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Primary conversion in non-resonant wave energy converter with floating buoy

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ABSTRACT

This paper studies one of the technical problems that occur in the process of moving from ”waves to electricity” in floating wave buoys converters located near the coast: to maximize the product force by displacement. It is proposed a first converter stage only with mechanical elements of low inertia and absence of fluids, showing the advantage of using a accumulator with spring to achieve high accelerations by means of a converter design suitable to mount the mentioned stage. A comparative analysis is made with the most suitable tension for the springs according to the height of the waves provided at the location of the converter.

1. Introduction.

Sea waves are a tertiary derivative of solar energy: the uneven heating of the earth's surface caused by solar radiation gives rise to high pressure and other low pressure areas that cause the winds. These, acting on the surface of the sea, yield part of their energy transforming into waves. The waves spread along thousands of kilometers along the surface of the sea and also with minimal energy losses, so the energy generated in any part of the ocean ends at the continental edge, so that the energy of the waves is concentrated on the coasts.

Thus, the waves created in the western area of the Atlantic travel, driven by winds from the west, to the coasts of Europe. The energetic density of the waves decreases near the coast due to the interaction of the waves with the seabed.

In spite of being a very little used resource until the present moment, the first patent of wave exploitation dates from 1799 in Paris, figuring as authors Pierre Simon Girard and his son. This patent, whose first embodiment is shown in Figure 1, taken directly from the original patent (Bibliothèque nationale de France.), did not materialize in reality. Girard proposes, with this design, a lever of first degree with the axis resting on solid ground. At one end a floating body, ”A”, which follows the movement of the wave, is suspended; the movement transmitted to the other end of the lever can be applied - in the words of the inventor - to operate a pump, a bucket wheel, a mill, a fuller, hammers, saws, etc. Located under the floating body is a regulator, ”B”, with the purpose of achieving a more regular ascent and preventing the floating body from wobbling..

The first British wave converter was patented in 1833. And in Spain the first wave converter patent, with the number 4564, was presented by Professor José Barrufet and Veciana on October 21, 1884, an apparatus called *Marmotor* for the use of waves of the sea as a driving force. This converter was tested in the waters of the sea of Barcelona, on the beach of ”*Mar Vieja*” in September of the following year, operating a mountain range (Minguela,2008). In the year 1973 there were 340 wave energy converter (WEC) patents and in the year 2002 this number increased to 1000 between Europe, Japan and the USA. Even

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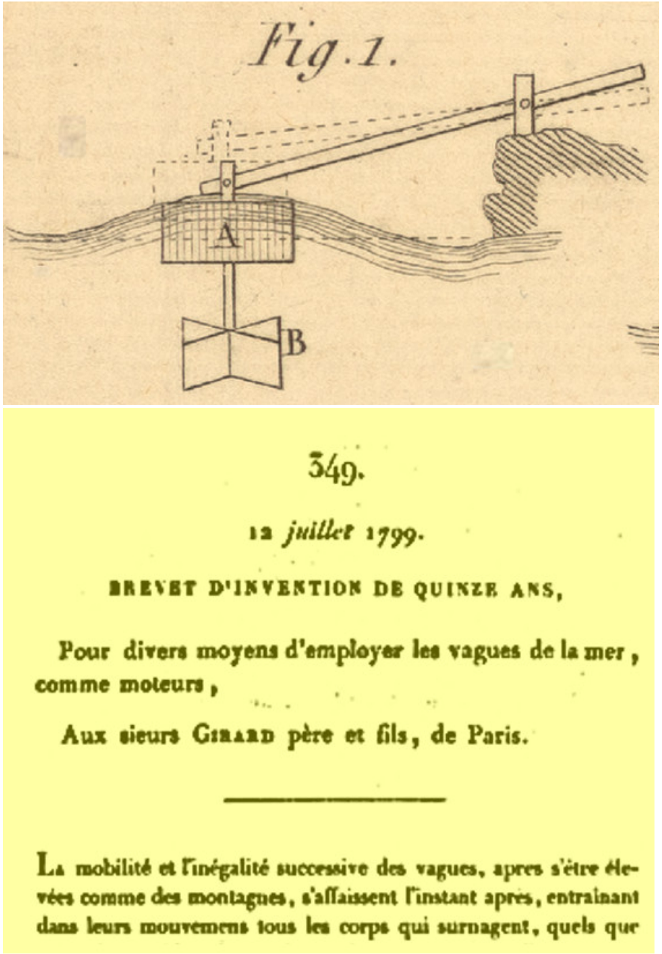
so, there are few converters in operation in the world. There is not yet a mature technology that allows competitive wave converters to be built in the difficult passage from wave energy to electrical energy.

