Mapping review on recurrent modeling techniques applied to Ocean Wave Energy Point Absorbers in the Canary Islands

Lorenzo Banos Hernandez, Alexis Lozano Medina

Abstract—**Point Absorbers are found in principle nearly everywhere in engineering science. They can therefore be considered relevant ocean wave energy identities. While clearly lacking industrial maturity and a current focus by means of determining prevailing efficient operating principles, latter field encompasses significantly increasing studies ever since the oil crisis. Emerging renewable concepts such as the upper one will play a major role in the energy mix as compared to offshore wind. Main advantages are its short-term predictability and higher energy density. This paper proposes point absorbers as relatively adaptive, flexible, low cost, combinable, performant, resonant, robust and simple systems with respect to other remarkably more complex and less efficient concepts. Carried out in plurality, patterns develop into interactions, which enable the escalation of the technology. From the mathematical to the physical model relating input waves towards electricity generation, hydrodynamics stand as intermediate medium, evolving into efficient & precise description of the fluid-structure interaction given. Hereby, the search for an ideal resonator is beneficial in order to find suitable geometries and operating principles for the floats. Software tools, gathered during the research, can find a broad application in fluid behavioral representation, such as Boundary element methods, Computational fluid dynamics and Smooth Particle Hydrodynamics, for instance. Point absorber research is employing key-modelling techniques, such as advanced algorithms, as well as high-performing computer scientific techniques, outlined in this study. This produces a remarkable result: Point absorbers are a more condensed and empowering technology than Line absorbers (about nearly 4 times the power per weight). Although the efficiency, addressed as capture width, is restricted as compared to Line absorber devices. Point absorbers reveal themselves as feasible enough to be installed instead due to its Levelized Cost of Energy. While resonance is determinant, it is de facto easier to tune the float to real waves, the smaller and simpler the geometry is. Examples reflect here, that it is a highly adaptive, e.g. combining Power-Take-Off mechanisms, or fitting alone its relative position, both in depth & on surface. For the heave mode, one can conclude that PA technology is by far the most promiscuous and researched Ocean wave energy subject in the recent past (2011-2018). Furthermore, it is also the most underrated sector with respect to the volume of commercially deployed units. Finally, hybrid combinations of electrical, hydraulic and mechanic equipment, and control strategies on its top are determining assets for the right integration on the marine environment. Far from promising, it is for certain that the technology will become real and valuable soon enough, even though restricted to coastal areas near & offshore from insular applications, such as the Canary Islands (Spain). Multidisciplinary concepts, fundamental for marine devices towards desalination, electricity generation and storage, artificial space generation, structural protection, transport, reinforcement of the ecosystem and concentration of flora and fauna around are added values to succeed.**

Keywords —**hydrodynamics, point absorber, buoy, wave energy converter**

ref: 52/1681/DV/87T; id:#1841. "This work was supported in part by the DESAL+ project under the INTERREG scope"

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TABLE I
EXAMPLE VARIABLES AND UNITS FOR MARINE RENEWABLE ENERGY

Symbol	Quantity	Unit
A_c	Cross-sectional area	1 m^2
$A_{r,\infty}$	Added mass at infinity	1 kg
C	Structural damping	1 kg/s
C_r	Radiation damping	1 kg/s
$c_w(c_{w,r})$	capture width (ratio)	- (1/m)
$d_{\o}$	floater diameter	1 m
$\Delta\delta$	resonance bandwidth	1 Hz
g	gravitational constant	9.81 m/s^2
J	wave-power flux	1 m/s
K	Structural stiffness	1 kg/s^2
l	buoy´s vertical length	1 m
λ	wave length	1 m
M	floater mass	1 t = 1000 kg
η	surface elevation	1 m
ω (ω_0)	wave frequency (natural resonant)	1 Hz
P_a	Absorbed Power	1 MW = 1000 kW

Vertical lines in tables are deprecated. Statements that serve as captions for the entire table do not need footnote letters.
[a] The Admiralty measured mile and Admiralty knot should not be used to avoid confusion.

