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Alves, M. A.; Costa, I. R.; Sarmento, A. J.; Chozas, Julia Fernandez

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Performance Evaluation of an Axysimmetric Floating OWC

M. A. Alves; I. R. Costa; A. J. Sarmento.
Wave Energy Centre
Lisbon, Portugal

J. F. Chozas
Spok ApS / Department Civil Engineering Aalborg University
Copenhagen / Aalborg, Denmark

ABSTRACT

The present paper reports a numerical study concerning a device for wave energy conversion which uses the relative vertical displacement between two bodies to absorb wave energy. Basically the device under analysis is a floating body with an internal oscillating water column (OWC), in which the wave energy is extracted through the relative displacement between the structure and the internal free surface. The paper presents in detail the methodology applied to define, from the hydrodynamic point of view, the device geometry. The numerical code used is a three-dimensional radiation-diffraction panel model based on the classic linear water wave theory and potential flow.

To proceed with the wave energy converter (WEC) evaluation the equations of motion (of each body), in the frequency domain, are expressed as functions of the complex amplitude of the displacements, which can be determined from the hydrodynamic coefficients (added mass and damping) and the complex amplitude of the excitation forces. From the relative stroke and the power take off (PTO) characterization the device mean power absorption is computed as well as the capture width. In the study it was assumed a turbine-generator for PTO equipment, as in a common fixed OWC system, being described through one term proportional to the relative velocity and another proportional to the relative displacement (which embody a spring effect related with the air compressibility). Both terms are controlled by the turbine characteristic. If the relative stroke is lower than a prescribed maximum, the (optimal) mechanical damping coefficient is computed from maximum power absorption. If larger, the mechanical damping coefficient is set to limit the stroke to the prescribed maximum value. To have a better understanding of the device power absorption level a dimensionless power absorption parameter is used (which relates the mean power absorption with the maximum attained with an axisymmetric heave motion buoy).

KEY WORDS: Wave energy; point absorber; oscillating water column; radiation; excitation force.

NOMENCLATURE

A =wave amplitude
a =diameter of the surface of flotation
D =hydrodynamic damping coefficient
DF =diffraction force
F =Force (excitation)
g =gravity acceleration
M =added mass coefficient
m =device mass
P =absorbed power
S =surface of flotation
k =wave number
ρ =water density
=angular frequency
=wave length
=heave complex amplitude

Subscripts

abs =absorbed
exc =excitation
max =maximum
pto =power take off
z =vertical direction
0 =resonance

Superscripts

$*$ =dimensionless
$-$ =mean value

INTRODUCTION

The performance of wave energy converters (WECs) is usually evaluated stochastically or through a frequency or time domain approach, as detailed in (Cândido and Justino, 2008). The stochastic and the frequency domain analysis allow a prompt evaluation of the device dynamics. However, for a more detailed analysis, in which, generally, the forces imposed by the PTO and the anchoring system are strongly non linear, a time domain approach is required. Nevertheless, it is commonly accepted that the frequency domain is suitable for the geometry optimization, as it allows a rapid understanding of the effect on the mean power absorption caused by a shape modification, as explored in (Ricci and Alves, 2006). Therefore, in order to optimize the shape of the OWC under evaluation, a frequency domain analysis was performed. Thus, a BEM numerical code was applied to compute the excitation force and the hydrodynamic coefficients (damping and added mass). The numerical code (WAMIT) is a three-dimensional radiation-diffraction panel model based on the classic linear water wave theory and potential flow.

