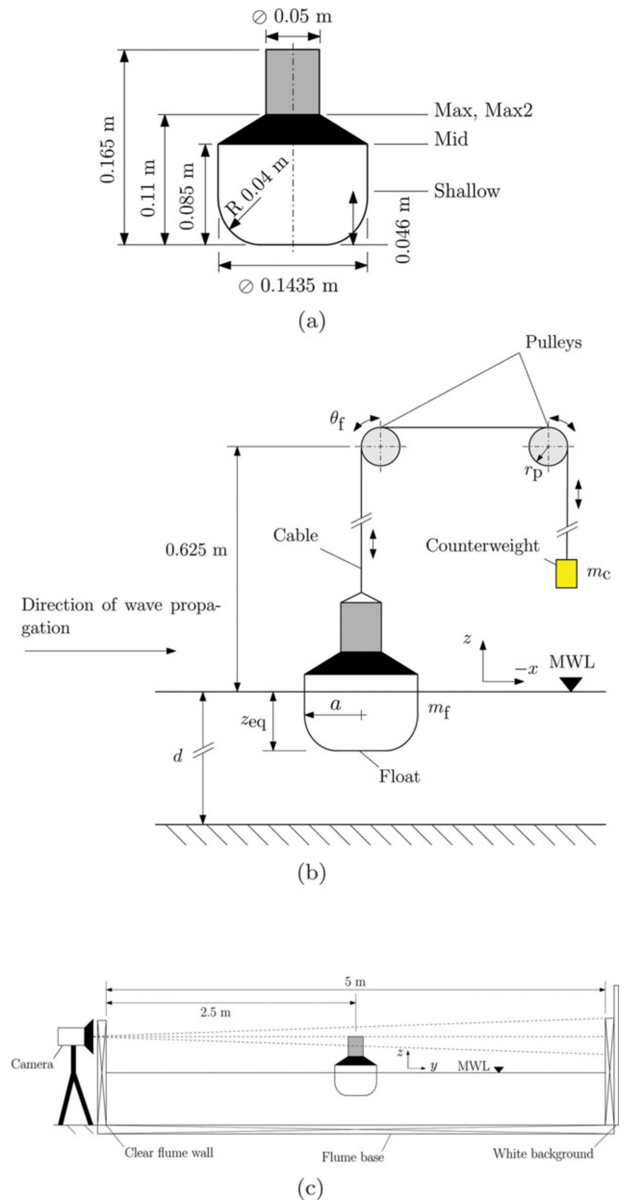


**Fig. 1.** (a) Dimensions of the float geometry and the four equilibrium draft levels used (denoted Shallow, Mid, Max and Max2). Dimensions and corresponding masses for the four drafts are given in Table 1. (b) Side view of the experimental model indicating the float, counterweight, supporting cable and pulleys. (c) Side view of the wave flume showing the location of the float, video camera and white background.

(such as those defined by the New Wave formulation [22]). This is because the wave component phases are defined assuming linear propagation. To enable reproduction of these incident waves in numerical models, the wave paddle input is provided (see Supplementary File1) in addition to the measured time-varying surface elevations in an empty flume (see Section 4).

Two near-focused wave groups are studied with peak frequencies equal to $f_p = 0.688$ Hz and 0.766 Hz with a measured maximum crest amplitude equal to 0.0763 m. At full-scale these peak frequencies are equivalent to peak wave periods equal to $T_p = 12.1$ s and 10.9 s with the maximum crest amplitude equivalent to 5.3 m.

### 2.2. Response measurement

The float is cable supported and therefore float motion may occur in four modes: heave ($z$-axis); surge ($x$-axis); sway ($y$-axis); and