Development of a near shore WEC for the Brazilian coast

Eliab Ricarte, Luiz A. Pinto, Joel S. Sales, and Marcos A. Freitas

Abstract—**The article shows a WEC under development within a postdoctoral program at the Federal University of Rio de Janeiro, suitable to the Brazilian coast. The near shore device proposes fixed submersible reflectors in its base in order to promote the concentration of the incident waves obtaining an increase in the wave height and the fluid velocity, important factor for the wave power. The main components of the WEC device are presented beside the respective criteria used to reach at the format presented by the way to explain its work principle. Positive results of hydrodynamic experiments are also showed.**

Keywords—*wave energy*, **WEC development, Brazilian coast.**

I. Introduction

In shallow water the waves begins to feel the effect from the seafloor modifying its behavior no longer governed by the physical theories of deep waters.

The wave orbital, which possesses a quantitative equilibrium of potential energy and kinetic energy in an offshore environment, is deformed in near shore and shallow waters (onshore), having greater kinetic energy in its orbital than potential energy, promoting mass transportation. The kinetic energy gain increases as the depth gradually decreases to contain only kinetic energy after the breaking. Phenomenon illustrated in Fig. 1.

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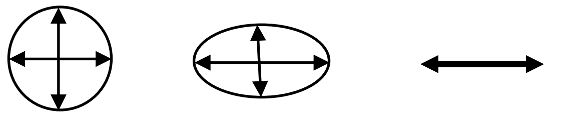

Fig. 1. Diagram of kinetic and potential energy content in the orbital of a wave as a function of local depth.

Certainly the greatest energetic potential of the waves lies in deep waters, usually far from the coast. However, studies such as [1] ratified by [2] state that the losses due to wave friction with the seabed in intermediate waters are only 5-10% justifying the preference for shallow waters in view of the costs of generation, logistics, operation, and maintenance.

The near shore environment promises lower generation costs, but in these low-lying environments there is the challenge of sea waves behaving differently from those in deep waters, and initiating mass transport, which does not exist in an offshore environment.

A strong feature of the Brazilian coastline is its near shore depth on a large surface. As an example in the northern Brazilian coast to reach a depth of 50m has to distance itself from the coast for 70 km.

The Brazilian coast line extends for 7367 km, a number that rises to more than 9200 km when considering the coastal cuts. This represents an EEZ of 3,500,000 km2. Development of technologies oriented to the ocean rise as an obligation.

The Brazilian coast can be considered as a calm area, since it is not affected by any climatic system capable of generating storms of great magnitudes. The wave climate in most of the Brazilian coast, considering all directions and climatic seasons, presents waves with heights between 1 - 2 m for most of the year. The predominant propagation periods are 5 to 9 seconds. There is also the seasonal appearance of some long swell waves [3].

Given the low energy density in the waves of the Brazilian coast the commercial use of this type of energy may not be attractive due to the high costs involved in the manufacture and installation of devices. Especially in Brazil that has options of mature and abundant energy both renewable and non-renewable. The main challenges are to improve the capability of the devices and make them cheaper, or still to design them for applications other than electricity generation using energy efficiency.

The present paper aims to describe a device that has been developed to face these realities and the main achievements.

II. THE DEVICE CONCEPT

Fig. 2 shows the model designed to be installed in regions very close to the coast, in near shore zones, prior to the formation of the "surf zone". This proximity allows a reduction in the installation effort and energy transmission to the land with results on the cost of generation, when compared to the offshore conversion models more distant from the coast.