Researchers are looking for new designs that make existing converters more efficient. As an example, within the wave energy converters with oscillating water column (WEC-OWC) have been proposed the Differential Pressure Storage Tanks (DPST) (Borrás-Formoso, 2014, 2016)

Figure 1: First world patent for wave power.



349.

12 juillet 1799.

BREVET D'INVENTION DE QUINZE ANS,

Pour divers moyens d'employer les vagues de la mer, comme moteurs,

Aux sieurs GIRARD père et fils, de Paris.

La mobilité et l'inégalité successive des vagues, après s'être élevées comme des montagnes, s'affaissent l'instant après, entraînant dans leurs mouvemens tous les corps qui surnagent, quels que

Source: BNF.

2. Wave Energy and Converter.

One of the fundamental parameters to take into account for the location of the wave converters is the power associated with the wave front length. The energy that the wave possesses is the sum of the potential energy, due to the vertical position of each particle of water with respect to the resting position, and the kinetic energy, due to the movement inherent to the waves. This value constitutes the upper limit of the power that could be obtained from the converter. If we had a continuous row of converters developing this power, the state of the sea downstream of the converters, would be a completely calm sea. This would be a collateral benefit in The energy that the wave possesses is the sum of the potential energy, due to the vertical position of each particle of water with respect to the resting position, and the kinetic energy, due to the movement inherent to the waves. This value constitutes the upper limit of the power that could be obtained from the converter. If we had a continuous row of converters developing this power, the state of the sea downstream of the converters, would be a completely calm sea. This would be a collateral benefit in order to avoid erosion and damage caused by waves in coastal areas.

Figure 2 shows a map with the average values of power per meter of wave front, also called power transported per meter of wave front, kW / m. Analogous terms to designate the same concept - but inadvisable - are energy flow of the wave or power flow of the wave (Falnes, 2004).

Figure 2: Power per meter of wave front on the coasts.

Source: http://www.oceanpowertech.com.

To evaluate the wave power, different formulas have been proposed that are not totally coincident because each one has a different spectral distribution and applies different simplifying hypotheses. Thus, among the most used, it is necessary to indicate the following:

$$P = 0,441 \cdot H_S^2 \cdot T_Z \quad {}^{kW}\!/_{m} \quad Bretschneider - Mitsuyasu$$
$$P = 0,458 \cdot H_S^2 \cdot T_Z \quad {}^{kW}\!/_{m} \quad JONSWAP$$
$$P = 0,549 \cdot H_S^2 \cdot T_Z \quad {}^{kW}\!/_{m} \quad Pierson - Moskowitz$$
$$P = 0,577 \cdot H_S^2 \cdot T_Z \quad {}^{kW}\!/_{m} \quad IEA, 2003$$
$$P = 0,5949 \cdot H_S^2 \cdot T_Z \quad {}^{kW}\!/_{m} \quad Espectro\ ISSC$$
$$P = 0,538 \cdot H_S^2 \cdot T_Z + 0,491 \frac{H_S^3}{T_Z} \quad {}^{kW}\!/_{m} \quad Nath$$

Where H_S is the significant average height (m), and T_Z the average period (s).

