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Study and Modelling of Submerged Wave Energy Converter Plates

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ABSTRACT: The need for clean and renewable energy sources has contributed to give relevance to the study of sea wave energy nowadays. The present study is about the geometric optimization of an ocean Wave Energy Converter (WEC) into electrical energy that has as operational principal the Oscillating Water Column (OWC). A parametric study is conducted to find an expression for the shallow water wave-induced loads on the structure based on the structure geometry and wave characteristics. The analytical solution was also utilized to examine the effects of relative plate width on the transmitted and reflected waves. The effects of the angle of incidence were also briefly discussed.

KEYWORDS: Submerged Plate; Wave Energy Convector; Renewable Energy.

SYMBOLS

A	cross sectional area of the OWC, m^2	P_{flow}	water flow power (W)
a	model collector height, (m)	P_{wave}	wave power (W)
b	model collector width, (m)	T	wave time period (s)
C_g	Celerity ms^{-1}	m	mass of the analytical model(kg)
f	fraction volumetric	k	stiffness coefficient of the analytical model
g	acceleration due to gravity ms^{-2}	c	damping coefficient of the analytical model
h	height of opening area under plate (m)	u	velocity component in x direction, m/s
H_i	incoming wave height (m)	$w(v)$	velocity component in y direction, m/s
K	wave number, m^{-1}	λ	wave length (m)
L	plate length (m)	η	efficiency of plate wave energy converter (dimensionless)
H_s	significant wave height (m)		

I.INTRODUCTION

Currently, one of the greatest challenges is to supply the world energetic demand. In this context, there are several discussions about generation and consumption of electrical energy. An important characteristic of sea waves is their high energy density, which is the highest among renewable energy sources. In the last years, many wave energy converters (WECs) were proposed, first in the world of research, then in the commercial one. Different classifications of WECs exist, according to their installation depth (off-shore, near-shore, inshore), or to their orientation with respect to waves (attenuator, terminator, and point-absorber).The most common classification however is based on their working principle: overtopping devices (OTDs), wave activated bodies (WABs) and oscillating water columns (OWCs). [E.Angelelliand et al, 2010].In coastal regions the wave energy density decreases due its interaction with the seabed. The wave power is proportional to its squared amplitude and its period. Waves with high amplitude (around 2m) and with high periods (7 to10s) normally exceed 50kW per meter of wave front (Cruz e Sarmento, 2004).Another possible classification is associated with the principle adopted to transform the wave energy into electricity, existing three principal groups: Oscillating Water Column (OWC), Wave Activated Bodies (WAB) and Over topping Devices (OTD). Fu and Price [1987] studied vibration responses of cantilevered vertical and horizontal plates partially or totally immersed in fluid. They assumed that the plates vibrated in a semi infinite fluid medium. A finite element method and a

Singularity distribution panel approaches were used to analyse the dynamic responses of plates in air and also to determine the hydrodynamic coefficients for each element in contact with fluid. Haddara and Cao [1996] investigated dynamic responses of plates in air and submerged in fluid under various boundary conditions. They presented an approximate solution for the equation of motion for a plate coupled with fluid and provided an analytical added-mass factor depending on the height of the free surface and the depth of fluid under the plate. This classification does not end the possibility of other operating principle to be able for convert the ocean wave energy, being an example the submerged plate device (Carter, 2005). According to the last criterion the converters are classified as follows: oscillating water column, floating bodies, and over-topping (Cruz and sarmento, 2004). Nowadays none of the mentioned devices are in a leading position from the commercial point of view and the different wave energy conversion principles are expected to be used according to the characteristics of the location of the converter (Chozas and Soerensen, 2009). The submerged horizontal plate problem has not been studied for solitary waves; the transformation of a solitary wave over a submerged step has been examined quite extensively. Two phenomena have been of primary interest: the solitary wave fission and breaking process above a submerged step (e.g.,Losada et al . 1998 , Liu and Cheng 2001 , and Lara et al . 2011) , and the generation and evolution of vortices that from near the two edges of a step (e.g., Chang et al . 2001 , Lin et al . 2006 , and Wu et al . 2012) . In this paper we shall present and discuss the results from a theoretical and modelling study.

