Fully Submerged Point Absorber in Santa Catarina, Brazil – A Feasibility Study

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FULLY SUBMERGED POINT ABSORBER IN SANTA CATARINA, BRAZIL - A FEASIBILITY STUDY

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Abstract. *The use of renewable energies is playing a major role to attend the rising energy demand and to reduce the environmental issues associated with the fossil fuels. In addition, renewable sources contribute to diversifying the energy mix, increasing the reliability of the system and promoting local potentials. In this regard, ocean wave energy remained insufficiently exploited in Brazil, and Santa Catarina has suitable wave resources for the installation of wave energy converters. Among the sites in Santa Catarina, Imbituba has shown a valid candidate for wave energy. The purpose of this work is to estimate the wave power available in Imbituba, Santa Catarina, and the performance of a fully submerged point absorber based on the CETO 5 technology in the site. The hydrodynamics are grounded on the linear wave theory, and the fully submerged point absorber dynamics are described using spectral domain model. The device optimal condition is evaluated using a parametric analysis to define the best-fixed magnitude of tether stiffness and PTO damping for Imbituba, which includes all sea states. The work concludes that Imbituba has shown a feasible site with a power per unit of horizontal area of 24.4 kW/m.*

Keywords: *Wave energy, Point Absorbers, Santa Catarina.*

Nomenclature list	m_{buoy} - Mass of the buoy
	P_{mean} - Mean power extracted
$A(\omega)$ - Hydrodynamic added mass	S_{Area} - Wetted area
$B(\omega)$ - Radiation damping	$S(\omega)$ - Power spectral density
B_{PTO} - PTO damping	T_p - Peak wave period
c - Wave velocity	V_{buoy} - Volume of the buoy
C_D - Drag coefficient	$\bar{W}$ - Mean wave power
c_g - Wave group velocity	
D_j - Quasi-linear coefficient	γ - Peak enhancement factor
F_{Drag} - Drag force	ζ_a - Wave amplitude
$F_{ext}(\omega)$ - Wave excitation force	ξ - Buoyant actuator displacement
g - Gravitational acceleration	ρ - Water density
H_s- Significant wave height	ω_n - Natural frequency
K_{tether} - Tether stiffness	ω_p - Peak wave frequency

1. INTRODUCTION

Brazil possesses the main electricity market in South America, wherein the current electrical system requires annually an addition of approximately 600 MW of capacity (Constestabile, Ferrante and Vicinanza, 2015). To supply this growing energy demand, governmental programs such as "*Programa de Incentivo às Fontes Alternativas de Energia Elétrica*" (PROINFA) and supports from the "*Banco Nacional de Desenvolvimento Econômico e Social* (BNDES)" (Brazil Portal, 2016) have encouraged the use of renewable sources of energy. The interest in renewable energies arisen due to the limitation of fossil fuels reserve and to overcome the environmental issues such as greenhouse gas emission, climate change, global warming, and pollution. Currently, several renewable sources such as wind, solar and hydropower have been used in the Brazilian energy matrix. The diversification of energy sources in the Brazilian energy matrix contributes to the development of regional and local potentials and the enhancement of the reliability in the energy supply. However, a primary resource of energy with a significant capacity to contribute to the energy grid remained unexploited, the ocean wave energy, wherein, the south coast of Brazil has favorable sites for wave energy installations.

The wave energy has an enormous market potential, which led to the development of Wave Energy Converters (WECs). Ocean waves accumulate energy by the contact to the wind blow over long distances, this ocean wave energy travels with a minimum loss of energy. As a result, waves have the highest power intensity compared to solar and wind sources of energy and can carry a substantial amount of power (Falnes, 2007). It is estimated that the world's wave energy potential is superior to 2 TW (Cruz, 2008). Moreover, waves have more regularity in the energy supply. According to Pelc and Fujita (2002), wave energy is available up to 90% of the time, compared to 20-30% for solar and wind energy. These benefits led to an interest in harvesting the wave energy. The idea of wave energy extraction exists for at least two centuries. Nevertheless, it mostly started after the oil crisis of the 1970s. Since then, several types of WECs have been created to extract the kinetic and potential energy from the waves. Currently, there are about one hundred projects in different stages of development (Falcão, 2010). However, just a limited quantity of models has reached feasibility, and even lower quantity has produced energy to the grid Karimirad (2014). Figure 1 illustrates several concepts of WECs. Among the WECs, Point Absorbers are one of the principal and earliest concepts in the wave energy industry (Karimirad, 2014). Point Absorbers are devices relatively small compared to the wavelength. There are different configurations of Point Absorbers, of which, the fully submerged can be a virtuous candidate for Santa Catarina.

