Modeling of Wave Energy Absorption: a Case Study for a Fishing Pier in Brazil

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***Abstract*- The paper addresses the evaluation of wave energy absorption at a fishing pier in the town of Balneário Arroio do Silva, coastal south region of Brazil. This study considers the use of oscillating-water-column (OWC) converters composed by tubes tied to the pillars of the pier. In order to evaluate the wave energy extraction, the mathematical model of the OWC device for this specific application is obtained. First, wave equations and fluid mechanics theory are used to describe the physical behavior of the air inside the tube. Then the air flux is converted to mechanical torque using *Wells* turbine equations. The time-domain model is simulated using computational tools and taking into account the actual parameters and the specific wave regime at the fishing pier. The study shall support a future experimental implementation of OWC devices at the fishing pier. In addition, an energy efficiency analysis is developed, in order to reduce the consumption of electricity and energy waste at the fishing pier, and aiming at sustainability and rational use of the energy produced by the proposed OWC device.**

***Index Terms*-- Energy efficiency, fishing pier, modeling, Oscillating-water column device, wave energy.**

I. INTRODUCTION

The search for new devices which are able to produce energy using sustainable sources is a subject in growing discussion in the world because there is an appeal to decrease the emission of pollutants gases and to reduce the impacts to the environment. For these reasons, sustainable sources are used nowadays, such as: sun, wind, rivers and, in this special case, waves.

The wave energy can be considered a concentrated form of solar energy. This statement can be used because the waves are consequence of the wind action, which in turn is originated from the solar energy.

There are many papers and studies about how to extract the wave energy and how to turn it into electrical energy. Therefore, many technologies and devices have been developed in order to obtain the best form from the extraction of this energy [1]-[2]-[3]-[4]. The main devices studied in the world can be divided into: oscillating water column (OWC); oscillating bodies; and overtopping. Each one of them has benefits in specific situations.

OWC devices prototypes can be found in China (Guangdong province, 2001), Japan (in Sakata, 1990), India (Vizhinjam, 1990), Portugal (Pico Azores, 1999) and the UK (on the island of Islay, Scotland, 2000). The prototypes PowerBuoy (Spain, 2008), AWS (Portugal, 2004), CETO (Australia, 2011), Pelamis (Portugal, 2008), Oyster (Scotland, 2009), FO3 "Buldra" (Norway, 2004) and Wave Star (Denmark, 2009) are devices in operation which can be classified as oscillating body devices. The overtopping devices are the less used and some prototypes are found in operation, as Tapchan (Norway, 1985) and WaveDragon (Denmark, 2003).

Basically, the OWC consist of a tube in which the internal wave motion produces a displacement of air that causes a turbine attached to the top of the tube to rotate the shaft of an electric generator. *Wells* turbines are used, so that the turbine's direction of rotation is the same in upward and downward movement of the wave (Fig. 1).

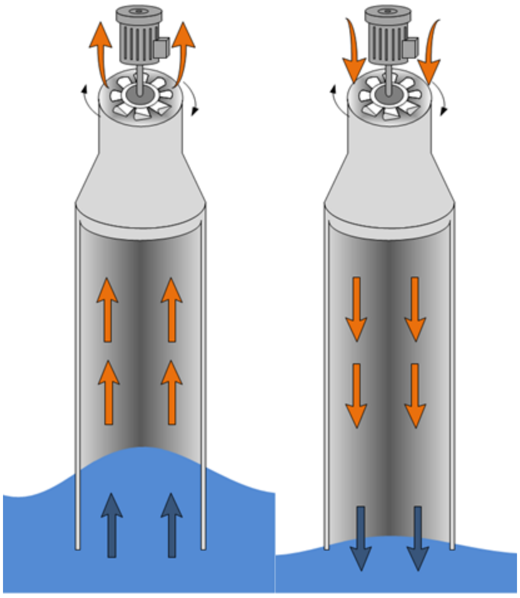

Fig. 1. OWC operating principle

In this paper, the chosen technology was the OWC, considering that the use of this technology allow us to tie the device to a fishing pier, using it as a support structure, as illustrated in Fig. 2. Hence, it would be possible to reduce installation and operation costs. This application represents a condition of operation that, to the best of authors' knowledge, has not been previously considered in studies about wave energy absorption.