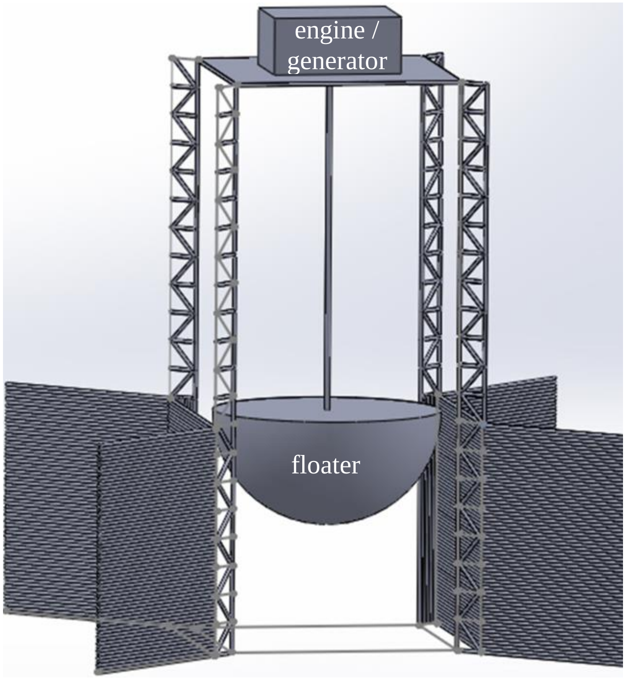

Fig. 2. The Device Concept
Art Impression by Harderson Lima

The hemisphere body has the function of acting as a buoy and, like any floating body it follows the vertical motion of the waves, ensuring that the potential energy of the wave will be absorbed by the body. The fins, in turn, aim to increase the uptake of the incident wave front along the width of the body, guaranteed once the kinetic energy portion of the wave is captured.

On the upper surface of the float, an axis of alternating movement, secondary action of the waves, drives the generator, which is installed in a fixed engine house in the top of a lattice jacket.

Optionally, instead of an electric generator, one can choose to install an alternative pump, where the fixed central shaft would act as a pump piston.

The tower, in turn, rests on a base formed by tubes with the functions of:

- Assembly transport raft;
- Floodable structure ballast tanks and
- Installation base in the seabed.

On the base of device four reflectors are arranged by the way to concentrate the incident waves in a Venturi effect, and additionally assist in the structural balance of the tower, combating the bending moment, and as auxiliary ballast in the sea bed fixation of the structure, by action of gravity.

It is desired to maximize the vertical displacement of the floating body, and for this purpose the limitation of movement in other directions is guaranteed by the insertion of the float into a lattice tower. The floating body slides along the legs of the tower by the inclusion of polyethylene rolls arranged at the edges of the body.

III. DEVELOPMENT STAGES

In this section we present the main components of the WEC device and the respective criteria used to reach to the format presented here, including results of the hydrodynamic experiments.

A. Floater

The first establishment is to acquire sensitivity over the range of characteristic lengths of the floater. The range of wave periods with the highest frequency of occurrence in the studied site is 5 to 15 seconds, with a higher concentration in the periods of 6 and 7 seconds. It is worth mentioning that, for the definition of the most frequent bands, only periods that had at least 5% frequency of occurrence were taken into account, whereas smaller frequencies were neglected.

Wave energy converters (WEC) must be relatively small. For this, it is interesting that the characteristic length of point absorbing devices is in the order of 5% to 10% the predominant wavelength at the site, so that the extracted energy is maximized in relation to the cost of construction and operation of the device [5]. The device is intended to act in shallow and intermediate waters.

Table 1 brings the float diameters obtained for the smallest characteristic length of 5% of the wavelength for 5 seconds and the larger 10% of the wavelength for 15 seconds wave periods, characteristic of the studied site. Diameters out of this range means inefficient body for wave energy capture.

TABLE I
FLOATER SIZE DEFINITION

Wave Period (s)	Wave Length (m)	Floater Size Ø (m)
5	36.5	1.825
15	143	14.3

Source: [6]

Aiming to obtain a model that optimizes the absorption of wave energy, floaters showing different geometries as those from the Fig. 3(a) were modeled using Rhinoceros and WAMIT software's to calculate the hydrodynamic parameters. A post-processing routine was developed in MATLAB for the float response calculations, the average power absorbed and the capture factor. Curves generated as a function of the incident wave periods are displayed in Fig. 3(b) and 3(c).

