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Assessing the size of a twin-cylinder wave energy converter designed for real sea-states

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ABSTRACT

We discuss the hydrodynamics of a wave energy converter consisting of two vertically floating, coaxial cylinders connected by dampers and allowed to heave, surge and pitch. This design, viable in deep water and able to extract energy independent of the incident wave direction, is examined for monochromatic waves as well as broad-banded seas described by a Pierson Moskowitz spectrum. Several possible device sizes are considered, and their performance is investigated for a design spectrum, as well as for more severe sea states, with a view towards survivability of the converters. In terms of device motions and captured power, a quantitative assessment of converter design as it relates to survival and operation is provided. Most results are given in dimensionless form to allow for a wide range of applications.

1. Introduction

The intention of this study is two-fold, providing on one hand a comprehensive account of the hydrodynamics of a system of two coaxial, vertically–floating cylinders envisioned as a model for a wave energy converter (WEC), and subsequently assessing the size and survivability of this system for various sea–states. The optimal size of a floating–body WEC will depend significantly on the length of the waves typically encountered. This dependence highlights a major difficulty of floating-body WEC design: the WEC must be small enough to undergo significant motions, and so generate power, and yet large enough to be robust and survive the challenges of the marine environment.

The system proposed here to model a WEC relies on the relative motion of two bodies, rather than on the motion of a body relative to a fixed frame (which may be either the sea bed or a bottom fixed structure), and is termed a *wave-activated body* or *self-reacting device.* Such devices may be installed in deep water, where the large distance between the sea-bed and the surface would otherwise be prohibitive. The mooring system for such devices has the sole role of counteracting drift and current forces, allowing the weight of moorings and anchors to be relatively small (see (Cerveira et al., 2013) and references therein).

Due to their ubiquity in ocean engineering, a rich literature exists on the interaction of water waves and cylindrical bodies. The radiation problem in heave only was addressed by Ursell (1949), and the scattering problem by Dean and Ursell (1959). Miles and Gilbert (1968) later employed a variational approximation to provide the far field potential for scattering by a circular dock, along with the lateral forces on the dock. However, their results were subsequently found to contain several inaccuracies, in particular in their calculations of the radiation forces. This prompted Garrett (1971) to take up the problem afresh, and establish the scattering forces for a circular dock. Subsequently, Black et al. (1971) revisited the application of variational methods to the radiation and scattering problem by several cylindrical geometries, employing Haskind's theorem to give the wave forces. This latter, variational approach did not yield the added mass and damping coefficients. Hence, some years later Yeung (1981) studied the radiation problem of a vertical cylinder floating on the water surface and undergoing the combined motions of heave, surge and pitch, and obtained these hydrodynamic coefficients. More recently, Bhatta (2007) also gave the added mass and damping coefficient of a vertical cylinder undergoing heave motion, in terms of the two dimensionless ratios characterizing the problem (depth to radius and draft to radius). While prior work had focused on the finite depth case, recently Finnegan et al. (2013) treated by means of an analytical approximation due to Leppington the forces on a truncated vertical cylinder in water of infinite depth.

In the context of wave energy, the consideration of floating cylinders as models of WECs goes back at least to Berggren and Johansson (1992), who approximated a device described by Hagerman by two floating,

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axisymmetric cylinders oscillating in heave, albeit without any considerations of captured power. More recently, Garnaud and Mei (2010) revisited the single buoy with the intention of studying it in densely packed arrays, giving the captured power for buoys hanging from a large frame. Such a floating, single-cylinder absorber was also employed by Child and Venugopal (2010) in their discussion of optimization of WEC arrays, by Borgarino et al. (2012) as a generic model to investigate wave interaction effects, and many others. Similarly, Teillant et al. (2012) employ an axisymmetric, heaving two-body device for their study of WEC economics, without detailed hydrodynamic considerations. A slightly different fixed–reference WEC was considered by Engström et al. (2009), who added a sphere under the floating cylinder. This two-body configuration of floating cylinder and submerged sphere was then assumed connected to the sea bed by a generator, and its performance analyzed. Zheng et al. (2005), in a generalization of Berggren & Johansson to three modes of motion, considered the hydrodynamics of two unconnected, coaxial floating cylinders, again without considering power capture. The power capture for a self-reacting device consisting of two vertical cylinders moving in heave was recently obtained for attacking monochromatic incident waves by Wu et al. (2014), albeit with a rather terse discussion of their results. Such self-reacting twin cylinder WEC models have the advantage of being feasible in deep water, where reaction against the fixed sea-bed is impractical, while nevertheless allowing for a closed form solution of the linear wave-structure interaction problem, albeit in series form. The submerged lower body can be demonstrated to present a very stable reference to react against, with the performance of such a two-body WEC matching that of a single bottom-referenced cylinder.

The present work combines features of several previous studies, and considers the novel case of two floating cylinders, each allowed to move in all three modes of motion available to an axisymmetric body, connected by an idealized power take–off (PTO) represented by a linear damper of constant characteristics.[3] Subsequent to a detailed description of the wave–structure interaction problem, based on eigenfunction expansion techniques, two main parameters characterizing the device size and damping coefficient are examined. The performance of WECs of different sizes, in terms of explicit values for the motions and captured power, is then given from solutions of the governing equations for various incident waves.