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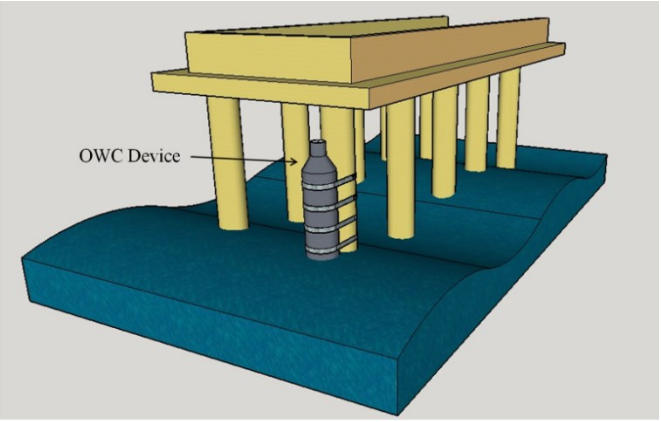

Fig. 2. OWC device tied in fishing pier.

One of the project's objectives is to estimate the power generated by the OWC device based on simulation results. These results would allow evaluating if the electricity transformed by the device is relevant to supply the energetic demand of the fishing pier. In addition, an energy efficiency analysis is developed, in order to reduce the consumption of electricity and energy waste at the fishing pier, and aiming at sustainability and rational use of the energy produced by the proposed OWC device.

II. DESCRIPTION

The fishing pier used for the proposed study is located in the city of Balneário Arroio do Silva, in Santa Catarina (SC), Brazil (28° 59' 3" South and 49° 24' 49" West). The fishing pier has about 450 m of length and is sustained by precast concrete pillars (Fig. 3).

Fig. 3. Fishing pier used as experimental base.

The OWC device considered in this project will have a cylinder form. With this format, it is expected to have an easier attachment, considering that the fishing pier pillars have the same geometry.

A previous analysis of energy consumption in the fishing pier was performed, with the installation of a power meter, local inspection and billing history. Fig. 4 shows the typical daily behaviour of energy demand. This figure points that the outdoor lighting system is the predominant electrical load in the pier. In the period between 20h00min and 6h00min the energy demand is around 2 kW.

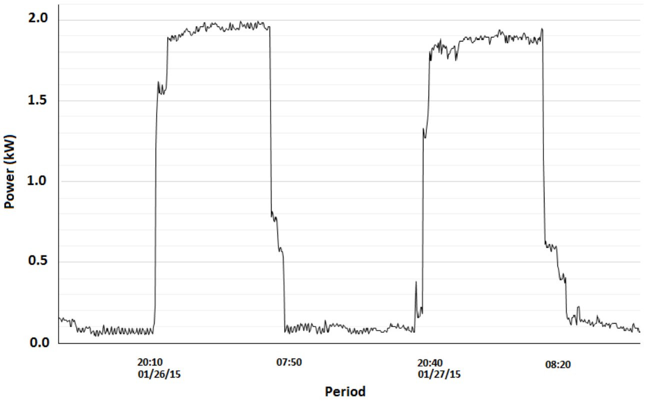

Fig. 4. Typical power demand of the fishing pier

III. MATHEMATICAL MODEL OF OWC

The mathematical modelling presented in this paper consists in determining the air velocity behaviour in section 3 of the tube (Fig. 5), based on the Fluid Mechanics theory. In this analysis it is intended to calculate the air velocity in section 3 based on the air velocity in section 1 passing by section 2, which is an intermediate section.

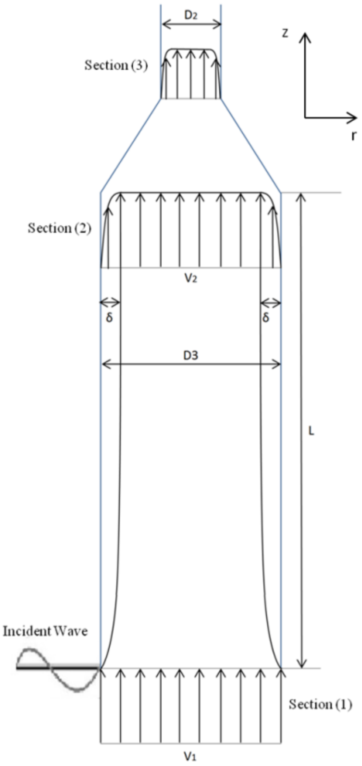

Fig. 5. The OWC device analyzed in the paper.