The paper reports a numerical study to optimize the shape and evaluate the performance of a floating OWC in which the energy absorption is achieved through the relative vertical motion between two heave oscillating parts, namely, a structure (floater) and an internal free surface. The floater (red part of fig. 1) is optimized according to the methodology developed in (Ricci and Alves, 2006). Basically it is decomposed into two interconnected parts: one at the free surface and the second one submerged. The upper part is defined to get good radiation capabilities. Moreover, the submerged mass adds the needed inertia to tune the device in accordance with the predominant local sea state. Besides, it also contributes for the device vertical stability. Thus, the submerged mass should be located deep enough to avoid a disturbance of the optimized radiation capabilities of the upper part. The other device constituent is an internal OWC (green part of fig. 1) where the free surface provides, basically, a reference for the relative motion which allows the energy extraction. Similarly to the submerged mass, the OWC water entrance must also be located at a high depth in order to not affect the radiation of the upper part of the floater (see fig. 1). The relative vertical displacement between the internal free surface and the floater causes a pressure fluctuation inside an air chamber. As a result, there is an air flow moving back and forth through a turbine coupled to an electric generator.

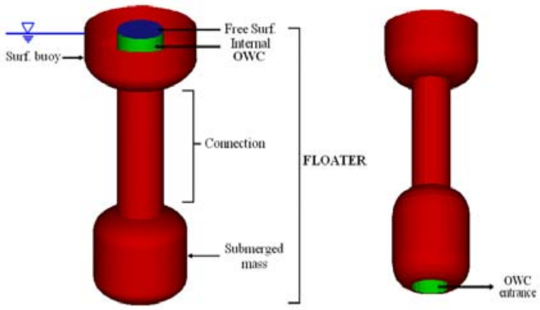

Fig. 1. Schematic representation of the wet surface of the floating OWC under analysis. Frontal view (left) and bottom view (right).

MESH OPTIMIZATION

For a suitable discretization the number of panels is obtained after a mesh convergence study, which consists in defining the lesser refined mesh for which no significant results variations have been verified. Fig. 2 presents schematically the wet surface discretization of the floating OWC. Two meshes have been considered: mesh A with 864 panels and mesh B with 1584 panels (www.wamit.com).

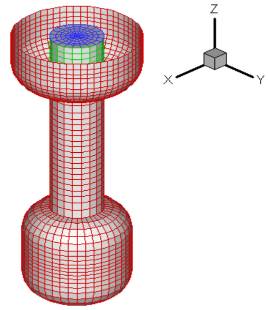

Fig. 2. Schematic representation of the device wet surface discretization.

Fig. 3 presents numerical results, from the BEM code, concerning the vertical complex amplitudes of the excitation forces acting on the structure and on the internal free surface (described by its piston oscillating mode). It is possible to verify the mesh convergence as there are no significant differences between the two meshes considered. Thus, the less refined mesh (mesh A), which represents a less computation effort and a reduction in the simulation time, were used in the remaining work.

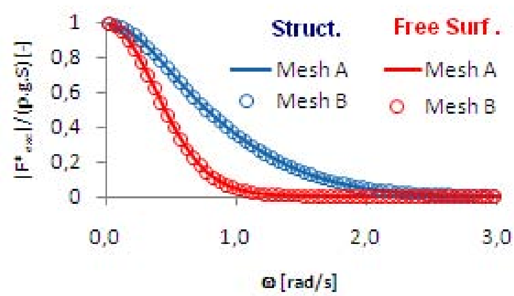

Fig. 3. Dimensionless modulus of the vertical complex amplitude of the excitation force acting on the structure and on the internal free surface.

SIMULATION RESULTS ANALISYS

Effect of the Shape of the Surface Buoy

In this section we analyse the effect of the shape of the surface buoy (see fig. 1) on the radiation capabilities and, consequently, on the energy absorption. The methodology followed consists in the evaluation of three different shapes with the same volume and water plane area. Thus, the remaining mass, necessary to tune the resonance in a common incident wave frequency, is approximately the same in all the three cases. It was assumed that the remaining mass is located at a very deep position to avoid its interference with the radiation capabilities of the surface buoy.