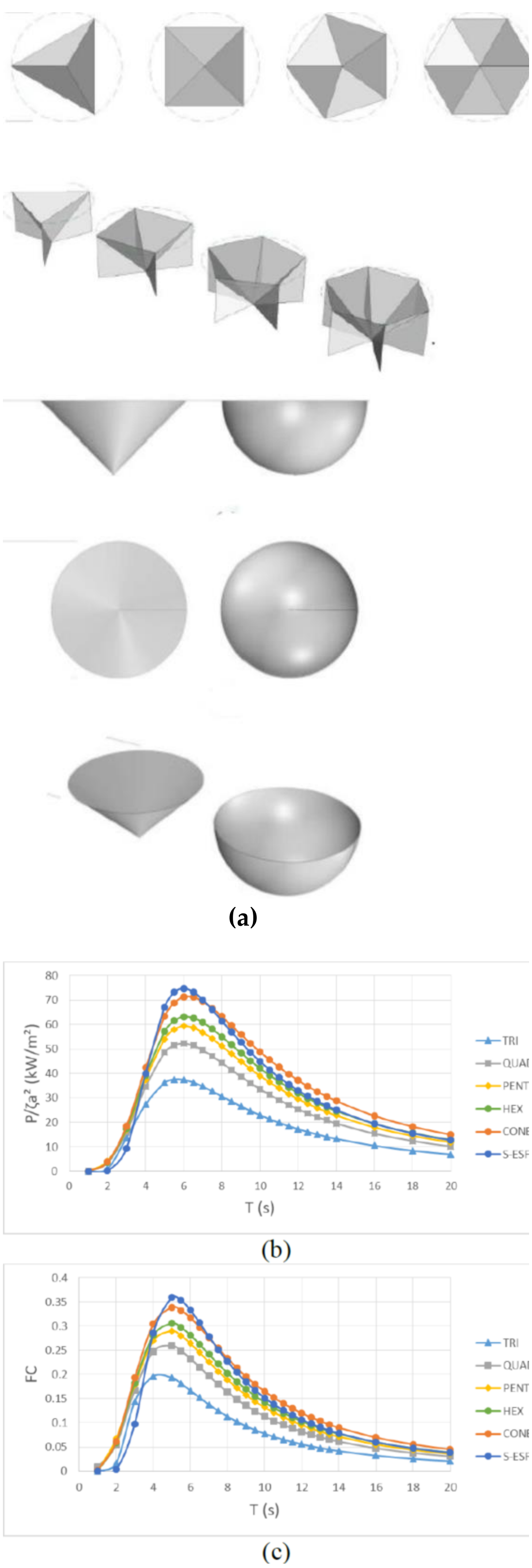

Fig. 3. Geometric Shapes and Curves: (b) Mean Power and (c) CF - capture factor
Source: [7]

Analyzing the Mean Power Curves extracted from Fig. 3(b), it can be seen that the conical and cylindrical floats presented similar and superior behavior to the other models for periods longer than 4 seconds, showing the peaks of the curves, which occur for the period equal to 6 s, respectively, of 71.29 kW / m² and 74.08 kW / m². The superiority of these two models can also be observed with the curves of the Capture Factor (Fig. 3c), but with the peaks of the curves occurring in the period equal to 5 s, presenting values for the conic model of 0.338 and cylindrical model of 0.359. In general the hemisphere floater presented the best results justifying its choice.

B. Rolls

A roller system serving as contact between the buoy and the lattice tower was sized to limit the displacement only in the vertical direction, considering the principal stresses on the rod of its support. Using the extreme wave loading and operating regime, the flexural, compression, shear, and fatigue effects were evaluated using elasticity theory, ratified using finite element methods to identify critical points and possible faults. For this evaluation, it was constructed models in the software *SolidWorks*© and applied the _nite element method with software *Ansys*©.

Fig. 4 shows one of the results of the simulation of the critical region of the converter for the safety coefficient for fatigue.