And for the case of ideal Airy waves, monochromatic:

$$P = \frac{\rho \cdot g^2 \cdot H^2 \cdot T}{1000 \cdot 32\pi} \cong 0,984 H^2 \cdot T \quad {}^{kW}\!/_{m}$$

The Where ρ is the density of seawater (kg/m^3), g the acceleration of gravity (m/s^2), H the height of the wave (m) and T the period (s). In the waves of Airy, the power corresponding to the potential energy and the kinetics are distributed at 50%. In these waves, Hs = H and Tz = T.

Notwithstanding the above, it must be borne in mind that, due to the antenna effect, a wave converter can capture the energy of a wave front much greater than the width of the device.

An approximate equation that relates the wavelength to the period for waves in deep water is given by:

$$\lambda = (g/2\pi)\,T^2 \cong 1,56 \cdot T^2 \quad m \tag{1}$$

Most of the energy content of waves is associated with waves of a period between 5 and 15 seconds and wavelengths, according to the previous expression, ec. (1), between 40 and 350 m (Falnes, 2004).

To increase the converted power, control strategies can be implemented, such as reactive control (based on the adaptation of the mechanical impedance) or interlocking control. (Cretel, 2011)

3. Coastal Waves.

In deep water you can find waves with a profile that can approach a sine wave, it is called the Airy wave. But when those waves approach the coast, intermediate waters, that profile is separated from a sine wave, the crest becomes higher and sinus flattens, is the so-called Stokes wave. Still closer to the coast, for depths less than 1/8 of the wavelength, shallow waters, a profile that best approximates the real wave is that of the cnoidal wave, defined by the Jacobi elliptic cosine function, characterized by more pointed crests and flatter valleys. An approximate profile of these wave types can be seen in Fig. (3).

The researcher Le Mehauté in 1976 proposed a graph to give the range of use of one or the other model (Méauté, 1976). It must also be taken into account that the behavior of water in a specific area is affected by extension, salinity, temperature, etc. (Guarda, 2014)

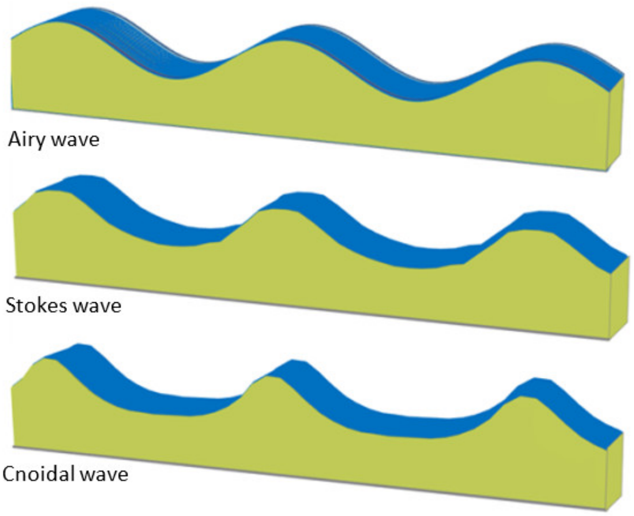
The appropriate location for converters with point absorbers, given their unit power and operating conditions, is in waters close to the coast. However, it must be borne in mind that as the converter is located closer to the coast, the energy it can convert is significantly reduced. An estimate of the percentage loss, with respect to energy in deep water, could be 21% if it is located at a point with a depth of 50m and 39% if the depth is 30m. (Monarcha, 2013) This is why a search criterion for a reasonable location can be, among others, to look for the depth of 50 m.

4. Movement of the Buoy.

A floating buoy can move with six degrees of freedom, but the only usable displacement for the proposed converter, figure 7, is the vertical upward displacement, when it exerts a "shot" action on the conversion train that is submerged. This movement of heave *(arfada)* is the only one that we will refer to. In the calm sea condition, the buoy, element of interface between the sea and the converter, acquires a stable position. When a wave arrives, due to the set of forces acting on it, the buoy suffers a displacement that can be described from the following equation according to Newton's laws (Ahn, 2012) (Falnes, 2004).

$$m_m \frac{d^2}{dt^2} s = F_e + F_r + F_b + F_v + F_f + F_{ext} \quad (N) \tag{2}$$

Figure 3: Wave models according to depth.