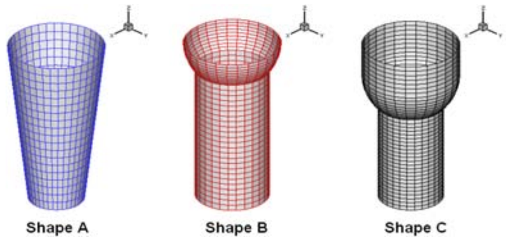

Fig. 4. Schematic representation of several surface buoy shapes.

According to the assumptions referred above, the device response was computed, namely the displacement amplitude and the dimensionless mean power absorbed (see fig. 5), considering a PTO connected to the ground and described through a term proportional to the velocity. It is well known (e.g. see (Falnes, 2002)) that, under harmonic motion, the absorbed mean power from a heaving wave energy converter is given by

$$\bar{P} = \frac{1}{2}\ {}^{2}D_{pto}\left|\ \right|^{2}, \tag{1}$$

where D_{pto} is the power take off damping and the heaving complex amplitude of the body, given by

$$\left|\ \right|^{2} = \frac{A^{2}\left|f_{exc}\right|^{2}}{\left[\ gS - {}^{2}(m+M)\right]^{2} + {}^{2}\left(D+D_{pto}\right)^{2}}. \tag{2}$$

From these two equations it is obvious that $gS - {}^{2}(m+M) = 0$ for maximum energy absorption. As the device is an heave axisymmetric oscillating system the maximum achievable power absorption is a known result (e.g. see (Falnes, 2002)) given by

$$\bar{P}_{\max} = \frac{A^{2}\left|f_{exc}\right|^{2}}{8D_{pto}}. \tag{3}$$

Therefore, from (1) and (3) it is possible to compute the dimensionless mean power absorption, given by

$$\bar{P}^{*} = \frac{\bar{P}}{\bar{P}_{\max}} = \left(\frac{A\left|f_{exc}\right|}{2\ D_{pto}\left|\ \right|}\right)^{2}. \tag{4}$$

Fig. 5 shows the displacement amplitude and the dimensionless mean power as a function of the dimensionless wave number, *ak*. In case of displacement amplitude lower than a prescribed maximum, which was assumed 3 m, the (optimal) mechanical damping coefficient was computed from maximum power absorption. In the opposite case, the mechanical damping coefficient was set to limit the stroke to the prescribed maximum value (see figure 5 -above).

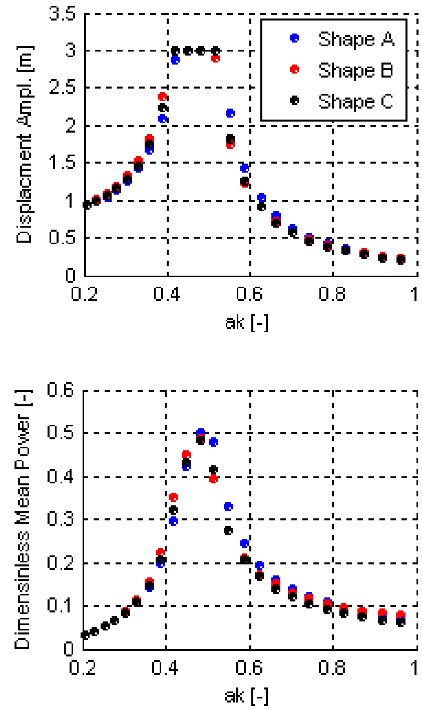

Fig. 5. Displacement amplitude (above) and dimensionless mean power absorbed (below) for the 3 different surface buoys analysed.

It is possible to verify, through the previous figure, that there are no significant differences between the 3 cases evaluated. This result indicates that, in a heave motion device, the shape of the surface buoy is a minor important parameter if its volume and water plane area are kept. On the other hand the volume of the surface buoy should be as small as possible to improve the radiation capabilities and consequently the power absorption. To confirm this effect on the energy absorption, we considered surface buoys with the same floating area (a=9) and different shapes (A, B, C, D and E) reducing progressively its volume as indicate in fig. 6.