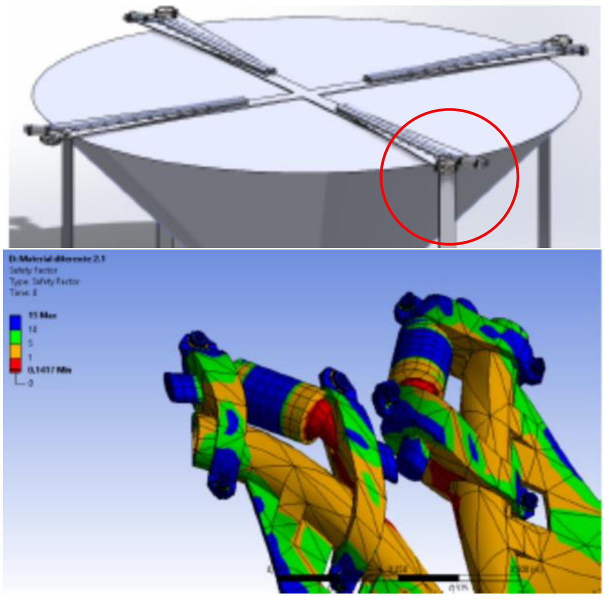

Fig. 4. Critical region of the converter for the safety coefficient for fatigue
Source: [8]

C. Base

An important factor for a wave energy conversion apparatus is the mooring system to which it is connected. Even if a device is perfectly sized in all technical, mechanical-electrical, and hydrodynamic aspects, if it is not properly anchored, the project as a whole will not be possible. Whether it is the technical aspects or high costs that hinder an inadequate project, a deep-water fixation system can in some cases be so complex that it inhibits a possible WEC design.

A lattice tower will be connected to this tubular structure base resembling a raft formed by ducts to carry the transport of the WEC assembly. The great advantage of this system is to ensure that all the construction and assembly of the wave power plant takes place on land or at the shipyard. Once the assembly of the plant in the yard is completed it can be towed to the site of implantation, where a process of flooding the ducts that constitute its adjoined base is initiated to occupy its place in the seabed.

In addition to the importance of macro and micro-logistics simplification involved in the assembly of wave power plants, the inclusion of the "base" brings positive effects in the form of environmental implications. The conversion of energy from the waves is a truly clean process, whereas the movement of vessels and teams used in the process during the period of assembly at sea is imputed as a negative aspect. The "base" design greatly reduces the time of permanence and movement at sea, besides ensuring the rapid decomposition of the structure, when desired, by injecting air into the ducts of the base allowing its emersion (inverse flood process).

There are some considerations that must be made regarding the fastening system so that one can consider the viability of the project as a whole:

- The system must be able to guarantee the stability of the apparatus, so that it can operate in good weather conditions as well as in storms;
- The appliance must be secured in such a way as to avoid high voltages on electrical transmission cables;
- All components must be mechanically resistant to both normal load and cyclic loads (fatigue resistance;
- Some degree of redundancy in more critical components is strongly recommended;
- The system as a whole must be able to work safely and efficiently for at least 30 years, and there may be component or maintenance changes every 5 years;
- The fastening system should be designed taking into account local tide variations;
- Removal of maintenance system components should be possible;
- The system must be designed to allow mooring of vessels with maintenance personnel;
- The contact between the ropes must be avoided;
- The fastening system should not adversely affect the efficiency of the power generation system.

It was carried out equilibrium and stability studies for the safe transport of the assembly and for an accurate installation of the proposed equipment. It was performed several simulations in the operations of transport and installation of the apparatus [9], ensuring the safety of the assembly from the shipyard where it will be mounted to the place of operation. In order to carry out the equilibrium study, the Archimedes principle must be satisfied and a number of pipe diameters have been tested in order to find the configuration with the lowest weight that can keep the system afloat.

The Floating and Stability analysis requires the definition of the floating body shape as well as the weight estimation of the constituent parts. The proposed WEC differs considerably from the shape of a conventional vessel. In the absence of proper regulation for this type of structure, the stability criteria described in NORMAN 01-2005, that regulates the vessels that navigate within the Brazilian coast, were used.

The Fig. 5 illustrates the stability of a vessel. When the roll movement occurs, the ship assumes a new fluctuation plane and the restoring moment is composed of the actions of the Weight (W) acting on the gravity center (G) and the Buoyancy acting on the Buoyancy center (B). The magnitude of these forces and the GZ distance must be designed to ensure the return to the original floating condition, without exaggerated intensities, to guarantee the comfort of the ship's crew. The WEC stability analysis was performed in a manner analogous to vessel stability.