I. INTRODUCTION

BOTH an appearent fossile fuel reserves decrease, as well as increasing population needs (growing population and augmenting electricity demand) let Ocean Wave Energy (OWE) arise as a potential asset in the renewable energy mix. Paradoxically, In the industrial revolution 4.0, stepping into renewables seems no drawback, but rather an effort. Offshore Wind (OW) and Solar energy, though location restricted, are a multidisciplinary alternative to support the electricity loads induced through latter scenarios. After a long incubation period starting from the oil crisis, OWE is emerging as well. Its arguments are a relatively high

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energy-density as compared to the rest of renewables, and its short-term predictability [1]. Since this renewable form of energy includes a broad range of operating types and principles, Point absorbers (PA) have been picked up for detailed analysis within the given scope of installed projects in the Canary Islands in Southern Spain, east of the African continent. Hereby, any kind of floating structure with a characteristic length relatively small as compared to the wave length, such as buoy, a submerged floater, or an offshore platform as a multi-point absorber, is considered by. This research outlines specifically for this concept certain matters being discussed recently. For this, it´s determinant to search through the databases in order to gather concrete details on patents, publications and real projects conducted. Assuming basically the latest industrial interval period of 2011-2018 for academic reasons, focus has been to quantify number of identities, such as theoretical optimum boundaries for geometries and modeling experience, while relating them to relevant projects deployed in the archipelago. Moreover, comparison to other concepts such as Attenuators or Line absorbers (LA) [2], [3] are being shown, and data analysis of recent Power-Take Off techniques gathered.

A. Canaries: a summary of projects during 2011-2018

In the past decade, several general reviews carried out by [4] and [5] have made assessments about the viability of marine energies in the archipelago. Thereby, perspective up to the 2050 horizon estimates about 62 MW installed marine energy capacity at 9-14 cents Euro per kWh. Considering 8 official islands, studies to 5 islands are at least known up to date. These publications adress the potential in the islands of El Hierro [6] Tenerife [7] Gran Canaria [8], Fuerteventura [9] and Lanzarote [10] . Acc. to [1], wave power values range typically between 20-30 kW/m Focusing on the capital islands in the core of the environment, both Gran Canaria [11] and Tenerife reveal similar conditions: long Atlantic fetch from North and NNE mainly, with the capability to absorb in average over 20 kW/m. Specifically, sites located in the northern area could be fairly suited for wave energy extraction, as stated separately by [12] and [6]. In Tenerife e.g., a mean wave-power of 23.86 kW/m is found, with annual average values of 209.01 $MWhm^{-1}$, sea states corresponding to energy periods of 10-14s and significant wave heights of about 1.5-3 m. Gran Canaria, on the other hand, presents 15 kW/m on average in the northern area, with energy periods of 6-7s and significant wave heights of aprox. 1.72-1.82 m. At a specific energetic site located in the northeast, an AquaBuoy device of the PA type could provide maximal 27 kW on average.

In terms of deployed renewable units in the Canary islands, a number of installations have been carried out in the past decade, as it can be seen on the next Fig. (1):

The upper table lists since 2011 relevant deployments up to date in the archipelago. It starts with the testing of two two-body PA types from Pipo Systems S.L. Pipo Systems and Wedge Global´s Undigen Wedge. During

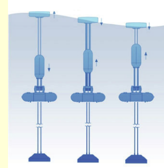
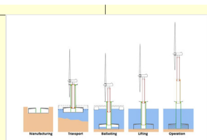
	Project	Model Deployment site	Tech Specs	IMG/sketch
2011	Pipo	APC-PiSys PLOCAN (Gran Canaria)		
2012	Wedge	Undigen PLOCAN (Gran Canaria)	-switched reluctance -P: 150 Kw -Lin. Generator -Resonant	
	Gorona	El Hierro	-Hydroelectric: 4 turbines, P: 11.3 MW -Wind: 5 turbines, P:11.5 MW	
2015	Wello	Penguin PLOCAN (Gran Canaria)	-M: 220 t -P: 600 KW (nominal) -W: 16 x 16 (m x m) 	
2018	Gamesa	ELISA PLOCAN (Gran Canaria)	-30m depth -PTTF -P: 5 MW -WTG -d: 132 m	

Fig. 1. Renewable projects in the Canaries during 2011-2018.

2012 , the hybrid project "Gorona del Viento" in El Hierro is set on to operation, combining wind and hydropower. Rated with over 20 MW, it presents 5 wind turbines and 4 turbomachinery modules with nearly equal power generative capability approx. halving the total rated. In terms of wave energy, during 2016, the platform PLOCAN for marine testing purposes is installed north east of Gran Canaria, offering 23 km^2 of test site area, and 4-8 kW/m available incident wave-power. This in turn, allows the testing of a pendulum type of PA called Wello Penguin Wello, a 600 kW rated unit with a dry mass of 120 t. At the end of the studied period, it is worth to mention the ELISA deployment, a bottom-mounted offshore wind turbine, uniquely characterized by a rotor of 132 m and a lifting hydraulic machinery. In total, the 3 OWE-PA projects mentioned constitute officially the Canaries core on ocean wave energy since then. In order to understand further key aspects about this WEC type, some characteristic relations and equations are introduced next.