II. NUMERICAL MODEL AND SIMULATION CONDITIONS

A submerged horizontal plate positioned in a middle of a tank is the numerical domain used to the study cases, as shown schematically in Fig.1. The working principle of the submerged plate type converter, shown in Fig.1, consists in the transformation of the mechanical energy in the flow that occurs under a submerged horizontal plate into electrical energy through a wells type turbine due to the incidence of waves (Flavio Medeiros Seib et al, 2012). The Wells type turbine maintains the same direction of rotation regardless of the flow direction. In the submerged plate type converters, this characteristic is particular well-applied because the flow under the plate is changed in both positive and negative direction. This water flow is pulsating and can be used to drive water turbines that rotate in the same direction no matter what the direction of the water flow.

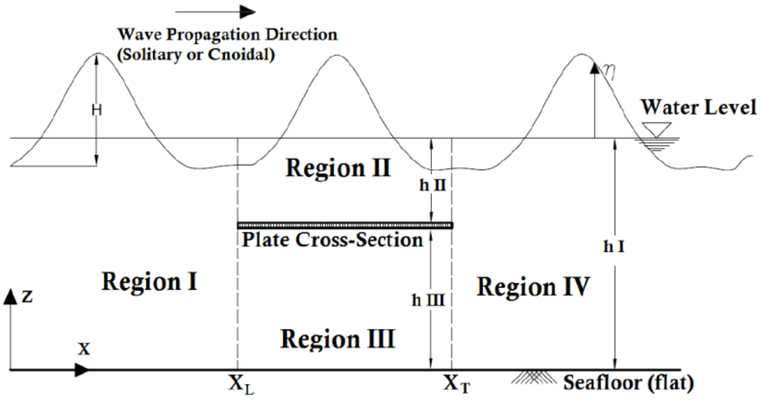

Fig 1: A sketch of nonlinear waves propagates over a submerged plate, showing the four regions referred to in the text.

The problem of nonlinear waves propagating over the submerged plate is studied by dividing the domain into four different regions, shown in Fig. 1. The solution for the entire domain, $-\infty < x < +\infty$, is obtained by finding the solutions for each region and matching them at the leading $(x = x_L)$ and trailing $(x = x_T)$ edges of the plate, where the regions meet, using the jump and matching conditions demanded by the theory and the physics of the problem(M.Hayatdavoodi and R.C. Ertekin 2012).

A) Incident impulse waves

The Incident impulse waves can be described in different ways as long as their Fourier transforms can be expressed in analytical forms. For instance, for Gaussian impulse wave of the shape

$$\eta_G(\xi,t) = He^{-[K(\xi-ct)]} \tag{1}$$

We find the wave spectrum to be

$$\zeta_G(\xi,t) = \frac{H\sqrt{\pi}}{Kc}e^{-\left(\frac{\omega}{2Kc}\right)^2}e^{-ik\xi} \tag{2}$$

Where, $= x\ cos\theta + y\ sin\theta$, H is the wave height, $c = \sqrt{gh}$ is the phase speed, and K is the arbitrary wave number of the impulse wave. Similarly, we can also find the analytical expression for the wave spectrum of an impulse wave in terms of $sech^2 -$ distribution, i.e.

$$\eta_{sec\,h}(\xi,t) = Hsech^2K(\xi - ct) \tag{3}$$

The corresponding wave spectrum can be written a

$$\zeta_{sec\,h}(\xi,t) = \frac{H\pi\omega}{K^2c^2}csch\frac{\omega}{2Kc}e^{-ik\xi} \tag{4}$$