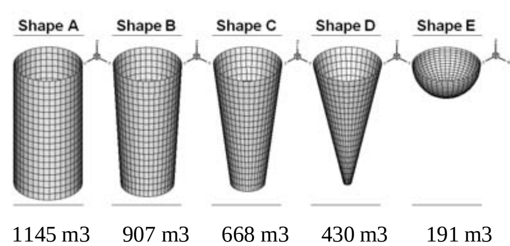

Fig. 6. Illustration of the progressive surface buoy volume reduction performed.

For each shape considered it is important to note, as referred above, that the remaining mass necessary to tune the resonance at the same frequency should be added back to the system sufficiently deep in the water to not affect the radiated wave from the surface buoy. Otherwise the resonance frequency, given by

$${}_{0} = \sqrt{\frac{gS}{m+M}}, \tag{5}$$

will increase if the surface buoy volume is reduced keeping the same floating surface S (which should not be reduced as it is a first order factor affecting the radiation capabilities of the body). Following we obtained the power absorption increment, presented in fig. 7 (below), assuming the same maximum vertical displacement amplitude for each shape, as shown in figure 8 (above).

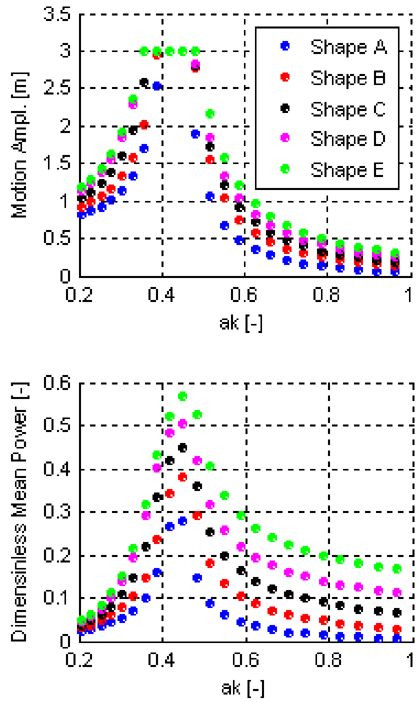

Fig. 7. Displacement amplitude (above) and dimensionless mean power absorbed (below) for a progressively surface buoy volume reduction.

Fig. 7 (below) indicates that it seems to be possible to reach nearly 60% of the theoretical maximum energy absorption with a relatively small device, in which the surface buoy has 9 m diameter and volume of 191 m3, for maximum displacement amplitude of 3 m. From the absorption point of view it seems that, if the floating surface S is kept, the surface buoy shape is a quite unimportant parameter and its volume should be as narrow as possible. However, to avoid non-linear effects due to slimming it is convenient to keep the same water plane area during the vertical displacements. For this reason we believe that the surface buoy should be composed by a cylinder with length approximately equal to the maximum allowable displacement (to keep constant the hydrodynamic coefficient) and perhaps a hemispherical base to minimize or avoid flow separations.

Floater Geometry Definition

In the previous section the geometry of the surface buoy was defined. Although it was assumed that the floating total inertia (m+M) was splited into two bodies, one at the surface (the surface buoy, with its submerged base sufficiently close to the free surface to have good radiation capabilities) and the other one, the submerged mass, sufficiently deep to not affect the radiated wave from the surface buoy. However, from constructive reasons it won't be possible to place the submerged mass very deep in the water and, consequently, a disturbance on the radiated wave from the surface buoy will come up. On the other hand both components, the surface buoy and the submerged mass, require a rigid connection which will reduce the radiation capabilities of the surface buoy too. Taking into account these constraints, it was evaluated a floater with 35 m length and diameter of the surface buoy and the connection of 10 and 4 m, respectively (shape A of fig. 8). To perform a comparison it was also evaluate the hypothetic situation (shape B of fig. 8) in which no disturbance on the radiated wave from the surface buoy, due to the connection and the submerged mass, occurs. In this case the whole inertia of the connection and the submerged mass is hypothetically added back to the system very deep in the water as it was explained above.