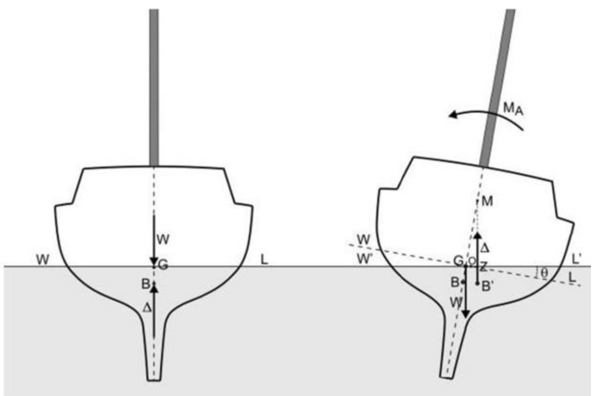

Fig. 5. Ship stability
Source: [9]

As expected, some of the criteria do not apply to floating bodies with shapes other than the shape of ships. Thus, 6 criteria were considered to guarantee the static stability of the WEC:

1) The area under the Static Stability Curve between 0° and 30° inclination angles shall not be less than 0.055 m.rad;

(2) The area under the Static Stability Curve between 0° and 40° inclination angles, or between 0° and flood angle (θf), if it is less than 40°, shall not be less than 0.090 m.rad;

(3) The area under the Static Stability Curve between 30° and 40° inclination angles, or between 30° and flood angle (θf), if it is less than 40°, shall not be less than 0.030 m.rad;

4) The straightening arm corresponding to the angle of inclination of 30° shall not be less than 0.20 m;

5) The maximum straightening arm should occur at an angle of inclination greater than or equal to 25°;

6) The initial metacentric height (GMo) should not be less than 0.15 m.

The sprinkler moment calculation due to towing (MR) must be done by means of equation (1):

$$MR = F \times d \times \cos \theta \qquad (1)$$

where:

MR = sprinkler moment due to trailer, in t.m;
F = half of the maximum static tensile force, in t;
d = arm of the tipping moment due to the trailer;
θ = angle of inclination of the vessel.

After a few iterations, the configuration of the floats that guarantees flotation and stability is shown in Fig. 6. Fig. 7 summarizes the approval of the 6 stability criteria for the proposed configuration.

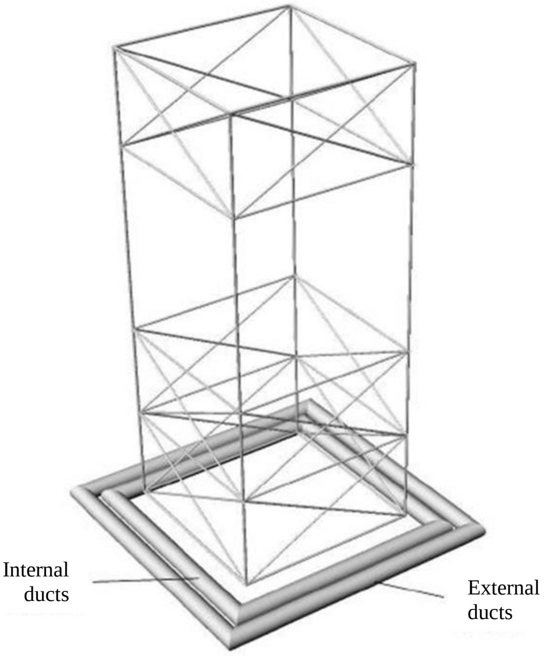

Fig. 6. Ducts Appliance for flotation and stability
Source: [9]

Limit	Min/Max	Actual	Margin
(1) GM at Equilibrium	>0.150 m		<large>
(2) Righting Arm at MaxRA	>0.250 m	3.866	3.616
(3) Righting Arm at 30.00 deg	>0.200 m	2.758	2.558
(4) Area from 0.00 deg to 30.00	>0.0550 m-R	1.563	1.508
(5) Area from 0.00 deg to 40.00	>0.0900 m-R	1.986	1.896
(6) Area from 30.00 deg to 40.00	>0.0300 m-R	0.423	0.393