In both formulae, (1) and (3), the wave height and wave number are independent of each other; the wave number can be specification arbitrarily.
For a special case where K, the effective wave number of the $sech^2 -$type impulse wave, is constrained by the wave height, H, and the water depth, h, in the following manner

$$K = \frac{1}{h}\sqrt{\frac{3H}{4h}} \quad and\ \ c = \sqrt{g(H+h)} \tag{5}$$

The impulse wave is a solitary wave. For a solitary wave the effective eave length and period can be defined as

$$\lambda = \frac{2\pi}{K} \quad and\ \ T = \frac{2\pi}{Kc} \tag{6}$$

The corresponding wave spectrum is also known (Miles 1976):

$$\zeta_{soli}(\xi,\omega) = A_{inc}(\omega)e^{-ik\xi} \quad ,with\ A_{inc}(\omega) = \frac{4\pi\omega\, h^3}{3c^2}csch\left[\left(\frac{h^3}{3H}\right)\left(\frac{\pi\omega}{c}\right)\right] \tag{7}$$

Clearly, in applying the linear solution to solitary wave, we must recognize its limitations. One obvious limitation is the need to use the linearized phase speed in $c = \sqrt{gh}$ (7) for solitary wave. Science true solitary wave are not solutions to the linear wave theory, we should be careful and refer to these impulse wave as "solution-like" impulse waves. As is the case with the use of all linear theory, we will show in the following discussions that the analytical solutions capture most of important physical feature and agree with experimental and numerical data reasonably well in the cases of small amplitude incident wave (Hong-Yueh Lo et al. 2013).

B) Boundary Conditions

As can be observed in Fig. 2, the wave maker is placed in the left side of the wave tank. For the regular wave generation it was employed the called Function Methodology (Gomes et al. 2009). This methodology consists of applying the horizontal (u) and vertical (w) components of wave velocity as boundary conditions (velocity inlet) of the computational model, by means and User Defined Function (UDF) in the FLUENT® software. These velocity components vary as functions of space and time and are based on the Linear Theory. So these wave velocity components are given by:

$$u = \frac{H}{2}gk\frac{\cosh(kz+kh)}{\omega\cosh(kh)}\cosh(kx-\omega t) + \frac{3}{4}\left(\frac{H}{2}\right)^2\omega k\frac{\cosh 2k(k+z)}{\omega\cosh(kh)}\cosh 2(kx-\omega t) \tag{8}$$

$$w = \frac{H}{2}gk\frac{\sinh(kz+kh)}{\omega\cosh(kh)}\sin(kx-\omega t) + \frac{3}{4}\left(\frac{H}{2}\right)^2\omega k\frac{\sinh 2k(k+z)}{\sinh^4(kh)}\sin 2(kx-\omega t) \tag{9}$$

where: H is the wave height (m); g is the gravitational acceleration (m/s^2); λ is the wave length (m); k is the wave number, given by $k = 2\pi/\lambda(m^{-1})$; h is the depth (m); T is the wave period (s); ω is the frequency, given by $\omega = 2\pi/T(rad/s)$; x is the stream wise coordinate (m); t is the time (s); and z is the normal coordinate (m).

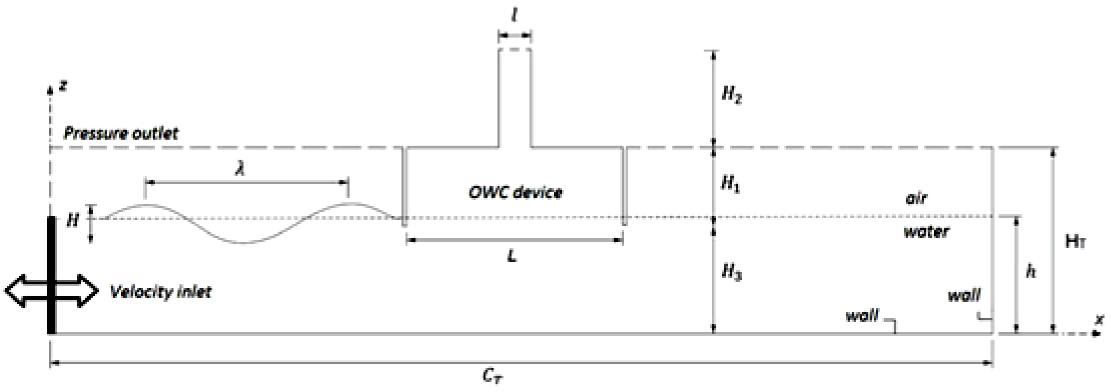

Fig 2: Schematic representation of the computational domain

Concerning the other boundary conditions, in the upper surfaces of wave tank and chimney and above the wave maker (dashed line in Fig. 2) it was considered the atmospheric pressure (pressure outlet). In the bottom and right side of computational domain a no slip and impermeability conditions (wall) were adopted.

