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# The dynamics and power extraction of bottom-hinged plate wave energy converters in regular and irregular waves

R.P.F. Gomes [a,*], M.F.P. Lopes [b], J.C.C. Henriques [a], L.M.C. Gato [a], A.F.O. Falcão [a]

[a] LAETA, IDMEC, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[b] WavEC – Offshore Renewables, Rua Dom Jerónimo Osório 11, 1400-119 Lisboa, Portugal

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ABSTRACT

This paper presents a numerical study on the hydrodynamics of bottom-hinged plate wave energy converters in regular and irregular waves. A parametric analysis of the plate width and height was performed. Both fully submerged and surface-piercing plates were considered. Two distinct models were developed based on linear hydrodynamics. The first one, in the frequency domain, assumes linear forces. The second one, incorporates fluid viscous and other nonlinear effects. For efficient wave power extraction, fully-submerged plates require amplitudes of motion larger than the surface-piercing ones. Such amplitudes may be unrealistically large close to resonance conditions, which in practice can negatively affect the efficiency. The adjustment of the plate natural period through the modification of the system inertia was tested without any significant improvement in the hydrodynamic efficiency. Resonance design criteria, used in heaving point absorbers, seem to be less effective in this case due to the large viscosity-induced damping and constraints in the plate displacement amplitude. Results show that a hydrodynamic efficient plate should have a width-to-water-depth ratio between 2 and 5, presenting a capture width per unit plate width of approximately 0.8 for regular waves and 0.65 for irregular waves, considering the most usual wave periods.



## 1. Introduction

Bottom-hinged plates are a particular class of oscillating body wave energy converters (WECs). They are devices resembling plates that are pivoted to the rotation axis on the sea bottom with several possibilities for the plate width and height. The plate thickness is much smaller than the other dimensions, yet allowing the device to be naturally buoyant, i.e., to present a vertical position in the absence of waves. The devices can either be fully submerged or pierce the water free surface. They are deployed near shore with water depth ranging between 10 and 20 m. The most well-known devices of this type, due to their advanced stage of development, are the Oyster (Whittaker and Folley, 2012) and the WaveRoller (Lucas et al., 2012).

The surface-piercing Oyster is being developed by the company Aquamarine Power since the early 2000s, in close collaboration with Queen's University Belfast (see e.g. Whittaker et al., 2007; Whittaker and Folley, 2012). Two full-scale prototypes of the Oyster were installed in Summer of 2009 and 2011 at EMEC, Orkney, Scotland.

The Finnish company AW-Energy has been developing the fully-submerged WaveRoller technology since 2004. Since 2008, they have been testing models of the WaveRoller off the coast of Peniche, Portugal. In 2013, a prototype with three flaps, rated 100 kW each, was deployed and connected to the Portuguese national electrical grid.

Other devices based on a similar concept are also being studied. The bioWAVE and the EB Fround (DTI, 2005) are hinged devices more adequate for deeper waters. Although the axis of rotation is near the sea bottom, the flap shaped body, connected to the hinge by a stalk, is located close to the sea surface. The Swinging Mace (Salter, 1992) is another device that falls into the category of bottom-hinged device, but is shaped as an axisymmetric spar rather than a plate. The Langlee is a WEC adequate for deep water (offshore locations). It consists of several flaps hinged below the sea surface to a floating offshore structure. The main advantage of this concept is the easier replication and the wider available areas for deployment.

Considering the history of research and development of WECs, the interest in bottom-hinged plates is recent. This may be explained by the lower available energy level at shallow waters when compared with deep-water offshore locations. As the waves come closer to the shore, the water depth becomes smaller and a large amount of wave energy is dissipated through bottom friction and wave breaking. Whittaker and Folley (2012) have showed that,

* Corresponding author.
*E-mail address:* ruigomes@tecnico.ulisboa.pt (R.P.F. Gomes).

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in terms of energy extraction, this difference is not so substantial. Due to refraction on the sea bottom, the wave crests become nearly parallel to the bathymetric isolines, and therefore the near-shore wave climate presents a narrower directional spread. The dissipative wave breaking effect provides a limitation in the wave height of incoming waves, which can result in an increase in the device load factor. Taking into account these effects and comparing the exploitable wave energy at different locations, it was shown that a 10–20 m water depth location (near-shore) has only 10–20% less useful energy than a 50–100 m water depth location (offshore) (Folley and Whittaker, 2009; Folley et al., 2009).

The hydrodynamics of two-dimensional bottom-hinged plates have been studied analytically by several authors using potential flow methods in a variety of theoretical cases. Evans (1970) studied the wave diffraction by a submerged vertical plate with small oscillations, obtaining expressions for the forces and the waves scattered away from the plate. The radiation of the waves from a surface-piercing hinged plate is an extension of the widely studied case of a two-dimensional pivoted wavemaker radiating waves from one side of the plate (see e.g. Dean and Dalrymple, 1984; Falnes, 2002). Evans and Porter (1996) addressed the hydrodynamic characteristics of a fully-submerged pivoted pitching plate, obtaining a semi-analytical solution for the added inertia and radiation damping coefficients for different water-depth-to-plate-height ratios.