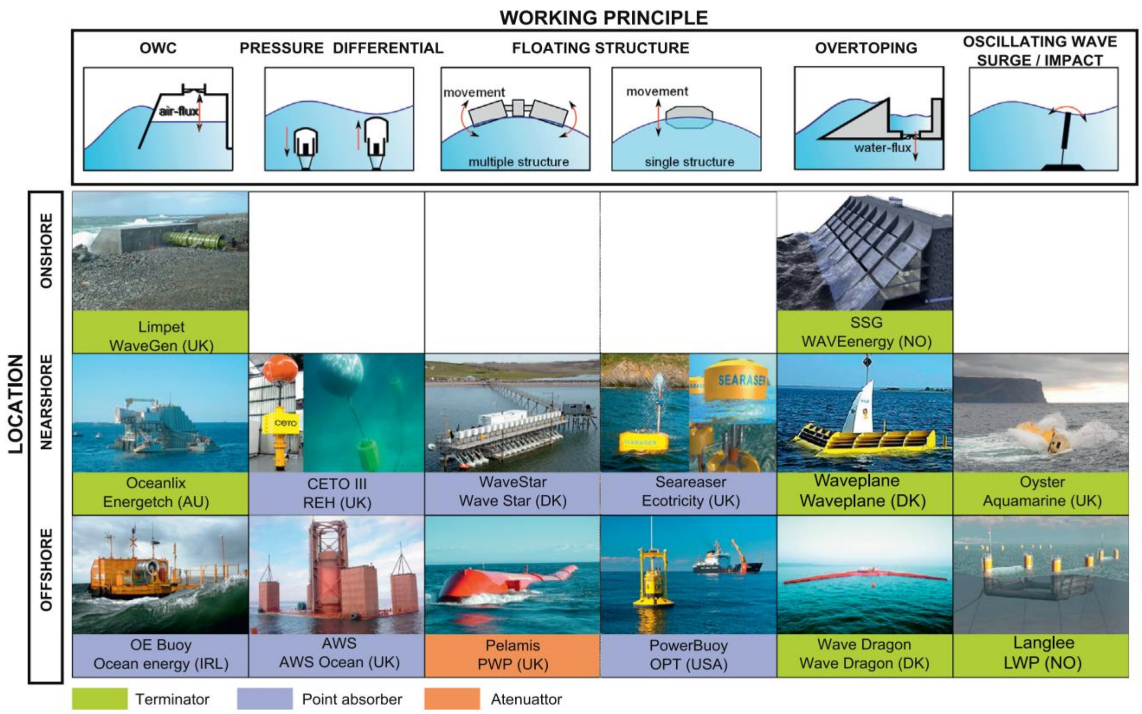


Figure 1. WEC classification (López et al., 2013).

Fully submerged Point Absorber is a type of Point Absorbers with additional benefits. Commonly, Point Absorbers are composed by a floating buoyant actuator that extracts energy mainly in heave motion. The buoy is attached via a pre-tensioned tether to the foundation at the seabed. The tether offers an additional stiffness to the floating structure. The system is usually set to operate in resonance condition with the incoming waves to enlarge the body motion. This body motion drives the power-take-off (PTO) mechanism that converts mechanical power into electric energy, and act as a damper in the wave energy device. An example of PTO mechanisms is a closed hydraulic system or an electric inductor.

Fully Submerged Point Absorber has a similar structure to the typical Point Absorbers, however, the buoy operates under the water and it is excited by dynamic pressure. This configuration presents technical benefits such as scalable to be effective in a particular wave climate, protected from storms and breaking waves which increases its survivability, and it can operate in an extensive range of conditions such as water depths, seabed conditions, and wave directions. Moreover, the device has a negligible visual impact and a minimal environmental impact on the marine life. The environmental and visual impact is an important aspect in Santa Catarina, due to the high concentrations of tourism activities and the vast marine fauna. An example of fully submerged point absorber is the CETO device which was implemented in Perth, Australia by the Carnegie Clean Energy Limited (see Fig. 2). Currently, the Carnegie Clean Energy Limited studies the implementation of CETO devices in Chile, South America.

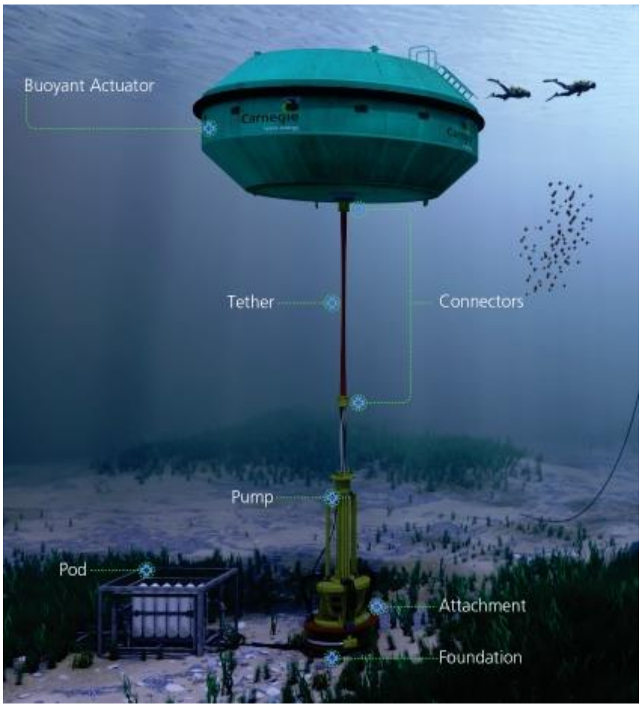


Figure 2. CETO 5 (adapted from Subsea world news, 2014).