Ref. [5] and Ref. [6] show that the equation of the incident wave in the OWC device, in z direction, is defined by:

$$w = \frac{H}{2}\frac{gk}{\omega}\frac{\sinh(kz+\omega t)}{\cosh(kh)}\sin(kx - \omega t) + \frac{3}{16}\frac{H^2\omega k \sin 2k(k+z)}{\sinh^4(kh)}\sin 2(kx - \omega t) \quad (1)$$

where A is the wave amplitude, g is the gravity acceleration, k is the wave number which is given by $k = 2\pi/L$ with L being the wavelength, h is the depth, ω is the frequency which is given by $\omega = 2\pi/T$ with T being the wave period, x is the position, t is the time and z is the variation of the position between the free surface of the water and the seafloor.

The space variation of the z variable, described in (1), can be written as $z = \eta + h$, where:

$$\eta = A\cos(kx - \omega t) + \frac{A^2 k \cosh(kh)}{4\sinh^3(kh)}[2 + \cosh(2kh)]\cos 2(kx - \omega t) \quad (2)$$

It is assumed that the device is constructed with a tube of small thickness. Thus, it is possible to consider that the vibrations originated by impact of the incident waves do not interfere significantly in the problem. Therefore, the diffracted and reflected waves' parts can be disregarded. Based on this consideration, it is assumed that the wave behaviour inside the tube can be described by the equation of the wave outside the tube.

It was also considered, as in [7], that the surface of the water inside of the tube can be treated as a rigid piston with negligible mass. Therefore, it is disregarded the speed variation in the *r* direction. Hence, the velocity profile in section 1 of Fig. 5 can be determined by equation (1).

In order to obtain the velocity profile in section 2 of Fig. 5, it was first analyzed the flow type into the tube. This analysis was developed by calculating the number of Reynolds (3) as a function of the tube length, and then calculating the thickness of the boundary layer (4)

$$Re = UL/\upsilon \quad (3)$$

$$\delta/\mathrm{L} = 0{,}382/Re^{1/5} \quad (4)$$

$$\mathrm{u/U} = (y/\delta)^{1/7} \quad (5)$$

in which δ is the thickness of the boundary layer, L is the tube length, υ is the air viscosity, U is the average velocity of flow, y is the distance between the wall and the point analyzed, and u is the velocity of flow in y.

In addition, it was used the mass conservation law to obtain the velocity profile in section 3 of Fig. 5. This law states that every mass that goes through the section 2 should, mandatorily, goes through the section 3. In other words, this means that the velocity in section 3 can be obtained by the simple ratio between the cylinder radius before the bottleneck and the cylinder radius after the bottleneck.

The turbine model chosen for this analysis was the *Wells* turbine. This device has the feature of keeping the same direction of rotation in upward and downward movement of the air flow. Fig. 6 shows the forces and the velocities on the blades of this type of turbine. In [8] and [9] it is presented a theoretical analysis performed for five different aerofoils (NACA0012, NACA0015, NACA0018, NACA0020 and NACA002) and their influence in the torque and power generated in a *Wells* turbine and in a generator. The aerofoil model selected in this project was NACA0021, because it has better performance compared to the other ones, according to [8]-[10]-[11]. The turbine's parameters are shown in Table II. This turbine profile was also used in the project "Mighty Whale" organized by Japan Agency for Marine-Earth Science and Technology (JMSTEC) and also in the Azores Pico Plant, supported by Europe Union [12].

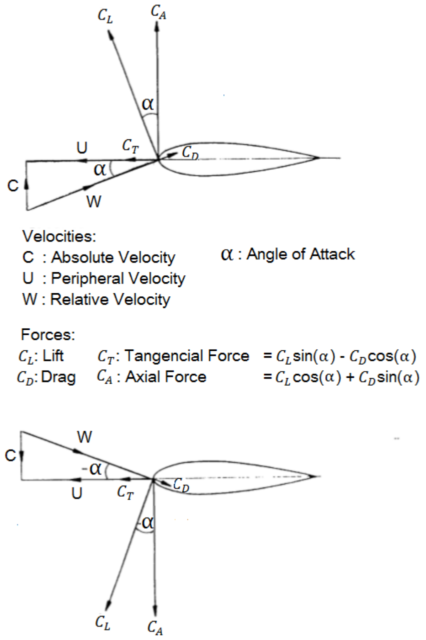

Fig. 6. Force and velocity diagram of *Wells* Turbine blades (Adapted from [13]).