We undertake our parametric study with an eye towards applications, and thus also consider irregular waves in the form of a Pierson-Moskowitz (PM) spectrum (see e.g. recent work on optimizing a floating box-barge under irregular waves by Bódai and Srinil (2015)). While scatter diagrams may be available for some sites where an assessment of the wave resource has been carried out, where this is not the case estimates based on wind speed will need to be made. To this end, we present our data nondimensionalized on the basis of wind speed, which uniquely determines the PM spectrum. Values of significant wave height and peak period may be readily derived therefrom, and the data recast in these terms if desired.

When an incident spectrum is considered, it is no longer possible to assign a simple value to the displacement in heave, surge, and pitch of a floating body. To remedy this, the notion of *significant displacement*, derived from the spectral description of the sea surface, is introduced to give some quantitative information about the three motions of the device. This also allows for a measure of survivability for various WEC sizes and sea-states, by examining under which conditions the device displacements grow large in a statistical sense. An illustrative grading system is devised to categorize the various performance metrics of the self-reacting WECs.

The paper is organized as follows: in Section 2 we present the physical set-up of the problem. This consists in presenting the twin cylinder WEC and characterizing its geometry, and subsequently presenting the PM spectra for design and survivability considerations. In Section 3 we present, very briefly, the basic mathematical formulation of the governing equations and sketch the solution procedure. Subsequently, we employ the hydrodynamic coefficients and forces found from solving the equations of Section 3 to characterizing WEC design under monochromatic waves in Section 4, and under irregular waves given by a Pierson-Moskowitz spectrum in Section 5. A discussion of these results with a view to applications is given in Section 6, which is subdivided into discussions of power capture, survivability, and a brief synthesis of the preceding sections. Finally, Section 7 presents some concluding remarks and perspectives.

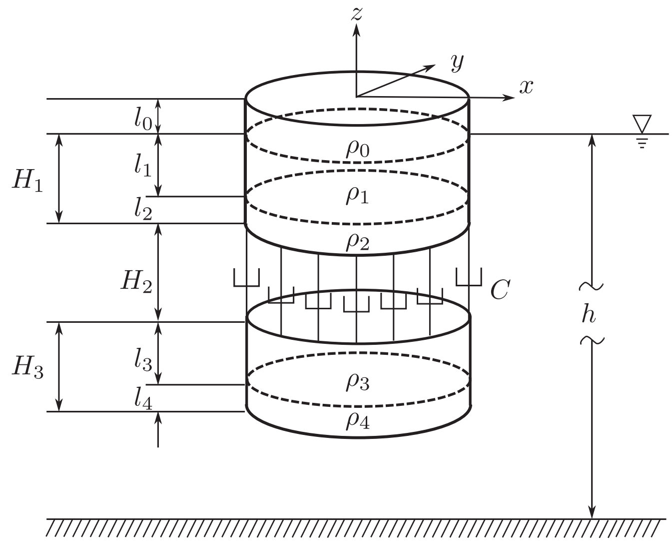

Fig. 1. Schematic depiction of the WEC geometry.

2. Physical preliminaries

2.1. Geometry

The geometry and basic parameters of the twin-cylinder WEC are depicted in Fig. 1. The *Oxy* plane is the still water surface and the *z*-axis points upwards. (r, θ) are polar coordinates in the horizontal plane, such that $x = r\cos\theta$ and $y = r\sin\theta$. The upper cylinder floats on the water surface with a draft H_1. To provide for flotational stability, it is important to note that the mass of this cylinder is not uniformly distributed, but is divided into three parts: a freeboard, i.e. the extension of the cylinder above the wave run-up with height l_0 and density ρ_0, as well as submerged sections with heights l_1 and l_2 and densities ρ_1 and ρ_2, respectively. The lower cylinder is entirely submerged with a height H_3, and assumed to be divided into two parts with densities ρ_3 and ρ_4 and lengths l_3 and l_4, respectively. The distance between the two cylinders in equilibrium is H_2. Both of them have the same radius R, and the water depth h is taken to be very large compared to the attacking wave length, with the intention of approximating deep-water conditions.

As shown in Fig. 1, the two cylinders are connected by a continuously distributed dashpot, which connects the upper edge of the lower cylinder with the lower edge of the upper cylinder at $r = R$. The integrated dashpot coefficient is C, which results in a dashpot coefficient per length $\frac{C}{2\pi R}$. The dashpot is considered to represent a PTO, which generates energy from both the relative heave and pitch motion of the cylinders.[4]

[3] While studies on PTO control show a promising potential for enhancing performance, particularly for devices with a narrow-banded natural response, practical and robust applications must still be developed (see Hong et al. (2014)).

[4] Although the surge motion itself is of first order, the take-off due to sway is a second order quantity, and thus negligible in comparison with the take-off in heave or pitch modes, which are first order.