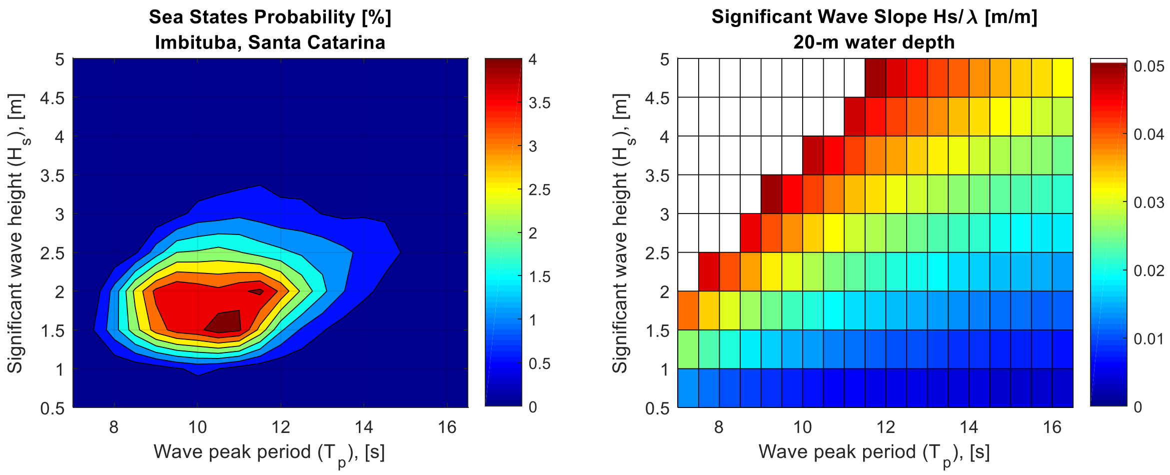
This work aims to investigate the power extracted by a fully submerged point absorber in Santa Catarina, Brazil. An initial procedure in ocean wave energy is the preliminary studies of the site location (Cruz, 2008). In this regard, this work initiates with the investigation of the site resources based on the recommendations in Constestabile, Ferrante and Vicinanza (2015). The authors state that Imbituba in Santa Catarina, Brazil is one of the most suitable regions to install WEC devices. An analysis of the wave power is investigated based on the linear wave theory for the proposed site. Posteriorly, the mathematical modeling of the proposed device is presented. The dynamics of the fully submerged point absorber is modeled in the spectral domain, which is an extension of the frequency domain model. This method is relatively new in the wave energy field and provides reliable estimations with a low computational effort. The device characteristics such as geometry, size, and operating conditions are based on the existing CETO technology given in the Babarit et al. (2012). Finally, the estimation of the mean energy delivered by a fully submerged point absorber is calculated based the sea states of Imbituba. This paper is based on the Silva (2017).

2. SITE

Santa Catarina possesses a great potential for wave energy, of which, Imbituba is one of the most suitable locations. Along the 7 km of extension of the Brazilian coast, the south region has a large wave potential with a low variability in the power distribution over the year. This potential has led an investigation of the wave energy extraction in states such as Santa Catarina and Rio Grande do Sul. In Constestabile, Ferrante and Vicinanza (2015), a study of several sites along the Santa Catarina coast was conducted to investigate the feasibility of WEC installations. In the article, a 20-m water depth was chosen as it reduces costs associated with installations, preserving nearly the same wave characteristics as deep water. The authors stated that Imbituba can be a worthy candidate for WEC installations based on technical and economic aspects. Firstly, the distance to the coastline and urban area is relatively small compared to other locations, which reduces the cost with undersea cables. Secondly, the reduced distance from the ports was also considered due to its importance during the installation and maintenance. Finally, the average power is superior in the south of Santa Catarina. Figure 3 shows the state of Santa Catarina, Brazil, where this study is based.

Figure 3. Santa Catarina, Brazil.

To determinate the amount of power, the site is monitored over a wide period to analyze the probability of occurrence of the various sea states (Cruz, 2008). Figure 4 (a) shows the sea state probability of occurrence in Imbituba based on the wave records from 2004 to 2014. Fundamentally, the wave energy in Imbituba occurs mainly at a Significant wave height (H_s) between 1.5 and 2 m, and Peak period (T_p) between 9 and 11.5 seconds. It's also advantageous to notice a poor occurrence of calm seas, approximately 4%. In addition, there are a few records of extreme storm conditions (Constestabile, Ferrante and Vicinanza, 2015). Therefore, during the operation, the energy is available consistently and without compromising the device survivability.