The equation that defines the torque generated by *Wells* turbine can be written as:

$$T = (1/2)\rho W^2 Z b c R_t C_T \quad (6)$$

where ρ is the air density, W is the relative velocity of the flow, Z is the number of blades, b is the length of the blade, c is the length of the chord, R_t is the radius of the turbine, and C_T is the coefficient of tangential force, which is given by $C_T = C_L\sin(\alpha) - C_D\cos(\alpha)$, in which C_L is the lift coefficient, C_D is the drag coefficient, s is the solidity, and α is the angle of attack.

Ref. [8] employs the equation (7) to estimate the mechanics power generated by turbine according to its efficiency, in which A is the area swept by the blades, C is the absolute velocity of the flow, and n is the turbine efficiency. Based on the mechanic power generated by the turbine, and the generator efficiency, it is possible to estimate the electrical power generated by OWC device.

$$P = (1/2)n\rho A(C)^3 \quad (7)$$

IV. SIMULATION RESULTS

For simulation, it was used a set of wave data of Tramandaí coast [14], located approximately 130 km south from Barneário Arroio do Silva. The use of data from this region to estimate the Balneário Arroio do Silva's potential is justified due to the oceanographic characteristics of the coast. According to reference [15], the coastal segment between Cabo de Santa Marta (SC) and Chuí (RS), has the same characterization given by a straight coast line, associated to extensive and sandy coastal plains and low altitude. Besides, references [16], [17] and [18] show that the wave climate in this region is similar, dominated by the same atmospheric mesos and large scales systems. Based on this assumption, the values of period, height, and depth used in this paper can be found in [14], and the wave's length was obtained through the equations available in [19]. The obtained and calculated data are presented in Table I.

TABLE I
WAVE CHARACTERISTIC.

Characteristic	**Value**
Period (T)	7.4 s
Height (H)	1.2 m
Length (L)	75.7 m
Depth (h)	17.0 m

Applying equation (3) for the time varying velocities, it was noticed that the flow is turbulent and not fully developed in the most part of the time. The result is that the velocity variation occurs only at the region close of the tube's wall. Based on this fact, it was applied equation (5) to determine this velocity variation and also the average velocity of the tube in section 2.

The constructive data of the tube was determined based on the waves' characteristics and the constructive data of the pier. Thus, the values used were L=3 m, D_2 =0.5 m and D_3=1 m.

The obtained set of equations was simulated in the software MATLAB/Simulink, and the influence of tube's walls in the velocity can be seen in Fig. 7. Fig. 8 presents the difference between the velocity with and without wall influence.

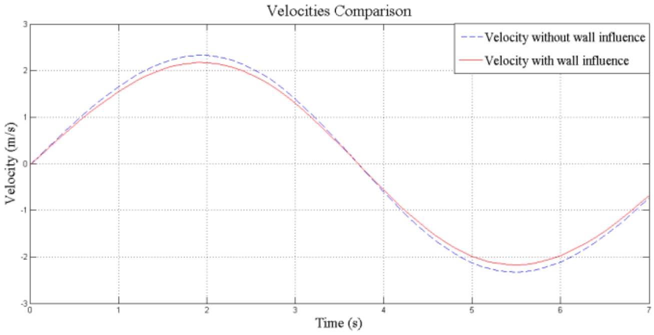

Fig. 7. Influence of tube's walls in the velocity.

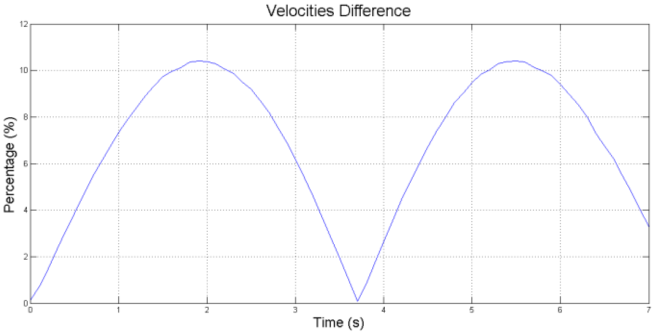

Fig. 8. Difference between the velocity with and without wall influence inside the tube.

