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A submerged cylinder wave energy converter with internal sloshing power take off

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ABSTRACT

This paper describes the operation of a new design of wave energy converter. The design consists of a buoyant tethered submerged circular cylinder which is allowed to pitch freely about an axis below its centre. Within the body of the cylinder a fluid half fills an annular tank whose shaped inner walls allow the fundamental sloshing mode of the fluid be to tuned to any period of interest. The pitching motion of the cylinder in waves induces a sloshing motion inside the annular tank which in turns drives an air turbine connecting air chambers above the two isolated internal free surfaces. The concept behind this design is to couple resonances of the pitching cylinder with natural sloshing resonances of the internal water tank and thus achieve a broadbanded power response over a wide range of physically-relevant wave periods. Mathematically, the problem introduces new techniques to solve the series of complex internal forced sloshing problems that arise and to efficiently determine key hydrodynamic coefficients needed for the calculation of the power from the device. The results show that practical configurations can be found in which the efficiency of a two-dimensional cylindrical device is close to its maximum theoretical limit over the target range of periods from 5 to 11 s.

1. Introduction

Converting the energy of ocean waves into a useable form remains a formidable challenge. This is despite several decades of research and development into different design concepts during which many designs of wave energy converter have been deployed and tested at full-scale. To date there is no clear convergence towards a single design philosophy. Indeed, many of the generic concepts developed during the early years of wave energy research in the 1970s and early 1980s continue to be reinvented in one form or another.

A successful wave energy converter (WEC) has to be able to address and balance many and varied challenges. Practically, the WEC must be robust enough to survive the harsh marine environment and it must be easy to install and maintain. But the WEC must also be economically viable and fundamentally this requires it to be an efficient converter of wave energy. Balancing these two demands is crucial since no current design is able to boast that it can do both independently better than any other design. Thus, at one end of the scale, theoretical WEC concepts developed to maximise energy capture such as the Salter Duck [1] or the Bristol Cylinder (e.g. [2]), have been mainly overlooked because of complex engineering design difficulties. In contrast, many simpler devices have been developed which have low capacity for energy conversion and are thus economically flawed. The Pelamis and Oyster WECs are promising recent examples whose design philosophies set out to balance these two demands — see, for example, [3] and [4]. Even so, they have encountered many difficulties which are yet to be fully overcome.

Recently Crowley et al. [5] described a new theoretical concept for a wave energy converter. Although it is based on theoretical ideas of multiple and coupled resonances, previously advocated in Evans and Porter [6], the design also tried to address some of the main practical challenges facing WECs. In particular, the device, being comprised of a cylinder submerged beneath the waves, is protected from the most severe wave forces on the surface of the ocean. In addition, the cylinder's mooring acts as a passive component in the conversion of wave energy — developing a frame of reference against which to take-off power is a key challenge in a converter design. Finally, the confinement of the power take-off mechanism, consisting of a mechanical system of large heavy pendulums connected to dampers, within the body of the cylinder has some desirable practical advantages in terms of maintenance and survivability. Designs based on a similar concept

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include SEAREV — see [7]. In constraining the cylinder to move in a predominantly surge motion with respect to incident waves, its two-dimensional theoretical maximum efficiency is limited to 50%; in contrast the Salter Duck or the Bristol Cylinder are theoretically capable of up to 100% maximum efficiency (see, for example, [8]). In spite of this theoretical compromise made in the design of the device described in [5], results have suggested that it is capable of operating close to its maximum efficiency over a broad range of (roughly 5–11 s) wave periods. Preliminary results for a three-dimensional finite-length cylinder device also suggest capture factors, based on model sea states, of close to one (implying that almost all of the wave energy incident on the length of the cylinder is absorbed). This is significantly higher than the capture factors of roughly 0.55 reported for the nearshore Oyster device and far in excess of the majority of most WECs which typically have a capture factor of below 0.3 — see [9].

One potential practical disadvantage of the proposed design of [5] is that the internal pendulums that form the components of the internal power-take system have to be very big. Thus, in this paper we have considered a different internal power take-off system based on the resonant sloshing motion of a large reservoir of fluid contained within the cylinder. The immediate advantage of this system is that the inertia-effect provided by the heavy pendulums is now replaced by water. Now the incident waves force the cylinder to pitch via its own mooring about an axis below its centre and this then drives the motion of the fluid contained within the internal tank. This has shaped inner walls and two isolated internal free surfaces designed so that the internal fluid is resonant at frequencies of interest. In turn, the sloshing motion of the fluid drives air through an electricity-producing Wells-type turbine connecting air chambers above each of the free surfaces. The idea behind the device described above is to couple natural resonances of the pitching cylinder in waves to internal sloshing resonances by selecting particular cylinder geometries, mooring systems and internal tank configurations. The generic idea of coupling wave induced oscillations of floating bodies with internal fluid motions is not new: see, for example, the desalination plant described in [10] and in other marine applications in [11].