(a) sea state probability.

(b) significant wave slope.

Figure 4. Statistical data of the site.

Figure 4 (b) shows the significant wave slopes for values inferior to 5%, wherein the waves are considered stable and the linear wave theory is typically valid. Based on the linear wave theory, the hypothesis of linear superposition is valid, which in combination with Statistical aspects, the aleatory behavior of the ocean can be represented. The superposition of regular waves is characterized by a sea spectrum that uses a limited number of parameters via statistical aspects, in this case, significant wave height and wave peak period for each sea state. In this region of Brazil, the Sea spectrum (S_ς) is appropriately represented by the JONSWAP spectrum given as (Fujarra, 2009):

$$S_\varsigma(\omega)=\alpha^* H_s^2 \frac{\omega^{-5}}{\omega_p^{-4}} \exp\left\{-1.25\left(\frac{\omega}{\omega_p}\right)^{-4}\right\} \gamma^{\exp\left\{-\frac{(\omega-\omega_p)^2}{2\tau^2\omega_p^2}\right\}}, \quad (1)$$

where:

$\tau = \tau_a = 0.07$ for $\omega \leq \omega_p$; $\tau = \tau_b = 0.09;$ for $\omega > \omega_p$

$$\alpha^* = \frac{-0.0624}{0.23+0.0336\gamma-1.185(1.9+\gamma)^{-1}}$$

$\gamma = 3$

Based on the sea spectrum, the Mean wave power ($\overline{W}$) for the sea state is calculated via (Mørk et al., 2010):

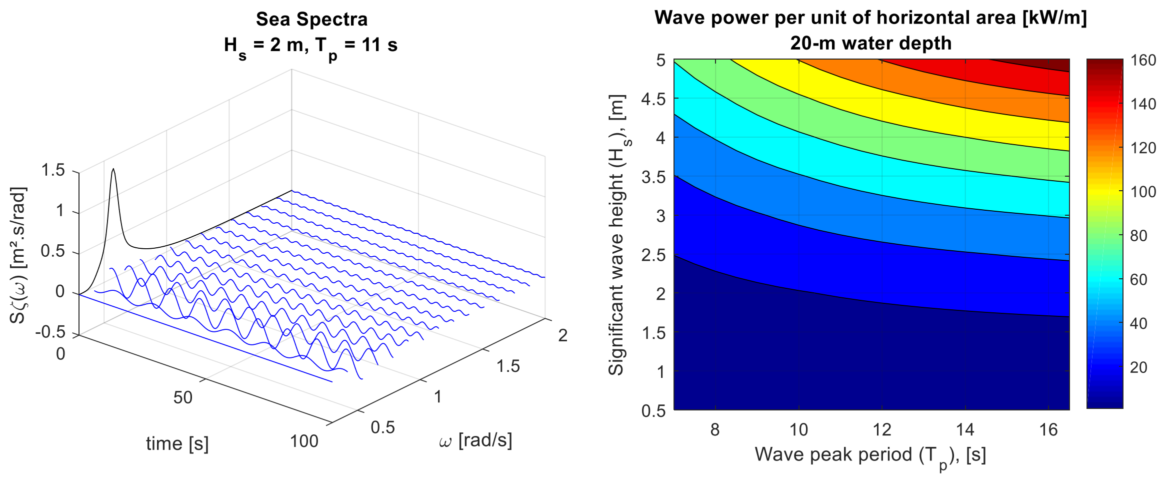
$$\overline{W} = p\,g \int_{-\infty}^{\infty} S_\varsigma(\omega)\, c_g(\omega)\, d\omega, \qquad (2)$$

where:

$$c_g = \frac{c}{2}\left(1 + \frac{2kh}{sinh(2kh)}\right)$$

$$c = \frac{\lambda}{T} = \frac{\omega}{k} = \sqrt{\frac{g}{k} tanh(kh)}$$

For each component of the spectrum, the wave group velocity c_g and wave velocity c are computed via dispersion equation that relates the cyclicity of time with the geometrical cyclicity of waves. This formulation allows to include the effects of the water depth in the wave power, which can be relevant for transitional and shallow waters. For all sea states, the respective sea spectrums and wave power are calculated. Figure 5 (a) shows a spectrum representation of a sea state, and Figure 5 (b) shows the wave power in each sea state for a 20-m water depth.



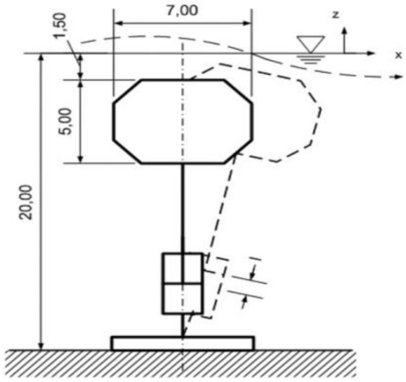
(a) Sea spectrum representation. (b) Wave power for a 20-m water depth.