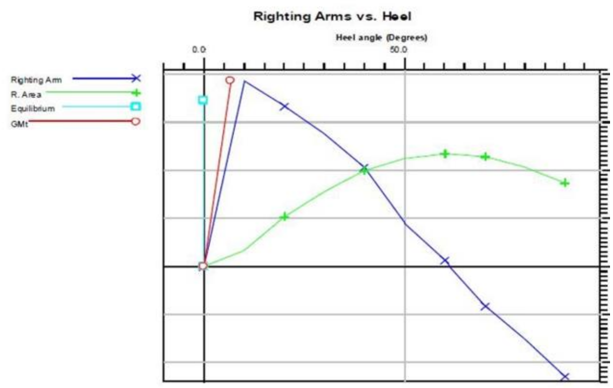

Fig. 7. Stability criteria for the proposed configuration
Source: [10]

D. Reflectors

On the "base" four reflectors are arranged with the main function of wave concentration They additionally assist in the structural balance of the tower by reducing the mechanical tensions due to the bending moment and working as "tanks" for ballast in the fixation of the structure on the sea bed, by action of gravity, please see Fig. 2 earlier. Experimental tests with a 1:15 model performed in ocean tank from INPH – National Institute of Waterways Research from the Brazil Transportation Ministry showed wave height amplification between 0%-15% for waves between 1m-2.5m height and 5s-9s periods.

Fig. 8. 1:15 scale model test at INPH 3D basin

E. Economics and Environmental Gains

In the exercise of the device cost reduction it was simulated the replacement of the steel required for manufacturing, whenever possible, by the reuse of residual ducts from the oil and gas industry. Ducts of different diameters were applied to the confection of the reflectors, the lattice tower and the base for transportation and mooring. Under the same operating conditions a reduction of 90% in the cost of steel required was achieved.

Additionally with the use of reusable material the device responsibility on exploration of the ore deposits and greenhouse emissions decreased substantially, besides contributing significantly in the Life Cycle Assessment of the material now used for the noble finality of the production of truly clean and renewable energy. This change was responsible for the reduction of total emission in the extraction and production phases of the raw material and of the final device from 74.4 tons to 37.2 tons of CO_2, approximately 50% reduction [11].

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F. Hydrodynamic analysis

The system behaviour on waves was tested at Laboratory of Waves and Currents (LOC – COPPE/UFRJ) in Brazil.

A scaled model with scale factor of 1:40 (Fig. 9) was constructed on PVC and calibrated so that the correct inertial and hydrodynamic characteristics could be represented.

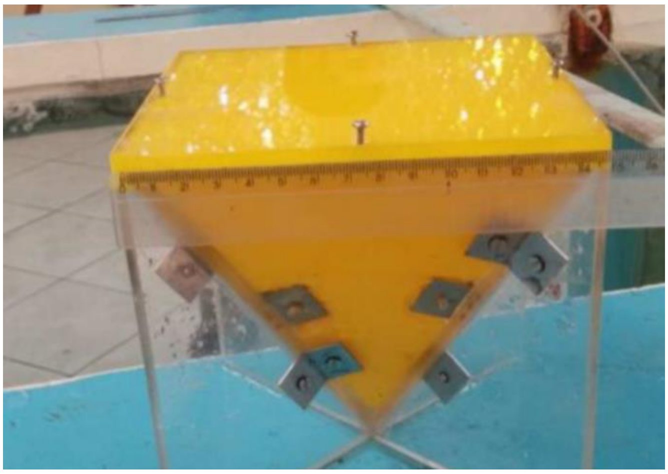

Fig. 9. Floater model

Both the mass and volume properties were kept in scale to give correct Heave behaviour of the floater.

The system was positioned at the wave flume bottom and a structure was used to represent the steel guides to restrict the model to vertical-only motions (Fig. 10).