The bottleneck in the end of the tube results in a velocity increase of about 300%. This increase happens because the ratio between D_3 and D_2 is equal to 0.7.

The constructive data of the *Wells* turbine used in simulation were the same used in [8], and can be seen in Table II. Fig. 9 presents the simulation results for the mechanical torque. The simulation data shows that the wall's influence causes a reduction of about 6.5% on average in the air velocity into the tube. When this comparison is performed in torque terms, it is possible to observe a reduction of about 12.7% on average, due to the quadratic dependence between torque and velocity.

The average value of the turbine's torque located in section 3 (Fig. 5) was the 0.6955 Nm, and the average value of the turbine's mechanical power was about 21W.

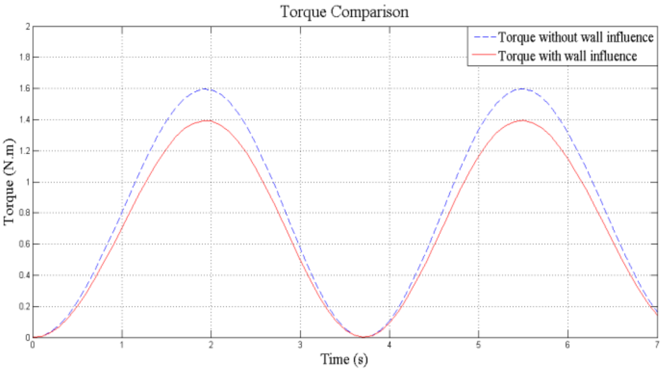

Fig. 9. Influence of tube's walls in the torque.

TABLE II
GEOMETRIC CONSTRAINTS AND THE PHYSICAL PROPERTIES OF THE AIRFOIL NACA0021

Group	Variables	Aerofoil NACA0021
Geometric Constraints	Number of blades - Z	5
	Solidity - s	0.4
	Ray of turbine - R_t (mm)	245
	Length of blade - b (mm)	73.5
	Chord - c (mm)	105
	Swept area - A (m²)	0.18857
Aerofoil Properties	Lift coefficient - C_L	1.20
	Drag coefficient - C_D	0.8859
	Angle of attack - $\propto$	15
	Coefficiente of tangencial force - C_T	0.22449
	Turbine efficiency - n	0.70995409

V. ENERGY EFFICIENCY OF THE PIER

In addition to the modelling of the power generation system it was also performed an energy efficiency study in the fishing pier, aiming to verify the possibility of reducing power consumption at the location. Thus, it is expected to size a generation system with a smaller rated power and that fully meets the local load.

As previously described, the outdoor lighting system comprises the predominant load of the pier, so that the efforts to improve the energy efficiency were focused in this system. The outdoor area of the pier was designed for a total of 52 points of light spread on the sides if the structure. Currently, low-efficiency lamps are used as incandescent and common fluorescent lamps. The data acquisition of the pier load curve was carried out during the summer period, when there is a greater presence if users. A power meter was installed to record the energy consumption at intervals of 10 min. The peak of the lighting system observed was about 1.8 kW.

As alternative for reducing the power consumption, it was proposed to replace the existing lamps by compact fluorescent lamps or LED lamps of 9 W, and to divide the lighting electric circuits in at least three lines so as to better branch the area of the pier.

With the replacement of the lamps, it is estimated that the lighting demand reaches approximately 0.7 kW peak. Thus, the generation system OWC could be sized to approximately 1.0 kW, with the possibility of connecting to conventional grid.

VI. CONCLUSIONS AND FUTURE WORKS

This paper presented a study about the wave energy absorption at a fishing pier in the town of Balneário Arroio do Silva, coastal south region of Brazil. For the modelling of the device it was analyzed the influence of the tube's wall in the velocity of the air's flow. Then it was estimated the torque and the power generated by OWC device.

An energy efficiency study was performed to stipulate the rated power of OWC System, which is intended to be in the range of 1 kW.

In future works it is intended to validate the results obtained with the modelling showed in this paper. It is also intended to study the geometric optimization of the OWC device analysed and the utilization of different generator's types, in order to achieve better efficiency. In addition, we seek to collect experimental wave data at the fishing pier to improve the modelling.

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