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Non-linear modelling of a heaving point absorber: the surge effect

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Abstract

1 This paper presents a numerical model that simulates the behaviour of an
2 offshore point absorber wave energy converter (WEC). The model receives
3 1st order irregular waves as input and delivers instantaneous displacements,
4 velocities and power as output. The model outputs are strongly non-linear
5 due to the nature of some parts of the device, such as the power take off
6 system (PTO), the mooring wires and the drag forces exerted on the wet
7 bodies.

8 Two different devices are modelled, a two-body device consisting in a
9 floating buoy attached to a linear generator placed at the sea bed and a
10 three-body device, which also includes a submerged sphere located halfway
11 from the float and the generator. For each device, the model takes into
12 account either the heave mode only or the heave and surge modes combined.

13 The devices have been tuned to the Mediterranean wave climate, taking
14 particular attention to the floater dimensions and to the geometrical design
15 of the PTO, which has been redesigned to adapt to the newly introduced
16 surge conditions.

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17 For the two-body device, although the dynamic behaviour changes when
18 the surge is included, no relevant differences are observed regarding the power
19 production. When studying the three-body device, results show two clear
20 trends. For high waves, the surge leads to a decrease in the production,
21 whereas for smaller waves it affects positively the power absorption. Overall,
22 the negative contribution is more relevant but also less frequent, leading to
23 no substantial change in the power production.

24 Including the surge mode in the model does not give significant varia-
25 tions in production rates and therefore, may be neglected only for energy
26 production assessment. However, it should always be taken into account at
27 the design stage.

Keywords: Wave Energy, Surge Effect, Non-linear Numerical Modelling,
Mediterranean Sea, Wave Power Production, Point Absorber, Linear
Generator

28 1. Introduction

29 Energy from the oceans is getting closer to become a reality in the renew-
30 able energy scenarios and not only where the energy resource is abundant
31 (offshore the Atlantic coasts). New concepts keep appearing [1, 2] and at
32 the same time some other WECs have reached the pre-commercial stages [3]
33 showing that the research carried in this field is very broad, diverse and still
34 open.

35 In the past decade a lot of effort has been put into device development
36 and the research on the estimation of the wave energy potential has also
37 grown, giving a more detailed picture of resource availability. Several studies
38 have been published assessing wave energy along the oceans' coasts [4, 5] and
39 more recently in milder seas [6], such as the Mediterranean and Black Sea
40 [7–11].

41 Nowadays, a number of full-scale wave energy devices have been deployed
42 in real seas and several others are at the end of their development phase
43 [12, 13]. Most of them have been installed in moderate to high latitudes
44 off the western coasts of Europe and America. Wave energy exploitation in
45 less energetic climates can be achieved in several ways: by scaling existing
46 WECs [14], by properly designing the power take off, as discussed in [15]
47 or by specifically designing a novel device, as proposed in this paper. Cur-
48 rently, only very few attempts have been made to exploit wave energy in

49 the Mediterranean Sea. A scaled prototype of an OWC has been installed
50 in Reggio Calabria a few years ago and recently it has been announced that
51 a prototype of an oscillating body is going to be deployed in the Tyrrhenian
52 Sea [16].

53 In the Mediterranean basin, estimations based on both, wave measure-
54 ments and wave hind-casts, showed that the mean annual wave power ranges
55 between 4 and 12 kW/m. The highest values occur in the south-western
56 Aegean Sea, which is characterized by a relatively long fetch and strong
57 winds. In Italy, two main wave climates can be identified: high waves com-
58 ing mostly from the II and III quadrants on the western coast and smaller
59 waves mainly coming from the north in the eastern coast. As a result, the
60 annual average wave power is around 2 kW/m off the Adriatic coast and be-
61 tween 3 and 5 kW/m off the Tyrrhenian coast. The most energetic sites were
62 identified in small offshore islands and in specific locations of Sicily and Sar-
63 dinia, where the mean wave power reaches 10 kW/m [9, 14, 17, 18]. Moreover,
64 wave data analysis has shown that the wave climate in the Mediterranean
65 Sea is characterized by high waves and high persistence of storms, but not
66 by long-wave conditions.

67 A WEC specifically designed for the Tyrrhenian Sea should have the
68 best performance for relatively short wave periods [18]. Some point ab-
69 sorber WECs with linear generators are currently being studied and devel-
70 oped in Europe and North America. Two promising technologies that already
71 reached an advanced development stage are the Archimedes Wave Swing de-
72 vice, developed by the company AWS Ocean Energy (www.awsoccean.com)
73 and the Seabased wave energy converter, developed by the Swedish Cen-
74 tre for Renewable Electric Energy Conversion of the Uppsala University
75 (www.seabased.com). The Seabased WEC consists of a buoy connected by
76 a rope to a linear generator [19]. The vertical buoy's motion brought about
77 by the ocean waves is transferred to the piston and the stator coils react to
78 the piston's movement inducing alternate current. The springs connecting
79 the bottom of the translator to the foundation act as a restoring force, thus
80 behaving as an energy storage unit. Each single device has a relatively low
81 power output and therefore, the idea is to install several devices in arrays of
82 many units.