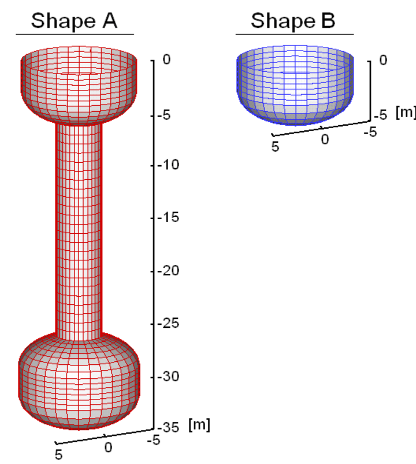

Fig. 8. Floater composed by surface buoy, submerged mass and connection between both components (shape A) and isolated surface buoy (shape B).

Fig. 9 (below) shows the power absorption attained in both cases, the entire floater and the surface buoy with the remaining mass added back deep in the water, keeping the same maximum heave motion amplitude (fig. 9 -above). It is possible to verify that the connection and the submerged mass induce a maximum absorption reduction of nearly 10% as the interference with the radiated wave from the surface buoy is not completed avoided. However, this value could be reduced in case of a higher depth of the submerged mass and a narrow connection between surface buoy and submerged mass.

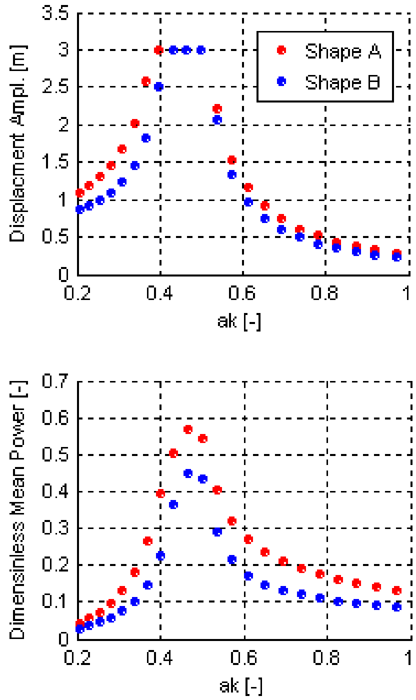

Fig. 9. Displacement amplitude (above) and dimensionless mean power absorbed (below) of the entire floater -surface buoy, submerged mass and connection- (shape A) and the isolated surface buoy (shape B).

It is important to note that the submerged mass might allow a reduction of the total device cost. From one side, as it is located in a deep position, it won't be loaded with high dynamic efforts, which means that the manufactured material could be cheaper. On the other side, to provide the total inertia, essential to tune the device in accordance with the predominant incident wave frequency, the shape of the submerged mass may allow a high hydrodynamic added mass and, consequently, a volume reduction (short and wide cylinders have high added mass coefficient associated and the opposite occurs for long and narrow cylinders). To define the most convenient shape of the submerged mass, additional experimental and/or non-linear numerical analysis should be done to identify how high the added mass coefficient can be taking into account the minimization of non-linear effects as vorticity.

Entire Device Geometry

To evaluate the power absorption we have been assuming a PTO connected to the ground. However, for practical reasons this could present several technical issues as this technology tend to be for an offshore application. On the other hand the idea behind the present concept was a floating WEC as compact as possible, which we believe that it has high advantages from the installation, maintenance and survivability point of view. Following we attempted to place an internal OWC that enables the energy absorption (see fig. 1). The energy extraction is achieved through the relative displacement between both bodies, being the PTO system an open field currently. However, we assume that it will be probably an air turbine as in a typical OWC device.

To evaluate the hydrodynamic effect of the internal OWC, the entire device (floater and OWC) is compared with the optimized floater with improved radiation capabilities (see fig. 11).