The case of the diffraction by three-dimensional surface-piercing plates has been addressed by several authors for the study of isolated breakwaters. An approximate solution has been derived for an isolated breakwater with negligible thickness (Penney and Price, 1952). The exact solution for the same problem can be found in Montefusco (1968) where computations of the wave elevation in the vicinity of the breakwater were presented for cases in which the incident wavelength is comparable to the breakwater width.

The group at Queen's University Belfast has documented several studies on seabed mounted wave energy devices (see e.g. Whittaker et al., 2007; Folley et al., 2007a, 2007b; Whittaker and Folley, 2012). These works, used in the development of the Oyster, highlighted the importance of having a surface-piercing device for the maximization of the hydrodynamic efficiency. Although being a device that responds to the horizontal water acceleration, and not a drag device, the importance of viscous effects is far from negligible. This device was designed not to have resonance characteristics over the working range of frequencies, avoiding large displacements and velocities, which would threaten the device integrity and would generate large vortex shedding at the edges.

Renzi and Dias (2012b) developed a mathematical model for the analysis of wave energy conversion from a surface-piercing hinged plate in a wave flume. Several flap widths were analyzed. The resonance of transverse sloshing modes results in an increase of the device efficiency. Using the same model, Renzi and Dias (2012a) analyzed the wave energy conversion from a periodic array of hinged plates. High array efficiency was again obtained by exploiting the resonance of the transverse modes. Renzi and Dias (2013) derived a mathematical model for the study of the hydrodynamics of the same device in the open ocean. Hydrodynamic radiation coefficients for three different plate widths, ranging between 12 and 26 m for 10.9 m water depth, were presented. A comparison between the behavior of the converter in the open ocean and in a channel was made.

Wave flume measurements of the energy extraction from a bottom-hinged plate, spanning all the channel width, were conducted at Instituto Superior Técnico, Lisbon, using an eddy current brake to simulate the power take-off (PTO) system (Lopes et al., 2009; Henriques et al., 2011). An experimental study on the enhancement of the hydrodynamic efficiency through the control of its inertia and hydrostatic restoring moment (centre of gravity) was performed by Lin et al. (2012), for a flap-type WEC with internal air/water chambers.

A bottom pivoted pitching cylinder for wave energy conversion was studied by Caska and Finnigan (2008). An empirically derived drag coefficient was included in the equation of motion to assess the losses from viscous effects, while using linear hydrodynamics. Laboratory experiments of the pitching vertical cylinder in a wave flume were carried out by Flocard and Finnigan (2010, 2012). Flocard and Finnigan (2012) focussed on the advantageous effect of the inertia adjustment on the hydrodynamic efficiency.

This paper presents a parametric analysis of the power extraction from bottom hinged plates, which can be fully-submerged or surface piercing. The device hydrodynamic model in the frequency domain is the object of Section 2. A parametric analysis of the linear hydrodynamic forces is shown in Section 3 for several plate heights and widths. Results of power extraction for several geometries and PTO conditions are presented in Section 4. A nonlinear model, which assumes viscous effects and end-stop forces, is described in Section 5, and numerical results are presented in Section 6 for regular and irregular waves. Section 7 presents a study on how the plate natural period can match the incident wave period, through adjustment of the system inertia, and its consequences in the power extraction efficiency, for regular and irregular waves. The conclusions are presented in Section 8.

## 2. Linear modeling

A bottom-hinged plate with width $W$, height $L$ and thickness $t_p$, hinged at the sea bottom with water depth $h$, is allowed to rotate about a horizontal axis perpendicular to the wave propagation direction, $y'$−axis. Fig. 1 represents the geometry and the Cartesian coordinate system which is adopted here. The body oscillates in a pitch degree of freedom, where the rotation is positive about the $y'$−axis as indicated. The variable $\theta$ represents the angular position of the plate, being zero when the plate is in the vertical position (perpendicular to the seabed).

A general equation of motion can be written to describe the interaction between the pitching body and the waves

$$I\ddot{\theta}(t) = m_e(t) + m_r(t) + m_h(t) + m_d(t) + m_m(t) + m_b(t). \quad (1)$$

Here, $I$ is the moment of inertia about the $y'$−axis, $\ddot{\theta}$ is the instantaneous plate angular acceleration, $t$ is the time, $m_e$ is the excitation moment caused by the incident wave action, $m_r$ is the radiation moment associated with the plate motions, $m_h$ is the

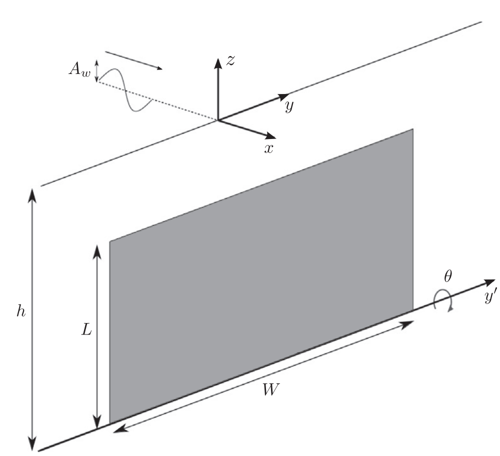


**Fig. 1.** Isometric representation of the bottom-hinged plate problem. The origin of the Cartesian coordinate system is placed at the free surface undisturbed position. Incoming waves, with amplitude $A_w$, propagate in the positive $x$-axis direction.