Source: Authors.

Where m_m is the mass of the buoy and its solidary elements, F_e is the force of excitation due to the incidence of the wave, F_r the force of radiation acting on the buoy due to the waves generated by the buoy as when a stone is thrown to a pond, F_b the hydrostatic force by the displacement, s, from its equilibrium position, F_v the viscous force, F_f the frictional force (these last two proportional to the relative speed and with the opposite direction to the movement) and F_{ext} the force transferred to the buoy by the conversion stage, the reaction of the power train (López, 2014).

The radiation force is usually represented by the terms of added mass and potential damping. The added mass is the practical translation of the hydrodynamic forces proportional to the acceleration of the buoy. (García, 2016).

As mentioned above, the coastal waves have a very short ridge, measured in the forward direction. This means that the transfer of energy from the wave to the converter has to be done in the short period of time between the moment in which the wave front reaches the buoy, t1, and the moment when it passes, t2 . This interval, smaller than t2-t1, can be of the order of only one second. The vertical position of the buoy corresponding to these instants passes from the elevation s1 to the elevation s2. The energy that is transferred for each wave period is given by:

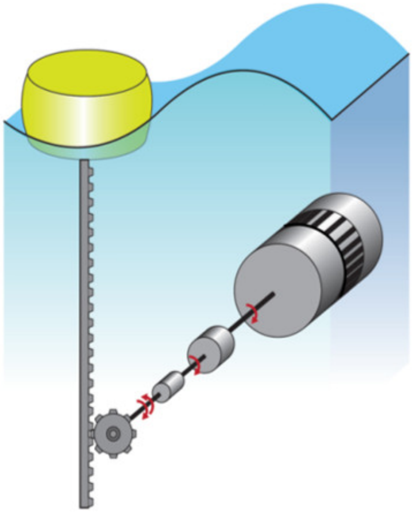
$$E = \int_{s1}^{s2} F ds \quad (J) \tag{3}$$

To transfer much energy, therefore, it is important that both the force and the displacement of the buoy, travel, be high. That the buoy makes a high tour in a short period of time, starting from rest, implies getting a high acceleration. It is therefore of interest that the primary conversion can be made by opposing the floating force a constant force with elements of low inertia and without viscous frictions, and with a design capable of being mounted in an offshore waveform converter but close to the coastline. This problem, to date, is unsolved satisfactorily. The following section shows a way to approach a possible solution.

5. Spring Accumulator.

Point-type buoy absorbers normally transfer energy directly, with linear electric generators, or through a hydraulic or pneumatic system. In the first case, these are unconventional and very expensive generators and, on the other hand, since they cannot easily dispose of an intermediate stage with accumulation of energy, they do not allow a continuous electrical supply (Grimwade, 2012) and in the other two cases the viscous forces are unavoidable. (approximately proportional to the speed) that apart from the loss of performance give rise to forces in opposition that slow the displacement preventing high accelerations. As previously mentioned, if a high acceleration of the buoy is not achieved, it is not possible to transfer a high energy to the converter. Accordingly, in order to avoid these drawbacks, a converter is proposed that employs only low-inertia mechanical elements in the primary conversion stage. In the secondary conversion stage (PTO) the energy from the first stage, accumulated in the form of mechanical energy for example, is transformed into another form of energy, such as electric power, the most usual way.

Figure 4: Primary conversion stage of WEC with floating point absorber.



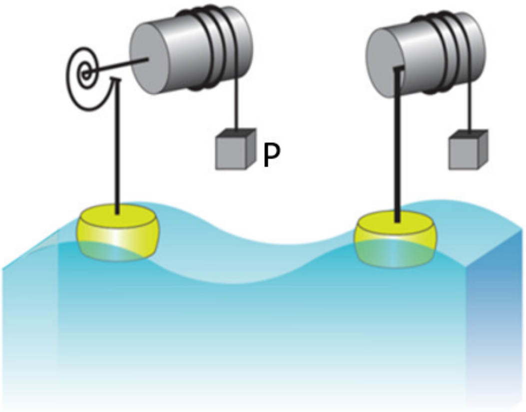
Source: Authors.