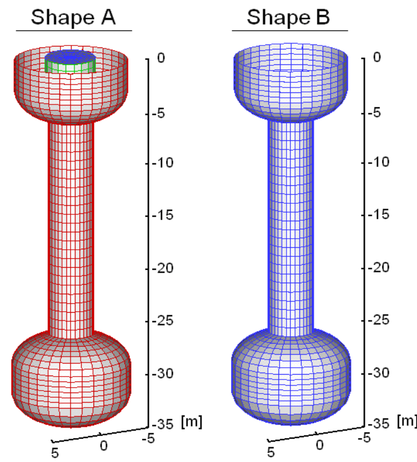

Fig. 10. Entire device -floater and OWC- (shape A) and the isolated floater (shape B).

Fig. 11 shows that the OWC does not disturb the improved radiation capabilities of the floater and, consequently, it allows the same absorption level of the isolated floater (connected to the ground). Indeed, it is possible to verify that there are a slightly power absorption increment visible for ak<0.4. Next figures try to explain the device dynamics.

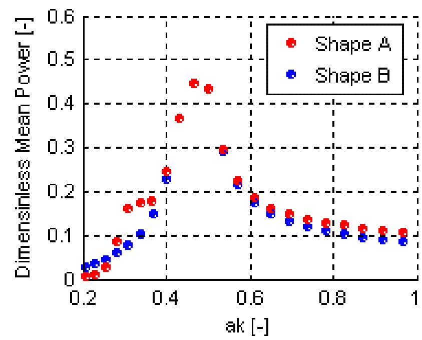

Fig. 11. Dimensionless mean power absorption by the entire device - floater and OWC - (shape A) and by the isolated floater -surface buoy, connection and submerged mass - connected to the ground (shape B).

Fig. 12 shows the displacement amplitude of each body (floater and OWC) and the respective phase shift with the incident wave elevation. It is possible to see two peaks on the floater motion (see fig. 12-above). The first one, at the higher frequency, corresponds to the floater resonance. The other one, at the lower frequency, is due to the motion of both bodies, approximately, in phase and nearly with the same amplitude. Thus, the device responds as a body with higher inertia and, consequently, its resonance will be at a higher period (lower frequency). This effect is the responsible for the slightly power absorption increment for ak<0.4, as shown in fig. 12.

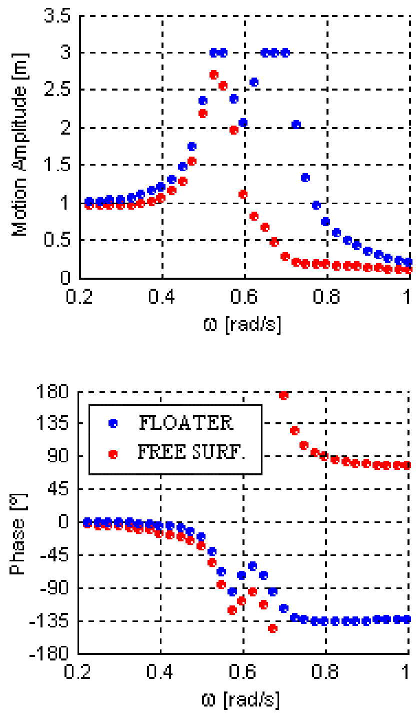

Fig. 12. Displacement amplitude of the floater and the OWC (above) and respective phase angle -with the incident wave elevation- (below) for restricted amplitude of motions below 3 m.

For practical reasons the device evaluation has been done imposing the relative motion amplitude, as well as the heave amplitude of the floater and the internal free surface, below 3 m. It is important to note that the control of the PTO mechanical damping seems to be enough to limit the relative heave amplitude and the vertical displacement of the floater and the OWC. Therefore, no external damping will be necessary to restrict the floater motion and so, a reduction in the power absorption is avoided. Fig. 13 presents the relative heave amplitude and the mechanical damping for maximum energy absorption, considering the referred motion restrictions. It is possible to verify that the energy absorption is maximized with a high mechanical damping and low relative heave amplitude if <0.6 and also that the opposite occurs for >0.6. This mechanical damping behaviour might typify an implementation problem as there are quite significant variations around its mean value.