C) Mathematical and Numerical Models

The Volume of Fluid (VOF) method is a multiphase numerical model that can be used to treat the interaction between water and air inside the wave tank. In this method, the free surface can be identified by the volume fraction (f) variable. In each mesh cell (volume), if *f = 1* the cell is full of water, when *f = 0* the cell contain only air and if *0 < f < 1* the cell has water and air simultaneously. Moreover, when the VOF method is used a single set of momentum and continuity equations is applied to all fluids, and the volume fraction of each fluid in every computational cell (control volume) is tracked throughout the domain by the addition of a transport equation for the volume fraction. Thus, the model is composed by the continuity, momentum and volume fraction equations, which are respectively given by (FLUENT, 2006; Gomes et al., 2009):

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho\vec{v}) = 0 \qquad (10)$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) = -\nabla \mathrm{p} + \nabla.(\bar{\bar{\tau}}) + \rho\vec{g} \qquad (11)$$

$$\frac{\partial(f)}{\partial t} + \nabla.(f\vec{v}) = 0 \qquad (12)$$

being: ρ the fluid density (kg/m^3), t the time (s), n r the flow velocity vector (m/s), p the static pressure (Pa), $\bar{\bar{\tau}}$ the stress tensor (Pa) and $\vec{g}$ the gravitational acceleration (m/s^2).

D) Efficiency of a Plate Wave Energy Converter

Efficiency of a plate wave energy converter can be calculated by the following equation [Graw, 1995]:

$$\eta = \frac{P_{flow}}{P_{wave}}$$

where P_{flow} and P_{wave} are power of water flow and wave power, respectively. P_{flow} and P_{wave} are given by the following equation:

$$P_{wave} = \frac{1}{16}\rho g H_i^2 \frac{\lambda}{T} b \left[1 + \frac{\frac{4\pi d}{\lambda}}{\sinh\left(\frac{4\pi d}{\lambda}\right)}\right] \tag{13}$$

$$P_{flow} = \frac{1}{2}\rho g h v_x^3 \tag{14}$$

where d is the water depth, λ the wave length, H_i the incoming wave height, ρ the water density $(1000 kg/m^3)$, g the gravitational acceleration $(9.81\ m/s^2)$,T the wave time period, b the width of opening area under plate, h the height of opening area under plate and v_x the axial water velocity.

III. RESULTS AND DISCUSSION

Hoebon [1986] proclaimed the effect of a pulsating water flow of the submerged plate, Graw [1993 a&b] proposed that this water flow can be used for energy production purposes and Klietsch [1993] has examined the efficiency of plate wave energy converter experimentally, with and without a wall under the horizontal plate. Two vertical walls of different heights were used in the middle of horizontal plate. In the experiments, the wave heights were $H_1 = 0.02\ cm$ and $H_2 = 0.03\ cm$ the heights of the walls were $h_1 = 0.1\ cm$ and $h_2 = 0.12\ cm$. The results of experiments are given in Fig.3.Opening ratio x in Fig. 3 means the ratio of the open section under the plate to total area under the plate. As shown in Fig. 3, axial water velocity under the plate is $1 - 6\ cm/s$ when λ/L is between 1 and 7. Graw [1993 a&b] has experimentally examined the efficiency of plate wave energy converter for different opening ratios. In Table 1, the axial water velocities are given as a function of opening ratio, wave period, wave length and wave height. In Fig. 4, the efficiencies of plate wave energy converter for different opening ratios vs. wave periods are given. As shown in Fig. 4, the efficiencies of plate wave energy converter are at most 3% and depend on wave period and opening ratio.

In this study, the efficiency of a plate wave energy converter is determined experimentally for eight conditions. These are as follows.