Figure 5. Spectrum representation and wave power.

The average power of the site is calculated by the summation of the wave power in each sea state multiplied by its respective probability of occurrence. The results estimate an average power per unit of horizontal area in Imbituba equal to 24.4 kW/m. This average power magnitude is superior to 20 kW/m, which is generally accepted as a profitability limit for WECs (Multon, 2012).

3. FULLY SUBMERGED POINT ABSORBER

This work uses an existing technology to estimate the power extraction in Imbituba. The geometry, size, and operating conditions are based on the CETO, which are shown in Fig. 6. The CETO 5 was the first project to build a complete grid-connected system in the world, and as stated formerly, the device can be a valid candidate to be implemented in Santa Catarina, Brazil. However, the successfulness of the CETO 5 implementation depends on its capacity of power extraction in the proposed location. The power extraction depends on the tether stiffness and PTO damping. As both coefficients vary with the site characteristics, their magnitudes are not described in Fig. 6.



Property	Value	Unit
Diameter	7	m
Height	5	m
Displacement	148	m³
Mass of the buoy	35000	kg
Stroke length	6	m
PTO model	Linear spring-damper	
C_D	1	
S_{Area}	38	m²
Water density	1025	kg/m^3
Water depth	20	m

Figure 6. CETO 5 dimensions (extracted from Babarit et al., 2012).

During preliminary studies, a common approach for WEC devices is a simplified modeling focused in a single degree-of-freedom (Cruz, 2008). In the case of point absorbers, the devices are modeled in heave motion. Its dynamics can be represented by a mechanical oscillator composed of mass, damper, spring and an external force. The following section starts with the frequency domain model, which contributed to the initial development of WEC, and posteriorly, presents the spectrum domain model.

3.1 Frequency Domain

The mathematical modeling couples the hydrodynamics and vibrations theory. The hydrodynamics of the WEC are grounded on the hypotheses of the linear wave theory. The fluid-induced forces are considered in the diffraction regime, and it can be divided into three components: excitation, radiation, and buoyancy forces. The excitation force F_{ext} refers to the force caused by the waves considering a body fixed in its nominal position. It is composed by two contributions: incident and diffracted. The incident component is obtained integrating the pressured over the wetted surface of the body, and the diffracted, which is necessary to determinate the pressure field over the entire body. The excitation force magnitude depends on the wave amplitude ς_a, buoy geometry and position.

$$F_{wave}(\omega)=\varsigma_a(\omega)\, F_{ext}(\omega) \tag{3}$$

Radiation force represents the forces caused by the body due to its oscillatory motion in the absence of the incident wave field. As the body oscillates in the water, it moves the surrounding fluids that dissipate part of the energy. The radiation force is composed of two terms in the linear theory. On the right side of Eq. (4), the first term is in phase with the body acceleration, the hydrodynamic added mass $A(\omega)$, and the second with the velocity, the radiation damping $B(\omega)$.

$$F_R = -A(\omega)\ddot{\xi} - B(\omega)\dot{\xi} \tag{4}$$

The determination of the hydrodynamic coefficients analytically is restricted to simple geometries. As a result, a numerical method is usually applied. In this work, the hydrodynamics coefficients: added mass, radiation damping, and wave excitation force, are calculated using the commercial software AQWA based on the CETO 5, which is shown in Fig. 7.

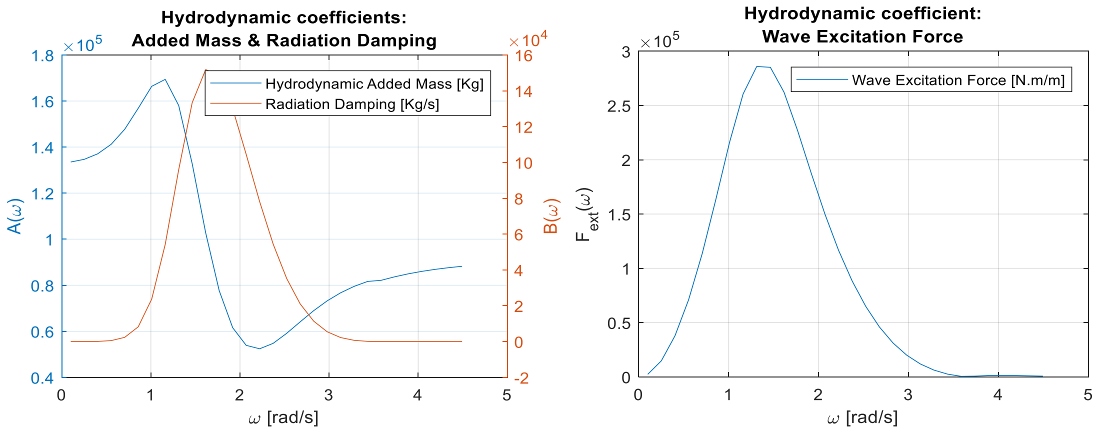


Figure 7. Hydrodynamic coefficients of the CETO 5.