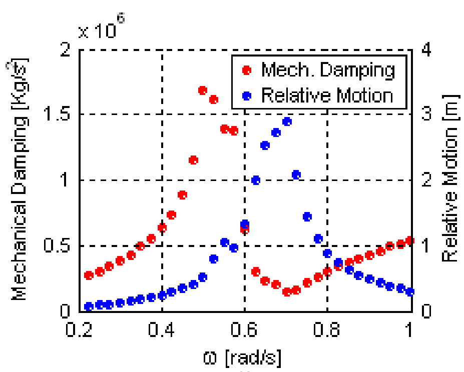

Fig. 13. Mechanical damping coefficient and relative displacement amplitude for maximum power absorption as legend of figure 13.

Fig. 14 presents the mean absorbed power and the capture width (which is a measure of the device efficiency) according to the mechanical damping and the relative heave motion presented in fig. 13. It is possible to confirm the second (lowest) absorption peak, at approximately =0.55, because the device is responding as a higher inertia body, as it was detailed before.

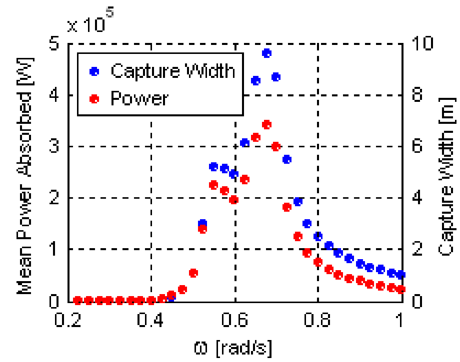

Fig. 14. Power absorption and capture width in case of motions amplitudes (individual and relative) restricted below 3 m.

CONCLUSIONS

The main conclusion of this work is that it is possible to optimize the energy absorption of an axisymmetric heave motion device, if we decompose it in two parts, a surface buoy with good radiation capabilities and a submerged mass (rigid connected with the surface buoy) with the remaining inertia (mass and added mass) to tune the device resonance on the desired frequency. The submerged mass must be immersed sufficiently deep to avoid a significant interference with the surface buoy hydrodynamics. Throughout this method it is possible to decouple the radiation problem from the device resonance (or inertia) issues, obtaining a shape with good radiation capabilities and consequently a good absorption capacity too. There are additional advantages allied to the submerged mass. From one side, it may reduce the total device cost as it won't be loaded with high dynamic efforts and consequently it could be manufactured with cheap materials. On the other hand, it may increase the gravity centre depth and consequently minimize the pendular oscillations of the device, contributing for its vertical stability.

The device proposed uses the relative motion between the floater (surface buoy, submerged mass and connection between both) and an internal OWC to absorb wave energy. Through the described arrangement seems to be possible to optimize the wave energy absorption of an axissymmetric heaving buoy (with improved radiation capabilities) which reacts against an OWC, instead of using the sea bed as a reference for energy extraction.

As a future work a numerical model of the entire energy conversion chain, already developed, will be applied in order to fully evaluate the device performance. This wave-to-wire model, based on linear hydrodynamics, allows to perform a time-domain analysis of a floating *OWC* equipped with a non-linear air-turbine, including also the non-linear effect of the anchoring system. Therefore, for a specified control strategy and sea climate, it is possible to assess the motions of the six degrees of freedom (rigid modes), the air pressure inside the chamber, the flow across the turbine, its rotational speed and the generator torque. Additionally, studies on the electrical power output quality and power smoothing parameters to meet *IEC* grid codes will be also performed.

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