Mathematically, the problem is considered using linearised wave theory and though most of the general wave power theory presented, in Sections 2 and 4, is applicable to devices working in both two-dimensions (practically realised by a cylinder spanning a narrow wave tank) and three-dimensions, results are only presented here for two-dimensional cylinders. The inclusion of an internal water tank increases the complexity of the system considered in [5] though it is shown in Section 4 that familiar-looking expressions (see, for example, [6]) for the wave power can be derived. More novel mathematical ideas are developed in Appendix B under Section 5 of the paper which concentrates on the method of solution for certain potentials relating to the forced motion of the internal wave tank which are defined earlier in Section 3. Here, a non-trivial internal tank shape acts as a mechanism for tuning the resonant sloshing frequency and the resulting boundary-value problems are treated analytically using a combination of mathematical techniques. First, the fluid domain is mapped conformally to a composite rectangular domain. Conformal mappings have seen considerable use in analysing sloshing problems in non-trivial domains; see, for example, [12]. The particular geometry chosen allows an eigenfunction expansion matching to be used to develop integral equations for unknown functions relating to the fluid velocity across a line segment in the fluid. This latter part of the solution method is reminiscent of [13] though the non-trivial mapping of the free surface condition here introduces additional mathematical complexity. It is shown in Appendix B how each of the hydrodynamic coefficients, representing forces, moments and fluxes, that are needed in the calculation of the power generated by the device are expressed in terms of fundamental properties related to the solution of the integral equations.

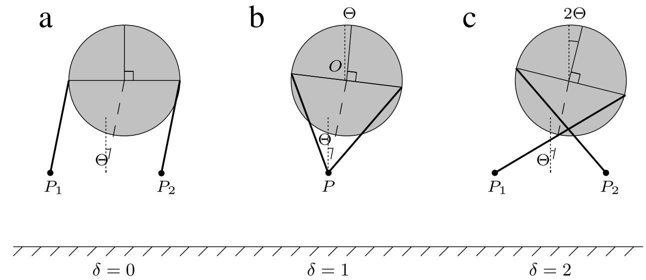

Fig. 1. Various mooring configurations applied to the submerged horizontal cylinder above the sea bed.

The main sets of results are shown in Section 6 where attention is focused on demonstrating the potential for this new sloshing-driven WEC design. In particular, with certain key parameters fixed and others determined by numerical optimisation methods similar to that described in [5] it is found that efficiencies close to maximum across a broad, roughly 5–11 s, range of frequencies are attainable.

2. Description of the device and its operation

In its most general form, the wave energy converter being considered here is a buoyant cylinder of constant cross section and finite length, which is held submerged below the surface of the fluid by a configuration of tensioned mooring lines which connect it to the sea bed. Fig. 1(b) illustrates a cross-section (internal details of the cylinder shown later) through a circular cylinder and the simplest mooring system to be adopted. Thus, the point P represents one of a number (two or more) pivots distributed along the length the cylinder which is assumed to be raised some distance above the bed but held fixed with respect to the bed, perhaps by a number of splayed cables. The tensioned lines which attach P to the cylinder allow the cylinder to pitch about P. Assuming small angles of pitch, $\Theta(t)$, the motion can be decomposed into coupled motions of surge and roll of the cylinder with respect to its local axis, O. Applying simple geometric arguments to Fig. 1(b) the roll angle is $\Theta(t)$ and the surge displacement is $L\Theta(t)$ where L is the vertical distance OP. The heave displacement is second-order in Θ and neglected.

In a second, more general, version of the mooring system examples of which are shown in Figs. 1(a), (c), the cylinder is again allowed to pitch via a pair of cables pivoted about two fixed points P_1 and P_2 held fixed at the same level above the sea bed. This system again induces a coupled surge/roll motion of the cylinder about its local axis, O, and, whilst the surge displacement remains $L\Theta(t)$ (where L is now the vertical distance from the midpoint of P_1 and P_2 to O) the pitch-induced roll angle is $\delta\Theta(t)$ where δ is a parameter dictated by the mooring connections of the cables from P_1 and P_2 to the cylinder. If P_1 and P_2 coincide, we return to the first case illustrated in Fig. 1(b) so that $\delta = 1$. If P_1 and P_2 connect to points on the cylinder directly above P_2 and P_1 (respectively) so that the mooring lines cross each other half way between cylinder and mooring point, then $\delta = 2$, as in Fig. 1(c). If P_1 and P_2 connect to points on the cylinder directly above P_1 and P_2 (respectively) so that mooring lines are parallel then $\delta = 0$ and there is no pitch-induced roll of the cylinder as in Fig. 1(a).

Inside the cylinder, an inner cylindrical section of constant cross section runs along the length of the cylinder and water half fills the annular region between the outer and inner cylindrical sections — see Fig. 2(a). The operation of this part of the device has already been described in the Introduction. We note that, in practice, the cylinder would be divided along its length into sections and/or