II. FUNDAMENTAL ASPECTS ABOUT THE HEAVING MOTION OF POINT ABSORBERS

Focusing on the introduced LA and PA concepts, relationships between them appear for the efficiency (absorption or capture width c_w):

$$c_{w,LA} \propto \lambda/(2\pi) \quad \text{and} \quad c_{w,PA} \propto \lambda/(\pi) \tag{1}$$

This means, PA are not able reach the energy absorption capability of LA [3], [13]. However, and due to the next equations, details on boundaries and limits are obtained for a generic axisymmetric buoy in heave [14], [15].

A first relationship i.e. establishes a link between the frequency and both the geometrical diameter $d_ø$ and l , which is the characteristic vertical length, namely

$$T_{0,3} = 2\pi\sqrt{\frac{l + d_ø/3}{g}} \tag{2}$$

Eq. (2) reveals acc. to Falnes specific geometrical conditions for the natural resonance of the device, ending up in maximum energy absorption as long as the radiation damping equals the structural damping of the PA. Moreover, with regard to the form and size of the device, the slenderness relates to $l/r_ø = 2.5$ for a hemispherical bottom hull with a concave shape. Latter one is optimally enhanced for PA acc. to [16] . Further assumptions for dimensioning the floater diameter are given through the inequality $(5\%)\lambda_I \leq d_ø \leq (10\%)\lambda_I$, where λ_I denotes the prevailing incident wavelength [17].

Additionally, the buoyancy must be considered and respected on the Archimedes principle premise. Here, it is primary to lower the centre of mass (coG), while increasing both the center of buoyancy coB and the cross-sectional area A_c in order to max. the body´s absorptive capacity [18].

Further general keys, while concieving a point absorber are to find the

- optimum resonance frequency
- widest resonance bandwidth
- max. displacement amplitude or RAO

From this it becomes clear, how it is the role of the wave frequency for the solution of the hydrodynamic problem. Structurally, resonance is achieved for $\omega_0 = 2\pi\sqrt{\frac{K}{m+A_{r,\infty}}}$ [19] with $A_{r,\infty}$ as a function of the buoy´s diameter in heave [20]. Thereby, it is [21] again, the one stressing the resonance bandwidth for given upper-lower frequency range ($\Delta\omega$) as

$$\Delta\delta = \frac{\Delta\omega}{\omega_0} = \frac{C_r}{\sqrt{K(m + A_{r,\infty})}} \tag{3}$$

where C_r stands for radiation damping. Finally, current tendency after [22] is to compute the so-called $c_{w,r}$ ratio as $c_{w,r} = c_{w,max}/d_ø \geq 3$, which is dependant on the max. absorption width $c_{w,max}$ [23],

All of this has to be considered, when making usage of the next introduced software packages available for hydrodynamic modeling.

III. Hydrodynamic modeling: Software distributions

In a similar fashion to other technological fields, applications and software packages enable the computational approach for calculating diverse eigenvalues of the WEC system. With regard to hydrodynamics, present work summarizes what has been made usage of in the sector in off-/near- and onshore conditions with regard to the PA allocation. Neglecting thereby coastal and ocean modeling tools, goal remains to point out the water wave mechanics apps for the fluid-structure interaction problem (FSI). As it can be checked on the following Fig. (2), the classical PA geometry (r)evolution is abstracted as front sectional sketch with a self-contained double entendre:

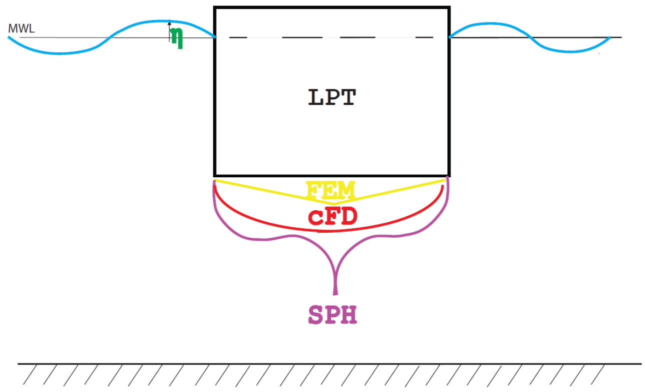


Fig. 2. Front sectional view of the OWE-PA´s geometrical hull evolution.