Figure 4 shows a simplified diagram, valid only for the operation during the upward movement of the float, with its essential components: buoy, chain / rack, cogwheel, ratchet, ratchet, accumulator.

To see the usefulness of the rotary accumulator with spring, a primary converter stage with and without accumulator interposed is shown in figure 5. In the primary conversion stage the energy of the wave will be transferred to potential energy represented as a mass with weight P hanging from a cable that is wound on the drum.

To obtain a first approximation, simplifying hypotheses are made to facilitate the calculations. First, as is customary, let us assume that water behaves like a non-viscous and irrotational fluid (Hongda, 2016), thus not taking into account the aforementioned F_v and F_r. We also neglect the excitation and radiation forces, Fe and Fr, for being several orders of magnitude smaller than the hydrostatic force, F_b. From the observation of Figure 5 in the equilibrium position, it follows that the reaction force of the power train, F_{ex}, in both cases, is equal to the weight of the suspended mass, P.

Figure 5: Primary converter with and without spring accumulator.

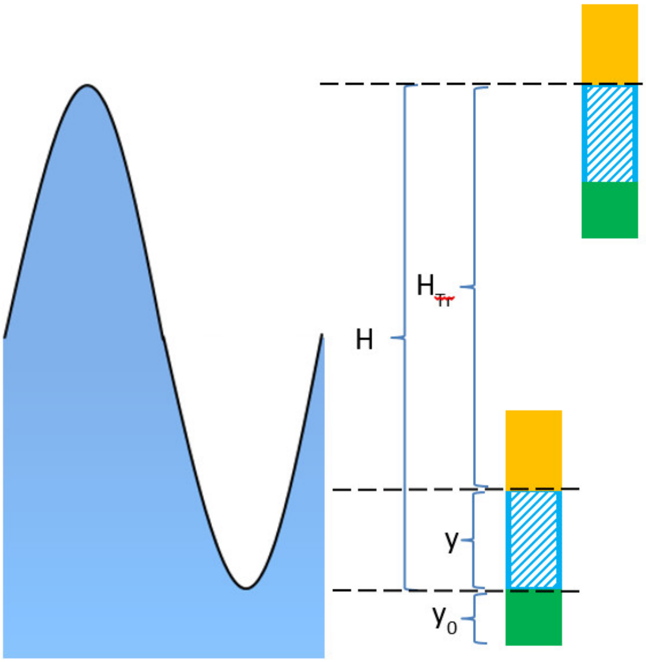


Source: Authors.

We will compare the acceleration of the float to be partially submerged by the incident wave for the two cases shown in Fig. (5).

The strong torque graph offered by a spiral mechanical spring as a function of the angle of rotation is similar to the induction characteristic of a magnetic material. It starts from zero when the spring is completely unstressed and grows approximately linearly until it reaches an angle of rotation, from which it remains substantially constant until it reaches a point where the axis does not allow more rotation. The practical verification of what has been said can be done by observing what happens when winding a classic alarm clock. Therefore, if the spiral spring is made to work outside the initial stretch, it can be considered that the torque remains at a substantially constant value. On the other hand, taking into account that its mass is very small, as it is a metal strip of very little thickness, in any case negligible compared to the mass of the float plus the mass of the mast, the moment of inertia will be neglected. spiral spring in its rotation movement. In the assembly of figure 5, by design, suspended weight of the cable and characteristic of the angle of rotation of the spring have to be considered simultaneously. Therefore, it can be considered then that both in the static position and in the dynamic, the torque offered by the spring is constant. On the other hand, if we make the radius of the drum equal to the radius of the spring, the force exerted by the spring on the mast must be equal to the weight suspended, P.