The last fluid-induced force is the hydrostatic force, which is constant for fully submerged devices. This component influences the pre-tension force which acts on the tether and affects the dynamic motion in surge (pendulum mode). However, it does not affect the oscillatory motion in heave for an uncoupled analysis.

$$F_{pre\text{-}tension} = F_{buoyancy} - F_{weight} = g\left(V_{buoy}\,\rho - m_{buoy}\right) \tag{5}$$

Besides the hydrodynamics, there are external forces acting on the point absorber. Generally, two main forces are exerted on the buoyant actuator, from the tether and the power-take-off system. Their mathematical representation is decisive in the analysis of the body motion and power extraction. As a preliminary study, the mooring forces are usually represented as a linear spring model and the PTO force is approximated by a linear viscous damper model.

$$F_{attached} = -\,B_{PTO}\,\dot{\xi} - K_{tether}\,\xi \tag{6}$$

Based on the forces acting on the body, the Response Amplitude Operator (RAO), for the fully submerged point absorber in heave motion is given by:

$$\left|\frac{\xi}{\varsigma_a}(\omega)\right| = \frac{F_{ext}(\omega)}{\{K_{tether} - [m_{buoy} + A(\omega)]\,\omega^2\} + [\,B(\omega) + B_{PTO}]\,i\omega} \tag{7}$$

With the RAO and the wave spectrum, the response spectrum is obtained by:

$$S_{\xi}(\omega) = \left|\frac{\xi}{\varsigma_a}(\omega)\right|^2 S_{\varsigma}(\omega) \tag{8}$$

Figure 8 shows the sea state of H_s= 2 m and T_p = 11 s and the body response in heave for a CETO with K_{tether}= 77 kN/m and B_{PTO}= 110 kN.s/m.

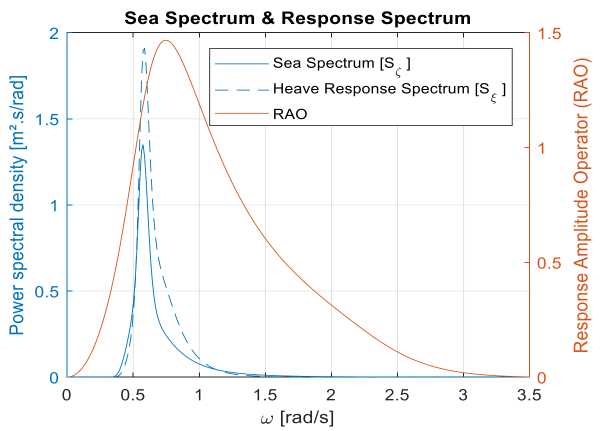


Figure 8. Sea Spectrum & Response Spectrum.

3.2 Spectral-domain

The frequency domain model has been extensively used in the modeling of Oil & Gas platforms and during the development of wave energy industry. However, a special treatment is necessary to describe the physics of WECs. As the WECs operates close to the resonance, the amplified motion leads to the non-linear hydrodynamic forces even in moderate sea states (Folley and Whittaker, 2010). In those circumstances, the spectral-domain is employed for an enhanced estimation of the WEC motion and power delivered. This method uses an iterative process to estimate the quasi-linear coefficients that can represent the viscous drag such as turbulent boundary layer and vortices. The Morison's equation models the drag force as a quadratic damping given by (Journée and Massie, 2001):

$$F_{Drag} = C_{quadratic}\;\dot{\xi}\,|\dot{\xi}|, \qquad C_{quadratic} = \frac{1}{2} C_D\,\rho\,S_{Area}\,, \tag{9}$$

where, F_{Drag} represents the drag force, C_D is the drag coefficient, S_{Area} is the projected area, ρ is the specific weight of the fluid, and $\dot{\xi}$ is the buoyant actuator velocity. The amplitude is obtained via:

$$\xi_{a_n}(\omega)=\sqrt{2\ S_\xi(\omega)\ d\omega} \tag{10}$$

For a quadratic damping, the quasi-linear coefficient D_j at the frequency ω_j represents the quadratic damping in spectrum domain, which is given by:

$$D_j=2\ C_{quadratic}\sqrt{\frac{1}{\pi}\sum_j\ \omega_j^{\,2}\left|\xi\left(\omega_j\right)\right|^2}\ , \tag{11}$$

