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Hydrodynamic characteristics of a cylindrical bottom-pivoted wave energy absorber

A.J. Caska*, T.D. Finnigan

School of Civil Engineering (J05), The University of Sydney, NSW 2006, Australia

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Abstract

A parametric study was carried out to investigate the hydrodynamics of a cylindrical wave energy absorber. Established methods of hydrodynamic analysis were applied to the case of a damped vertically oriented cylinder pivoted near the sea floor in intermediate depth water. The simple geometry provides a canonical reference for more complex structure shapes and configurations that may be considered for either wave energy conversion or wave energy absorption. The study makes use of the relative velocity Morison equation, with force coefficients derived from radiation and diffraction theory. Viscous effects were accounted for by including a drag term with an empirically derived coefficient, C_D. A non-linear first-order formulation was used to calculate the cylinder motion response in regular waves. It was found that the non-linear drag term, which is often neglected in studies on wave energy conversion, has a large effect on performance. Results from the study suggest a set of design criteria based on Keulegan–Carpenter (KC) number, ratio of cylinder radius to water depth (a/h), and ratio of water depth to wavelength (h/L). Respectively, these parameters account for viscous, wave radiation, and water depth effects, and optimal ranges are provided.

Keywords: Morison's equation; Wave energy; Vertical cylinder; Radiation damping; Wave maker

1. Introduction

Proposed installations of wave energy devices can be categorized according to proximity to land as either: shoreline, nearshore or offshore. The nearshore, defined here as approximately 25 m in depth and less than 2 km from land, is a relatively attractive option for wave energy conversion due to higher wave energy density, and lower environmental impact, compared to shore line systems, with shorter cabling distances relative to offshore installations. Waves in this region, herein represented by linear theory, are generally classified as intermediate depth water waves defined by $1/20 < h/L < 0.5$, where h is water depth and L is wavelength. In addition, the moderate water depth allows for designs that react the hydrodynamic body against the seafloor via a power take off (PTO) mechanism.

Previously investigated bottom-pivoted wave energy concepts include a deep water cylindrical point absorber (Salter, 1992) and a shallow water flap (Whittaker and Folley, 2005). This paper focuses on the case of a single bottom-pivoted circular cylinder that extends from near the seabed to the mean water level (MWL). As a buoyant axi-symmetric body that is restricted to oscillate in one mode of motion (i.e. pitch), the cylinder will act as a point absorber under a limited set of linear conditions. In the context of surface gravity waves, a point absorber is defined as a device that can absorb energy from a width greater than its physical dimension. This effect was reported independently by Falnes and Budal (1978) and Evans (1976), with the maximum capture width for a pitching body being defined as $C_w = L/\pi$. The physical interpretation of this effect is the creation of a dipole-like radiating wave with phase such that the interference between the radiated wave and incident wave field is destructive (Falnes, 2002).

It has been suggested that a good wave maker is also a good wave absorber. The wave-making component represents the power radiated away from the body undergoing motion. Cylindrical wave makers have been studied

*Corresponding author. Fax: +61 2 9351 2136.
E-mail address: a.caska@civil.usyd.edu.au (A.J. Caska).

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theoretically and experimentally by Dean and Dalrymple (1972) and Hudspeth (2006), who define the wave maker using size relationships, a/h and h/L, where a is the cylinder radius. It was found that the cylinder can be an effective wave maker for large sizes, $a/h \approx 0.5$, but requires large motions as the cylinder becomes small, say $a/h \approx 0.1$, with the situation being exacerbated as the water becomes shallower than $h/L < 1/25$ (Hudspeth, 2006).

At and near to resonance, the cylinder will oscillate approximately in phase with the fluid particle acceleration and thus the relative velocity (U_n) normal to the cylinder surface can become large, particularly near the tip of the cylinder. For an oscillating structure, the relative velocity Keulegan–Carpenter (KC) number, defined as $U_n T/D$ with wave period T and cylinder diameter D, may be used to specify the onset of viscous effects such as drag. For a circular cylinder, viscous effects become important as KC increases, in particular, as KC approaches 10. Thus, the analytical model described in this paper is considered valid only where $KC < 10$. This avoids excessive viscous effects that significantly modify force coefficients (such as that for added mass) derived from potential flow theory. These viscous effects act as a loss mechanism and significantly reduce the device performance if the oscillation amplitude becomes large. This occurs if the cylinder is a poor wave maker (small a/h) or if incident waves are in the shallow water regime ($h/L < 1/20$). In this paper we show that only cylinders (or similar structures) within specific a/h and h/L ranges exhibit the point-absorber effect.