Figure 6: Buoy dive and work route.



Source: Authors.

When the sea is calm, the force due to the evacuation of water by the buoy, vertical thrust upwards or Archimedes force, F_{Arq}, must be compensated by the force due to the spring, P, plus float and mast weights, with mass M_F. The float, which is supposed to be prismatic, is submerged in a height Y_0. When a wave arrives, the float will be submerged to a height of $Y_0 + Y$, and therefore the strength of Archimedes will now be greater, with which the float will move upwards. The acceleration that the float-mast set will suffer, applying Newton's laws, will be:

$$a = \frac{F_{Arq} - (P + M_F \cdot g)}{M_F} \tag{4}$$

Let's see now the case of figure 5 right, without intermediate accumulator. With the sea calm, the float will be submerged a height Y_0, as in the previous case. When the wave arrives, when the float is submerged to a height of $Y_0 + Y$, the acceleration of the float-mast assembly will now be:

$$a = \frac{F_{Arq} - (P + M_F \cdot g)}{M_F + \frac{P}{g} + \frac{I}{r^2}} \tag{5}$$

where I represents the moment of inertia of the rope winding drum assembly.

Comparing both obtained acceleration results, it is observed that the acceleration in the first case is much greater since in both the numerator is the same but in the second case the denominator is much higher. Recall that it had been said that intentionally was looking for the mass of the float to be reduced.

On the other hand, for a weight or opposing force of the given spring, P, in order to achieve maximum acceleration, "doubly" interests the mass of the float-mast assembly to be as small as possible. Observing Eq. (4), a low M_F causes the numerator to increase and the denominator to decrease, resulting in both changes in an increase in acceleration. The interest in obtaining a float with a reduced mass is therefore appreciated.

Another consequence is also deduced and that, according to Eq. (4), it is observed that the accumulator spring acts isolating the effect of the moment of inertia of the masses that are downstream, it is a decoupler of moment of inertia.

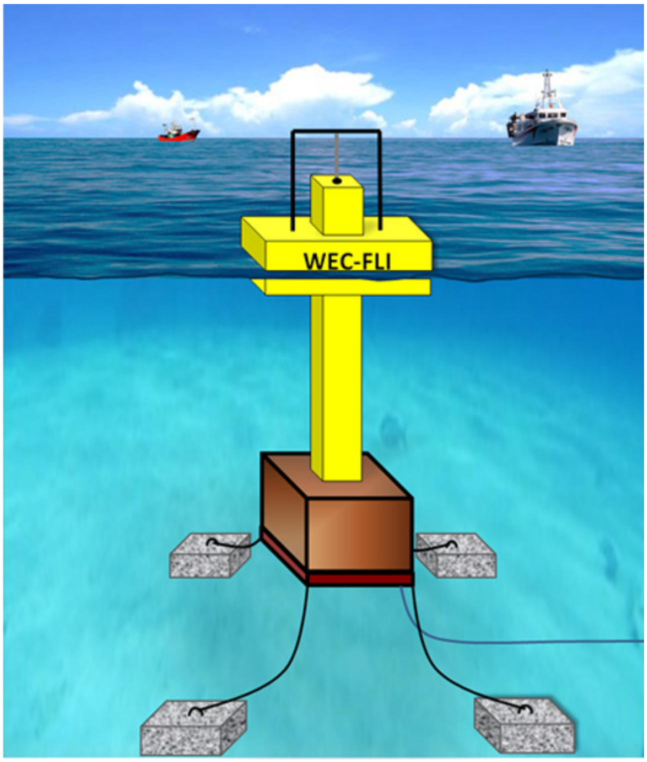
6. Primary Stage of the Converter.

The primary phase proposed for the wave converter will be described. Starting from the low mass float, for example a hollow prism filled with a high expansion foam that gives resistance to deformation by the external pressure without hardly increasing the weight, there are basically two possibilities: afloat converter, where the whole system of conversion is above sea level, or with the partially submerged structure containing the machinery. In the first case the float would be equipped with a mast working in compression and in the second case, as in Figure 4, the float would pull by, for example, a cable or chain, working under tension.