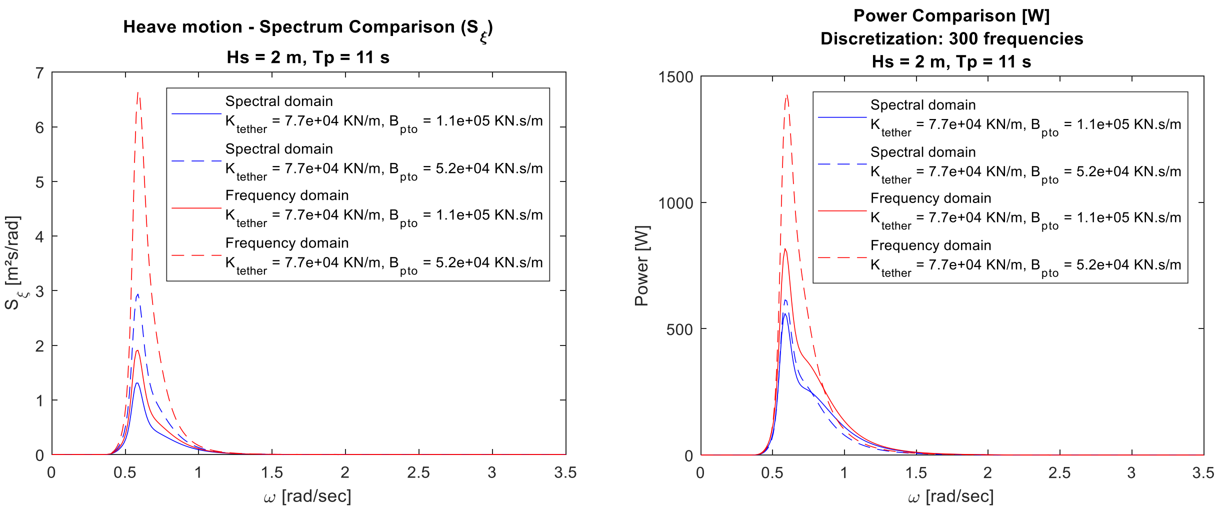
where, $\left|\xi\left(\omega_j\right)\right|$ is the buoyant actuator displacement for the j^{th} frequency. As can be observed in Eq. (11), the response depends on the entire spectrum response to calculate the quasi-linear coefficient D_j. The displacement in spectrum domain for a fully submerged Point Absorber is described as (Folley, 2016):

$$\xi(\omega)=\frac{\zeta_a(\omega)\ F_{ext}(\omega)}{\{K_{tether}-[m_{buoy}+A(\omega)]\ \omega^2\}+[B(\omega)+B_{PTO}+D_j]\ i\omega} \tag{12}$$

The equation has no analytical solution, and therefore, an iterative method is applied. As an initial guess, the quasi-linear coefficient is dismissed, which results in the frequency domain model. Subsequently, the iteration starts to calculate the response based on the last estimation until an error of 0.1% is achieved. Since the non-linear forces are not dominant, the solution converges effortlessly. However, a relaxation method can be employed to guarantee the convergence, where r represents the weight factor (this work uses $r = 0.5$)

$$D_j=rD_j^{-}+(1-r)D_j^{+} \tag{13}$$

Figure 9 (a) shows the difference in the buoyant actuator displacement between the frequency domain and spectral-domain model for the two different PTO damping described.



(a) Heave motion. (b) Power extraction.

Figure 9. Frequency-domain and Spectral-domain.

Based on the buoyant actuator displacement, the mean power extracted from the waves can be calculated by

$$P_{mean}=\sum_{j=1}^{N}\ \frac{1}{2}\ B_{PTO}\left|\omega_j\ \xi\left(\omega_j\right)\right|^2 \tag{14}$$

Figure 9 (b) shows the power extracted comparison. To calculate the power extraction, the range of sea frequencies in this work was discretized into 300 divisions, from 0.001 to 3.5 rad/s. Figure 9 (b) illustrates the considerable impact of viscous losses in the WEC response for lower damping, where the viscous losses are higher, and the resulting power extraction reduces drastically.

4. POWER EXTRACTION

Fully submerged point absorbers require a highly efficient performance to extract the energy from the ocean, which can be challenging due to the stochastic behavior of the ocean. The power is enlarged when the WEC operates close to the resonance. This condition is achieved setting the tether stiffness to match the natural frequency of the system with the incident wave. Moreover, based on the frequency domain model, when the PTO damping is equal to the hydrodynamic radiation damping, an optimal condition is achieved.

$$\omega_n = \sqrt{\frac{K_{tether}}{m_{buoy} + A(\omega_p)}} = \omega_p \tag{15}$$