Vertical cylinders pivoted at the sea floor have been studied previously by the offshore engineering community in relation to articulated tower platforms (e.g. Chakrabarti et al., 1983; Eatock Taylor et al., 1983; Ran and Kim, 1995). The aim of articulated tower structures is to minimize movement at the surface to provide a stable, safe platform for the respective use. Conversely, the aim of a wave energy device is to induce large motions and thus the natural frequency is deliberately made close to that of the wave environment.

In this paper, vertical bottom mounted cylinders are considered over the range $a = 2.5$–10 m. For the wave conditions considered, this range of cylinder sizes is approximately within the inertia regime, extending from the edge of the Morison regime for $a = 2.5$ m to where diffraction effects become important at approximately $a = 10$ m. Conceptually, this is simply a region where water particle excursion relative to body motion is small enough to avoid formation of an appreciable wake and the structure is not large enough to cause significant diffraction effects.

As described in Section 4, matched PTO damping ensures that the pitch amplitude of the resulting motion remained relatively small allowing the application of existing linear methods, such as those used by Venkataramana and Yoshihara (1989), Rahman and Bhatta (1993) and Chakrabarti (1987), to model the frequency dependent added mass and radiation damping. It must be acknowledged that these methods can only be considered valid if pitch angle, defined as the deviation from vertical, is less than approximately 10° as linear methods, in particular the quantification of radiation and diffraction effects, are based on small perturbations around the vertical position. Also, only inline forces and motions were considered, while transverse vortex induced forces were neglected.

The present paper investigates a damped vertical bottom-pivoted cylinder as a wave energy absorbing device and we provide an analysis of the motion response and corresponding power conversion capability of such a device. Although a single circular cylinder with constant radius may not be the most practical means for wave energy conversion (as incident energy is generally concentrated towards the sea surface), the purpose of this paper is to explore the basic mechanics of the concept using a simple model based on established and validated methods. From the outcome of the study, extensions can be made to include larger motions, various geometrical configurations and advanced device control strategies.

The next section describes the device equation of motion, Section 3 presents power and damping conditions, Section 4 explores device response and associated hydrodynamics through a parametric study, and section 5 presents conclusions of the study.

2. Equation of motion

As shown in Fig. 1, the idealized geometry under consideration involves a wave energy absorbing device consisting of a vertical buoyant cylinder of radius a, hinged on a single horizontal axis near the seafloor and restricted to motions parallel to the direction of wave propagation. The equation of motion for this device was derived from the relative velocity formulation of the Morison equation and rigid body dynamics (as structural effects are assumed insignificant). Assuming that the excitation

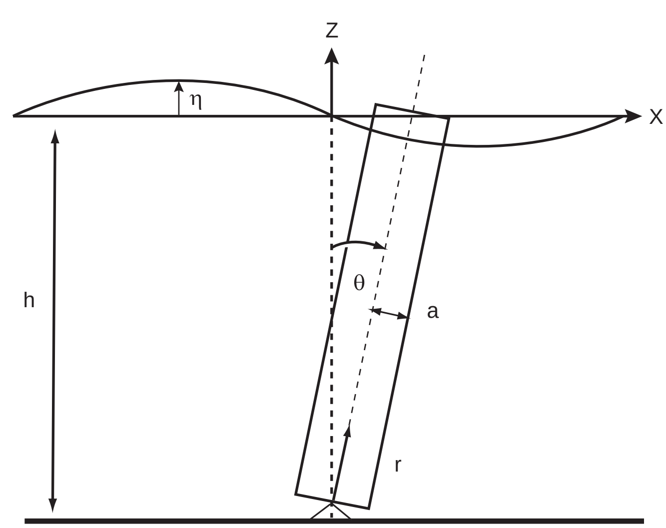

Fig. 1. Definition sketch.