Achieving a good design of the primary conversion stage is vital to obtain a good conversion performance. An output power greater than that captured in this first stage can not be obtained.

Figure 7 shows a converter proposal, WEC-FLI, suitable for mounting the above mentioned primary stage.

Figure 7: Wave energy converter with point absorber.



Source: Authors.

7. Spring Tension.

By designing the primary stage of the converter with the criteria justified in the previous section, float with reduced mass and decoupling moment of inertia, a high acceleration can be obtained in the upward movement. The extraction of energy from the wave will occur only in the upward stroke of the float. No energy will be transferred taking advantage of the potential energy of the float-mast assembly in the downward travel, since for this to occur it should be able to overcome the tension of the accumulator spring and, as justified, with its low value would be null or negligible.

It is going to calculate the tension of the spiral spring that maximizes the work used. With a design like the one shown in figure 5 left, suppose that a prism-shaped buoy or float with area of the base Ab is used. Due to the weight of the float and mast, the float will have submerged a height y_0, Figure 6, given by:

$$M_F \cdot g = A_b \cdot y_0 \cdot \rho \cdot g \tag{6}$$

When the wave arrives, the buoy will have to submerge an additional height, and, exerting on the spring a force Fr before it begins its upward movement. The thrust force of the float acting on the end of the spiral spring will remain substantially constant throughout the ascending travel, H_{Tr}, upward working stroke, storing the energy converted in the form of elastic energy in the spring. The force exerted on the spring will be:

$$F_r = A_b \cdot y \cdot \rho \cdot g \tag{7}$$

Being the height of the wave (from ridge to valley) H, the work route will have a value of:

$$H_{Tr} = H - y \tag{8}$$

And the energy stored for each cycle:

$$E = F_r \cdot H_{Tr} = A_b \cdot y \cdot \rho \cdot g (H - y) \tag{9}$$

To obtain the immersion, y, that maximizes the Energy stored per cycle, we derive the equation (9) with respect to y, equaling to zero:

$$\frac{dE}{dy} = A_b \cdot \rho \cdot g\,(H - 2y) = 0 \quad \Rightarrow y = \frac{H}{2} \tag{10}$$

Therefore, the spring has to work by exerting a force on the mast:

$$F_r = A_b \cdot \rho \cdot g \cdot \frac{H}{2} \tag{11}$$

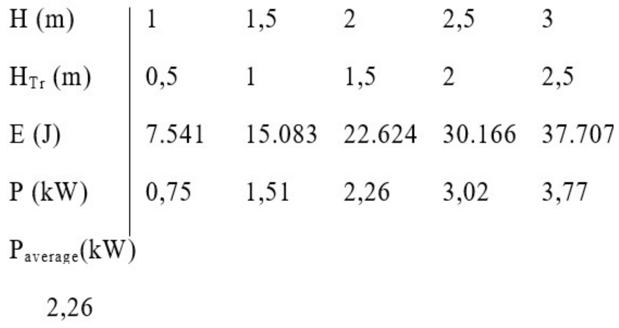
That is to say, the buoy will have to be submerged, during the entire working race, an additional height equal to half the height of the wave. Note that for this purpose, the mass of the float assembly does not influence. That is, for a given float mass, it tells us what the additional depth of immersion must be during the entire upward run.

8. Study of a Practical Case.

Given the difficulty presented by the continuous adjustment of the tension of the spring, depending on the height of the incident wave, to achieve the maximum transfer of energy from the wave, it starts from a constant value of the voltage. Starting from the operation described for a wave converter as shown in Fig. (7), the study of the behavior at different wave heights is done according to the tension of the accumulator spring.