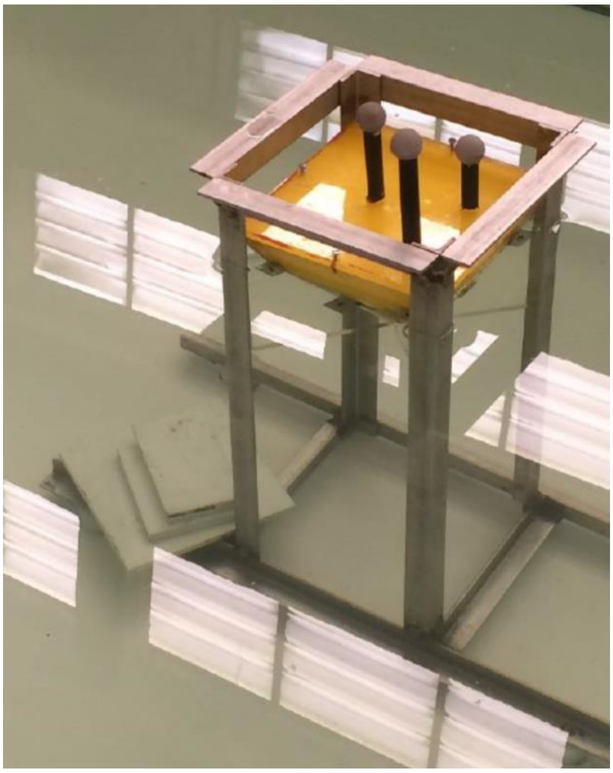

Fig. 10. Floater model and guide structure installed at the flume

The test matrix consisted of regular waves with different periods and heights. Moreover, two headings were tested to check the influence of wave direction of incidence.

A data acquisition system was used to sample data at 60Hz, with connected wave height probes to measure instantaneous wave heights, while the Heave motion of the floater was measured by a visual tracking system synchronized with the wave probes signals see Fig. 11.

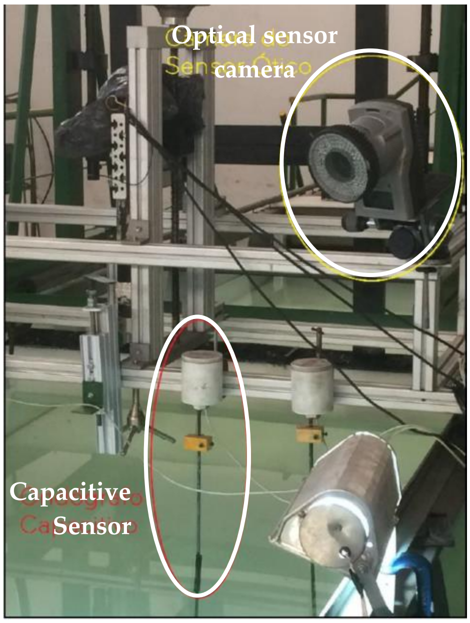

Fig. 11. Instrumentation with wave probes (red line) and visual tracking cameras (yellow line)

Each wave was calibrated at the flume before the model was installed, to allow the measurement of the non-disturbed wave signal, i.e., without the diffraction of the floater. The Test Matrix is presented on Table 2 below.

Table 2 – Wave tests Matrix (model scale)

	Height H (mm)	Period T (s)
Wave 1	30	0.8
Wave 2	20	1.0
Wave 3	12	1.35
Wave 4	16	1.63

The obtained Heave Heights measured for each regular wave were then plotted against wave periods so that the RAO (response amplitude operators) could be constructed. The RAO curves allow the analysis of the best period ranges for the operation of the system, and also for the power generation estimates based on the response of the floater.

The Fig. 12 and 13 show some results obtained for the floater.