Fig. (2) depicts a sectional view of a generic PA, which contains the floater geometry on the one hand, and numerical methodologies and hydrodynamic codes applied on the other. From top to bottom, for an axisymmetric float in heave mode, the reader is first addressed to Airy theory (also known as Linear Potential or Potential flow theory LPT). Boxed within the squared bottom buoy shape, it reveals itself key to modeling linear water waves oscillation through Boundary Integral Element Method B(I)EM application. In order to be able to calculate the hydrodynamic coefficients exciting the buoy's reactive displacement efficiently [24], [25], WAMIT is key. It is being used in 80.5% of WEC modeling publications as compared to the rest, where ANSYS AQWA predominates acc. To [26], [27]. Yet, a number of tools have arisen, which have proved to provide sufficiently accurate solutions on either open-source, academical or commercial base. These are i.e NEMOH [28], and SHIPBEM (AAU) on the frequency domain, while ACHIL3D (ECN) solves time domain issues. In summary, it is ACHIL3D, which employs 100% OWE-PA samples, while 62.5% of NEMOH applied publications refer to the same field. Furthermore, it is Alves, M. [18], who explains further characteristics of codes available for solving PFT through panel method modeling of the floater outer shell. Worth to note at this stage are e.g. WaveDyn, InWave, LAMSWEC, WEC Sim (Matlab/Simulink) and OPENWEC (discontinued acc. To GitHub), as well. Additionally on the sketch, [29]Vantorre arguees, that the cone cylinder shape is optimally suited for wave power extraction and slamming reduction. Within this assumption of a hull tip, one finds another numerical procedure to model the floating body, namely the Finite Element Method (FEM), applied in Structural Dynamics [30] . Latter one is applied via COMSOL [31] and FreeFEM [32] Recently, a number of publications has presented another innovative hull shape, commonly denominated as "Berkeley Wedge" [16]

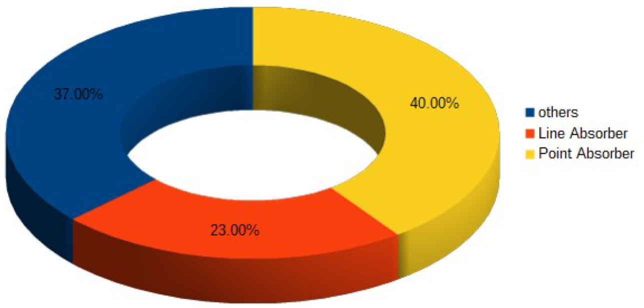


Fig. 3. OWE worldwide distribution in 2014.

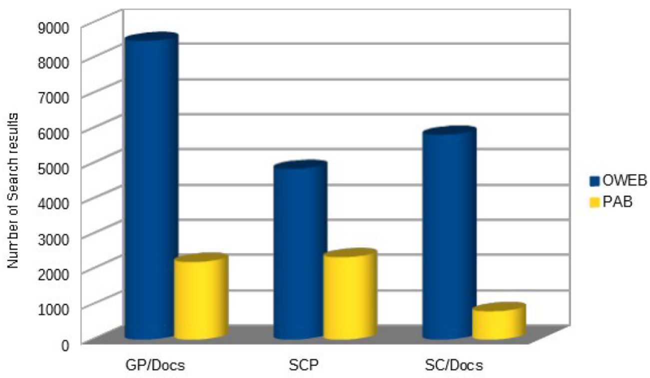


Fig. 4. OWE Buoy (OWEB) patent search.

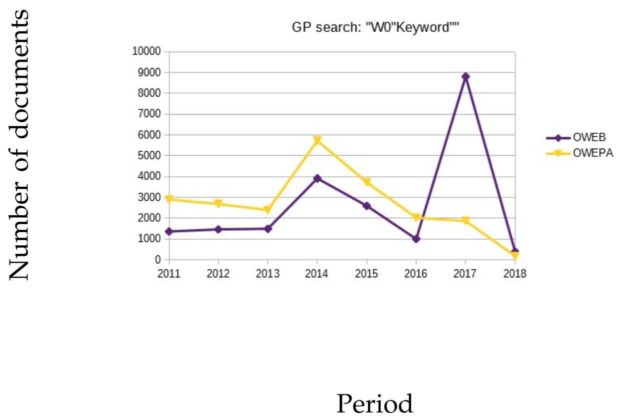


Fig. 5. Number of OWE-Buoy (OWEB) and OWE-PA documents found.