The height of the wave, H, from crest to valley, in m, is indicated in the rows; the working height, H_{Tr}, in m; the energy transferred to the spring during the upward stroke, E, in J; and the absorbed power, P, in kW. Be part of a period of the wave, T, equal for all assumptions, of 10 s. For the density of sea water 1025kg/m^3 is taken. It is taken as equivalent dimensions of the base of the prismatic float (buoy) 1m x 3m.

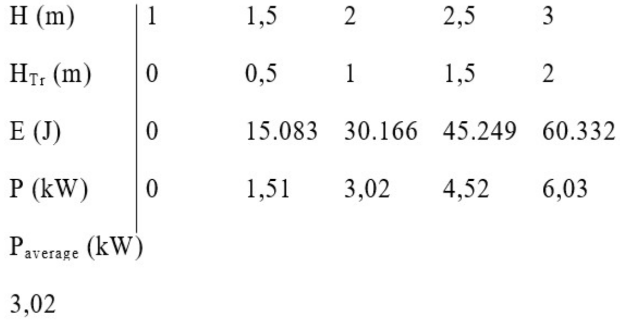
Table 1: Converter adjusted for wave height of 1m.



H (m)	1	1,5	2	2,5	3
H_{Tr} (m)	0,5	1	1,5	2	2,5
E (J)	7.541	15.083	22.624	30.166	37.707
P (kW)	0,75	1,51	2,26	3,02	3,77
$P_{average}$(kW)					
2,26					

Source: Authors.

Table 2: Converter adjusted for wave height of 2m



H (m)	1	1,5	2	2,5	3
H_{Tr} (m)	0	0,5	1	1,5	2
E (J)	0	15.083	30.166	45.249	60.332
P (kW)	0	1,51	3,02	4,52	6,03
$P_{average}$ (kW)					
3,02					

Source: Authors.

Table 3: Converter adjusted for wave height of 3m.

H (m)	1	1,5	2	2,5	3
HTr (m)	0	0	0,5	1	1,5
E (J)	0	0	22.624	45.249	67.873
P (kW)	0	0	2,26	4,52	6,79
$P_{average}$ (kW)					
2,71					

Source: Authors.

9. Analysis of Results.

Table 1 shows the results when adjusting the tension of the spring to make the most of the waves with the smallest amplitude, 1m. The energy use would be for waves of amplitude greater than half a meter. When the height of the incident wave increases, the energy transfer, and therefore the power, will increase. It would be an appropriate setting when the converter is mounted where the waves are most of the time of small amplitude

In table 2, adjustment of the spring for waves of 2 m, it is observed that with waves of 1 m or less the use of the waves is zero, given that the work race would be zero. On the contrary, the power with waves of 2m is maximized. From two meters of wave amplitude the converted power will increase.

In table 3, adjust to maximize energy transfer with waves of 3 m. The energy of the waves less than 1.5 m will not be used. In this case the use will be the maximum for waves of greater amplitude: higher performance and greater power. It must be borne in mind that in case of large waves it is in sea conditions of large storms. There are limits derived from the conditions of survival of the converters themselves that require the converter to be taken out of service, placing it in a safe condition. Something similar happens with wind generators located on shore or off shore.

n the last cell of the three tables the average value of the power is indicated assuming the same number of waves of each amplitude. If this is the condition, it is observed that the value to which the spring must adjust to maximize the power must be around the mean value of the height of the waves.

Conclusions

In a wave converter designed as a non-resonant point converter with floating buoy, with a design of the primary conversion stage with only mechanical elements, to maximize energy use it is advisable to respect the following golden rules:

- Minimize the weight of the float-mast set.
- Insert an accumulator spring acting as decoupler of the moment of inertia of the power train.
- Arrange an accumulator spring that exerts an antagonistic force to be overcome with a dip of the buoy equal to half the height of the wave.

The first two points to achieve a high acceleration in vertical upward displacement, and that the buoy moves following the profile of the wave. The third point has to do with the conditions of waves. Its antagonist force is a parameter that must be adjusted as sea conditions vary if you want to maximize performance. Its adjustment presents notable practical difficulties.

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