1. The plate only,
2. The plate and a triangular form below it; with five different heights,
3. The plate and a vertical wall below it; with two different heights.

The experiments were carried out for wave periods of *T = 1.16, 1.50, 1.87* and 2.05 s and wave heights of H = 2, 4, 6 and 8 – 10 cm, resulting in a total of 20 different wave properties and the conditions where the maximum efficiency is obtained are exposed [A. Ozdamar, 2007].

G .Orer, and A. Ozdmar in 2007, studies experimentally that were carried out in a wave channel located at the Hydraulics Lab of Ministry of communications, DLH, Ankara- Turkey. The wave channel is 40m long, 60 cm wide and 1 m high. The length of the plate *L = 1 m*, water depth the width of the plate *b = 60* cm and thickness of the plate *t = 2 cm* were help constant during the experiments in the wave channel. Each experiment set has a total number of 20 different wave properties composed of *T = 1.16, 1.50, 1.87* and 2.05s wave periods and *H = 2, 4, 6 – 8* and *10 cm* wave height values. The velocity of the water flow below the plate and the length of the wave generated are measured each time for eight conditions. The maximum velocity values are measured at the midpoint between rights under the plate and uppermost point of the form placed below the plate.

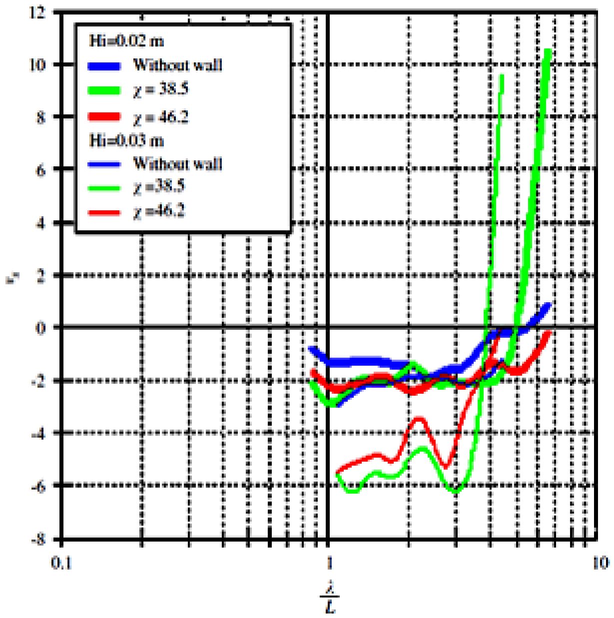

Fig. 3: Axial flow velocity (cm/s) under the plate vs. λ/L [Klietsch S. Labormessungen].

Wave period T (s)	Wave length λ (m)	Wave height *H* (m)	Opening ratio		
			12.5% Axial water velocities (m/s)	25%	100%
0.44	0.30	0.021	0.087	0.025	0.02
0.49	0.37	0.030	0.129	0.094	0.0375
0.55	0.46	0.038	0.1625	0.125	0.05
0.61	0.55	0.041	0.1625	0.125	0.05
0.73	0.73	0.036	0.11	0.11	0.038
0.77	0.79	0.032	0.10	0.10	0.0375
0.88	0.95	0.030	0.0625	0.08	0.025
1.10	0.95	0.030	0.0625	0.08	0.025
1.10	1.26	0.021	0.0625	0.0625	0.018
1.40	1.66	0.014	0	0	0
2.20	2.69	0.011	0	0	0

Table 1: Axial water velocities (m/s) as a function of opening ratio, wave period, wave length and wave height [Graw, 1995]

The length of the waves generated with *T = 1.16, 1.50, 1.87* and *2.05* s periods and *H = 2,4,6,8 and 10 cm* heights and the maximum flow velocity values opposite to the wave propagation direction were measured.