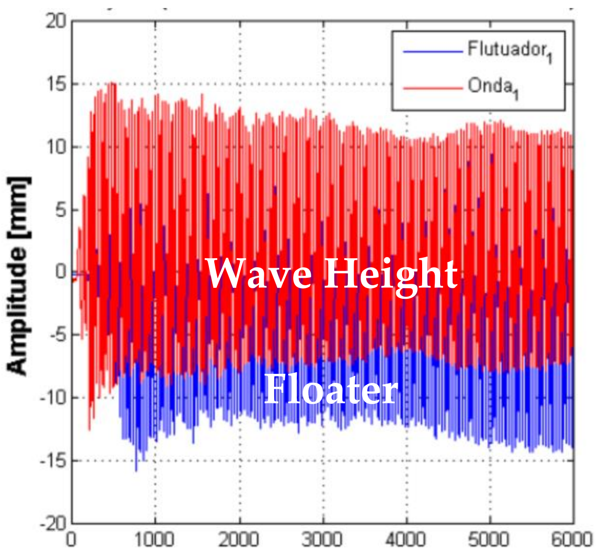

Fig. 12. Result for wave height of 30mm (model scale) and period of 0.8s (model scale) at 0deg heading– Floater heave in blue and wave height in red

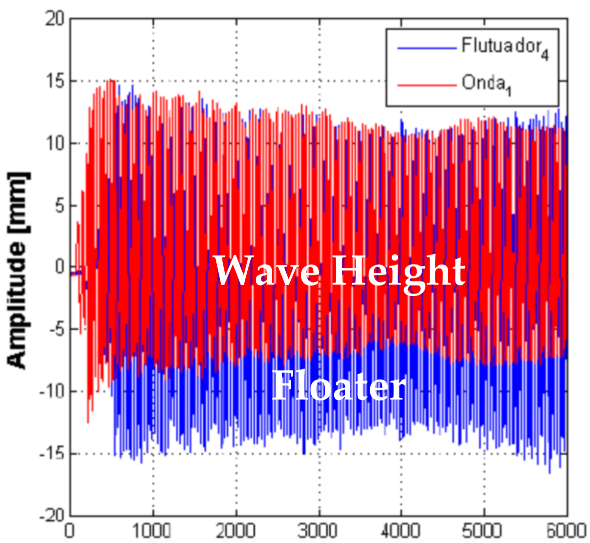

Fig. 13. Result for wave height of 30mm (model scale) and period of 0.8s (model scale) at 45 deg heading – Floater heave in blue and wave height in red

It was observed good amplification factors, i.e., RAOs, for the floater motion in relation to the wave motion (from 1.1 to 1.6) for the range of tested wave periods (Please see fig. 14). This indicates a good hydrodynamic behavior of the system.

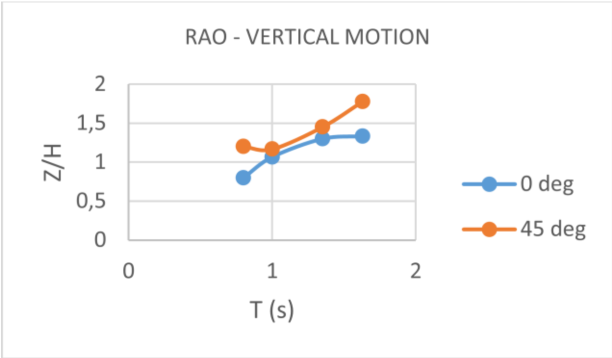

Fig. 14. RAO results (model scale) – at 0 deg and 45 deg

IV. Conclusion

This paper has shown a near shore WEC device under development in Brazil and the main technical achievements to its main subsystems. It takes in count the weak wave climate on the Brazilian coast and proposed submerged reflector to concentrate the incident waves and achieve a Venturi effect resulting an 0% - 15% increment in wave height. Experimental tests for different floater shapes and wave attack angles showed a RAO varying from 0.75 to 1.75, best results to low wave periods 5s-9s.

Previous simulation introducing material reuse to structural and mooring subsystems resulted in a 90% on steel cost reduction on the Brazilian market. Additionally there was an environmental gain decreasing the carbon footprint of this device to 50% from 74.4 to 37.2 tons de CO_2.

Studies under development dedicated to this device point to different application in the future than electricity generation seeking the energy efficiency like the fluid pumping, CAES and PHS energy storage, wave powered desalination and hybrid devices.

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LOC – Waves and Currents Laboratory from the Federal University of Rio de Janeiro

INPH – National Institute of Waterways Research from the Brazil Transportation Ministry

BRAZILIAN NAVY – Science and Technology Secretary

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