Presenting a concave "pen tip" alike form, it is a more complex and expensive geometry to model, though [33] assures it has even greater capturing width capabilities. This geometrical space on the sketch embraces Computational Fluid Dynamics (CFD), which is the current rationale in fluid modeling. Main complexity thereby is the inclusion of non-linear effects such as viscosity in the solution of the Navier-Stokes equations [34]. Here, the number of available packages grows considerably. Note therefore the open.source OpenFoam (incl. waves2foam and IHfoam modules), while commercial Fluent, LS Dyna and Star CCM acknowledge experience from other sectors such as the automotive. Additionally, Icare (ECN),Reef3D,Marin and SU2 have also presented modeling results to floating body dynamics. Nevertheless, there is also a nose on the sketch pointing at the buoy tip, where Smooth Particle hydrodynamics (SPH) are highlighted. More complex and expensive by means of computational payload, it has been adopted recently in WEC simulations, providing insights about [35].

On this sample programs base, a number of key searches has taken place during the study, and leads the ensuing results.

IV. Results

The research course positions the reader nearly on half of the interval studied, 2014, where there is evidence suggesting a possible ratio of installed device types [36]. This is showed in the ensuing Fig. (3)

From the upper colored ring in Fig. (3), one can infer a major insertion of Point Absorber concepts into motion, as compared to the others and doubling LA, with 23% participation. It is noted, that the tag "others" simply refers to other device types, such as terminators of any kind, for example Oscillating Water Columns or Surge converters.

However, project report results [37] are not sufficient information to outline a specific source, so therefore, a more detailed research on patents and publications is introduced next:

With focus on PA improvements following details pop up:

- two-body PA double at least the efficiency capability of single PA [38], [39]
- simulations show as a function of different incident sea-states, that a butterfly or star like shape seen from a top view seems to outperforming terms of capture width [16]
- not just concave forms perform better, but is the cone-cylinder provided with angles between 60%-80% which reflects better overall performance in terms of absorption, slamming avoidance, and viscous damping [20], [40].

Moreover, if one looks at the publications on Power-Take Off (PTO) mechanisms, in charge of enabling electricity generation out of any kind of system type, it is a matter of fact, that this is key for the technology to succeed. Latest review on OWE-PA [38] emphasizes the percentages of developed mechanisms on the next graph:

Fig. (6) depicts a major participation of mechanical developments with nearly a 61.54% lately. It is also noted, that there is a significant level of electromagnetic concepts, despite its higher investment costs and weight. Purely hydraulic sources, as well as mixed concepts involving combinations of latter mechanisms end up in due draw. For specific details on PTO details, the reader is adressed to [41]. Also it is worth to mention systems with additional oscillation systems inside the floating body (Dual Mass-Spring-Damper MSD [42]. Besides, there is another option available from the dynamic point of view, which is the definition

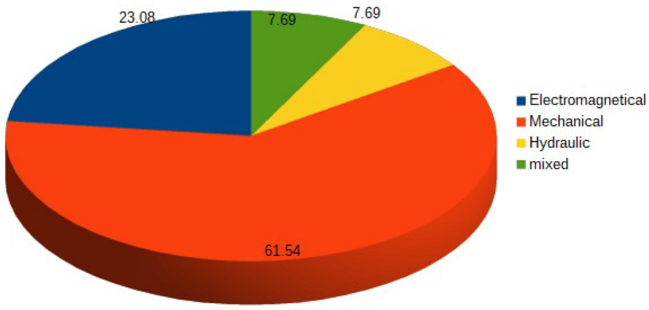


Fig. 6. PTO project distribution.

and simulation of so called bistable PA mechanisms. These consist of additional MSD within the PTO system, which allow to cover a wider frequency range, while in theory capable of absorbing more energy. Agreeing to Fig. (1), and noting many projects are still being "incubated", the reader is adressed to [43]

Still, question from the abstract remains how to improve the levelized cost of energy (LCOE). For this, there are recent references, which approach the matter with certain experience degree and consistency [44]–[47].

V. Conclusion

The following conclusions can be drawn from the current research:

- OW vs OWE-PA lacks maturity and a convergence by means of characteristic sizing towards estimated power output
- PA is currently experiencing a "revival" by means of increasing patents, and research publications, as presented in Figures
- OWE-PA technology is the most promising and efficient one by means of wave power conversion per volume unit [48] . Furthermore, it is specially suited for low energy density locations).
- The given document and patent search reveals a considerable correlation between both Google and Scopus, granting the study a certain credibility, and enabling possible newer search key methodologies.
- Regarding the many projects tested within the Canaries, perspective shows, it is worth to investigate about the viability of certification roles in the marine sector locally [49], [50]

Acknowledgement

This research has been co-funded by ERDF funds, INTERREG MAC 2014-2020 programme, within the DESAL+ project (MAC/1.1a/094). No funding sources had any influence on study design, collection, analysis, or interpretation of data, manuscript preparation, or the decision to submit for publication.

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