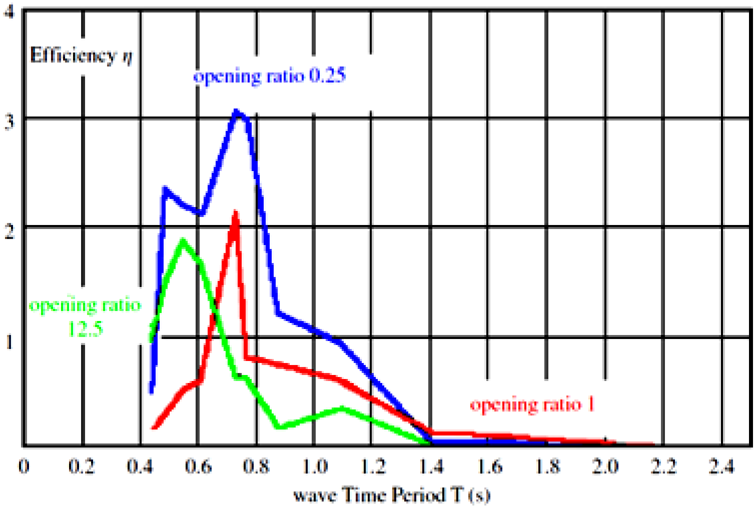

Fig. 4: The efficiencies of plate wave energy converter for different opening ratios vs. wave period [Graw, 1995].

Highest efficiency value, 60.47%, was obtained by locating a wall below the plate and setting the distance between the uppermost point of the wall and bottom of the plate to 12 cm, which is case C7.

For the conditions of small periods, efficiency value was small for all wave heights. The maximum value was recorded for *T = 1.87 s*. For the conditions of big periods, efficiency was small again .As a result, the best system efficiency is obtained at period *T =1.87*[Orer et al, 2007].

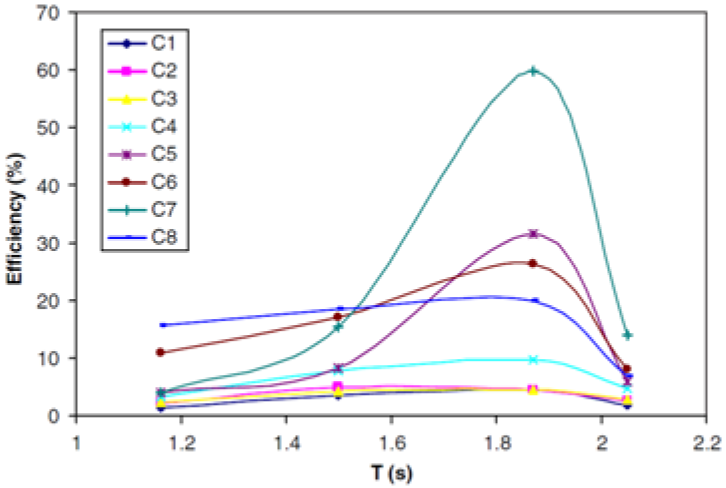

Fig.5: Variation of Efficiency vs. Wave Period for the investigated cases (*H=8cm*)

IV. CONCLUSION

The Wave Piston is able to convert wave energy into useful mechanical energy, which then, through further mechanical and electrical systems, can be converted into electricity. As an OWC, the Wave Piston has the advantage of a near shore location that in turns leads to:

−an easy access for operation and maintenance work;

−lower energy transmission costs;

and similarly has the disadvantage of the lower available wave power compared to the off-shore zone. Experiments provided useful indications for design optimisation. In fact the device efficiency increases significantly with increasing the height of the collectors. The plate wave energy converter efficiency which has been represented as 3% in the literature was found to be 60% from the experimental study. This enhancement is achieved by locating a structure below the plate. In addition, a wall structure gives better efficiency values than a triangular form structure. A future study regarding a farm of Wave Piston is suggested, because based on experiments with multi collectors, installations with multi-devices should not interfere one another and increase wave energy harvesting capacity.

These results are very promising because they provide a theoretical recommendation about the optimal geometry of an OWC-WEC device which allows the incident waves harnessing maximization. Moreover, in accordance with the Constructor formulation adopted, it is possible to relate the OWC-WEC dimensions with the incident wave's characteristics. So, if the wave climate is known it is possible to design the OWC-WEC for a specific region reaching its best performance.

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