83 In this study, a two-body and a three-body device have been modelled.
84 They both share the same bottom anchored PTO, characterized by a permanent-
85 magnet generator with a highly non-linear behaviour, where the PTO's trans-
86 lator is one of the modelled bodies. Both devices have also another body, a

87 cylindrical floater w
88 The third body is a
89 add inertia to the
90 ods without increas
91 connected to the ot



Figure 1: *Device's Layout.*

92 The PTO of the studied WEC is inspired on the Seabased's linear gener-
93 ator [19, 21–24]; more specifically, it is simulated using the model presented
94 in [21] and adopted by [20] afterwards. The hydrodynamic behaviour of dif-
95 ferent types of floaters has been investigated in [25], where two different buoy
96 geometries: hemisphere-cylindrical and cone-cylindrical with 18 different in-
97 ternal configurations have been analysed.

98 A study on the optimal buoy dimensions is presented in [20]. Two cylin-
99 drical buoys with different diameters and drafts are compared to select the
100 best buoy size for several representative locations in the Italian Seas. The
101 power output is then maximised by adding a submerged body connected to
102 the floating buoy, which allows the shifting of the natural frequency of the
103 system in order to match it with the typical wave frequency of the study-
104 sites. Furthermore, this body is placed at a depth where it can barely feel the
105 presence of waves. Thus, the energy loss caused by radiation is negligible.
106 Only one degree of freedom was modelled (Heave) for the whole device and

	N. of Bodies	N. of DoFs	Surge
A	2	2	X
B	2	3	✓
C	3	3	X
D	3	5	✓

Table 1: *Studied WEC devices.*

107 regular waves were used to simulate the sea state conditions. A further study
 108 on the optimization of the numerical modelling if the device was presented
 109 in [26].

110 The aim of this paper is to present a comprehensive analysis and discus-
 111 sion of the modelling of the considered WEC under irregular wave sea states.
 112 For the first time the surge effect is modelled and quantified by estimating
 113 the energy production when considering a point absorber WEC excited in the
 114 horizontal direction and comparing it to the simplified model, which takes
 115 into account only the heave mode. See [20, 24].

116 The comparison of the generic performance of the devices is presented
 117 depending on the number of bodies (floater + piston or floater + piston +
 118 submerged sphere) and degrees of freedom (heave only or heave + surge).
 119 Table 1 summarizes all the combinations studied in this work.

120 The presented comparison yields a large number of combinations, there-
 121 fore the computational effort of the model has been a relevant issue in this
 122 study. According to the available computational resources (i.e:server), a rea-
 123 sonable computational cost has been reached by parallelizing the code and
 124 through implementing the Prony's approach.

125 The paper is organized as follows: in section 2, the mathematical model
 126 is presented, in subsection 2.1 the theoretical approach is described, in sub-
 127 section 2.2 the theoretical basis are applied according to the requirements of
 128 the analysed devices, highlighting the introduced novelties. In section 3, a re-
 129 capitulation of the application sites characterisation is shown. Subsequently,
 130 section 4 goes through the optimization process of the device. Afterwards,
 131 the obtained results are presented in section 5, giving a general overview of
 132 the devices performance in subsection 5.1 and the site application cases in
 133 subsection 5.2. Finally, in the last section, some discussions and conclusions
 134 are drawn, focusing on the differences between the improved variants com-
 135 pared to the simplified ones, on the energy production and on the device

136 performance.

137 2. Modelling

138 2.1. Theory

139 The dynamic behaviour of the wave energy converter is expressed through
140 the general governing equation of motion (1), which links the components
141 from different nature altogether.

$$m\ddot{z}(t) = F_e(t) + F_r(t) + F_h(t) + F_{moor}(t) + F_{drag}(t) + F_{pto}(t) \quad (1)$$

142 where m is the mass of the system, z refers to the coordinate system of
143 the model, $F_e(t)$ is the wave excitation force, $F_r(t)$ is the radiation force,
144 $F_h(t)$ is the hydrostatic restoring force, $F_{moor}(t)$ is the force exerted by the
145 mooring system, $F_{drag}(t)$ is the viscous drag force and $F_{pto}(t)$ is the resistant
146 force due to the power take off action. The excitation force is obtained by
147 convoluting the impulse response function $f_e(t)$ and the sea surface elevation
148 $\eta(t)$ as stated in equation (2):

$$F_e(t) = f_e(t) * \eta(t) \quad (2)$$

149 The term expressing the resistance of the body due to the radiated waves
150 is composed by two terms, a convolution between the body velocity and its
151 impulse response function and an inertial term, as shown in equation (3):

$$F_r(t) = -m_\infty \ddot{z}(t) - k(t) * \dot{z}(t) \quad (3)$$

152 where m_∞ is the added mass at infinite frequency, the body velocity $\dot{z}(t)$
153 and $k(t)$, which is the radiation impulse response function that acts as kernel
154 of the convolution. According to the Kramers-Kronig relations, takes the
155 form shown in eq. (4), as deeply discussed in Falnes, p.31-36, [27].