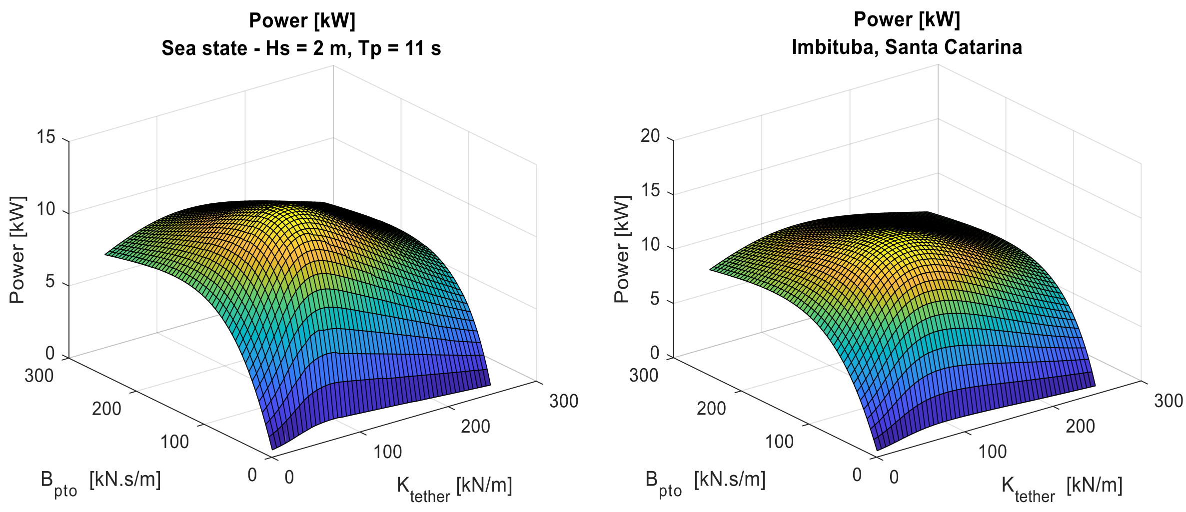
$$B_{PTO} = B(\omega_n) \tag{16}$$

This condition is achieved for a single frequency. However, as the sea can be modeled as a summation of regular components, the device must have an efficient performance over the entire range of the spectrum. Moreover, as observed in Fig. 9, the viscous losses are significant, and therefore, the PTO damping coefficient is not trivial. For instance, for a wave peak period of 11 s, the PTO damping according to Eq. (16) is 2.5 kN.s/m. However, this optimal condition of Eq. (16) is unrealistic due to the huge displacements required that are not reachable in real life due to viscous losses. On another hand, as the natural frequency is independent of the damping of the system, the stiffness presents a reasonable result. However, it is important to investigate the response for the entire spectrum and all sea states. Based on these considerations, a parametric analysis is conducted to estimate the optimal stiffness and damping coefficients. The parametric analysis discretized the range of interested described in Table 1 into 50 elements, total of 2500 combinations. Due to the viscous forces, the range of PTO damping uses the radiation damping of 11 s period as a lower limit.

Table 1. The range of parametric analysis.

	$K_{tether}\ kN/m$	$B_{PTO}\ kN.s/m$
Minimum	2.5	2.5
Maximum	250	250

The power extraction is calculated for each PTO damping and stiffness configurations considering all sea states. Figure 10 (a) illustrates the power absorbed by the fully submerged point absorber at sea state with 2-m of significant wave height and 11-second of wave peak period. The procedure is replicated for all sea states. Posteriorly, the mean power is obtained by the multiplication of the power absorbed in each sea state by its respective probability of occurrence. Figure 10 (b) represents the mean power of the site. The optimal condition for Imbituba occurs for a PTO damping of 90 kN.s/m, and tether stiffness of 90 kN/m, resulting in a mean power of 15.3 kW.



(a) Sea state (H_s= 2 m, T_p = 11 s) (b) Imbituba, Santa Catarina

Figure 10. Power extraction.

5. CONCLUSION

Renewable energy exerts a major role in the future of the energy industry due to the limited reserve of fossil fuels and environmental awareness. Moreover, the use of renewable sources can increase the energy mix reliability. In this context, ocean energy presents several benefits such as the amount of power and availability. However, its extraction remains unexploited in Brazil. The south coast of Brazil presents viable sites for WEC installations, of which Imbituba, in Santa Catarina, is a feasible location with an average power per unit of horizontal area of 24.4 kW/m. Among the WEC options, fully submerged point absorber can be a virtuous candidate. The results showed a discrepancy between the frequency domain and spectral-domain due to the viscous losses. These differences were larger for low PTO damping, which affected the power extraction. Different from the optimal condition in the frequency domain, where the optimized power requires huge displacements, the spectrum domain resulted in a higher PTO damping and consequently, minor displacements and viscous losses. Based on the spectrum domain, a single device can produce an average power of 15.3 kW, for a PTO damping of 90 kN.s/m, and tether stiffness of 90 kN/m. As the power produced is limited, it is recommended for further studies the investigation of WEC farms layout in the spectral domain, and their geometry, construction, costs, etc. Moreover, other types of WECs that meets the requirements need to be investigated.

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7. RESPONSIBILITY NOTICE

The authors Silva, LSP.; Tancredi, TP.; Ding, B.; Sergiienko, N.; Morishita, HM. are the only responsible for the printed material included in this paper.