$$k(t) = \frac{2}{\pi} \int_0^\infty B(\omega) \cos(\omega t) d\omega \quad (4)$$

156 where ω is the monochromatic wave frequency and $B(\omega)$ is its radiation
157 damping coefficient. The hydrostatic force $F_h(t)$ acting on a cylindrical shape
158 can be linearised on the heave mode as follows, when its centre of gravity is
159 coincident with the origin of the coordinate system $z(t)$:

$$F_h(t) = -\rho g A_w z(t) \quad (5)$$

160 where ρ is the seawater density, g is the gravity acceleration and A_w is
 161 the water plane area of the cylinder. Since the PTO is fixed on the seabed,
 162 the mooring forces are expressed as the non-linear elastic forces occurring
 163 at the lines, which interconnect the different bodies of the device. Therefore,
 164 they have been modelled as stiff springs acting only when in tension.

$$F_{moor}(t) = \begin{cases} -K_{line}\Delta l(t) & \text{for } \Delta l(t) > 0 \\ 0 & \text{Otherwise} \end{cases} \quad (6)$$

165 where K_{line} is the elastic constant of the wire and $\Delta l(t)$ is the relative
 166 displacement between bodies. The drag forces have been described according
 167 to the Morison expression for oscillatory flows:

$$F_{drag}(t) = -\frac{1}{2}\rho C_d A_d |\dot{V}(t) - \dot{z}(t)|(\dot{V}(t) - \dot{z}(t)) \quad (7)$$

168 where C_d is the drag coefficient, which depends on the shape of the body
 169 and has been chosen according to the tabulated values in [28], assuming a
 170 value of 1.1 for the cylinder and 0.47 for the sphere. A_d is the area of the
 171 body projected perpendicularly to the flow direction and $\dot{V}(t)$ is the fluid
 172 velocity.

173 The Power Take Off system introduces three different forces, two mechan-
 174 ical ones and an electromagnetic one. The PTO has a spring attached to the
 175 bottom that stores part of the energy and helps to smooth the translator's
 176 displacements. To enhance its survivability, the generator includes two end-
 177 stop mechanism, consisting of an upper and a lower spring, in order to avoid
 178 any damage when the device be subjected to stormy conditions. The elec-
 179 tromagnetic resistant force is derived from the instantaneous electric power,
 180 which in turn is yielded from the electric currents and tensions found in the
 181 electric equivalent circuit of the stator coils. Equations (8), (9) and (10)
 182 describe forces mentioned above:

$$F_{spring}(t) = -K_{pto}z(t) \quad (8)$$

$$F_{end}(t) = \begin{cases} -K_{end}(z(t) - Z_{lim}) & \text{for } |z(t)| > |Z_{lim}| \\ 0 & \text{Otherwise} \end{cases} \quad (9)$$

$$F_M(t) = \frac{\sum_{i=1}^3 U_i(t) I_i(t)}{\dot{z}(t) \mu} \quad (10)$$

183 where K_{pto} is the elastic constant of the spring attached to the translator,
 184 K_{end} is the elastic constant of the end-stop spring, and Z_{lim} is the activation
 185 coordinate of the end-stop. $U_i(t)$ and $I_i(t)$ are the electric tension and cur-
 186 rent of the i^{th} phase of the equivalent circuit respectively, which have been
 187 obtained applying the Faraday's laws. The electric field is found using the
 188 analytical model presented by [21], which uses the Maxwell's equations that
 189 describe the electromagnetic induction phenomenon in the stator-translator
 190 structure. The total instantaneous electric power is the sum of the power for
 191 any electric phase, each of them computed as the product of the tension times
 192 the current. By dividing the power by the translator velocity $\dot{z}(t)$ and the
 193 overall generator's efficiency μ , the electromagnetic resistant force is yielded.
 194 As already applied in [20].

195 2.2. Model

196 All the mathematical expressions presented in the previous section are
 197 written in the generic form and they have been adapted to each device and
 198 model variant as exposed on the introduction chapter. Some specific modi-
 199 fications need to be done too in order to meet the numerical requirements.

200 Each DoF of the system is expressed mathematically by an equation of
 201 motion. Hence, the total number of degrees of freedom per device deter-
 202 mines the dimension of the matrix system of the model, varying from a
 203 two-dimension system for the simplest case (2 bodies, 2 DoFs) up to a five-
 204 dimension system (3 bodies, 5 DoFs). In order to give better understanding,
 205 the left side of equation (1) is displayed below for the most complete situation
 206 i.e. three-body device considering the heave and surge modes. Each body
 207 is specified with the superscript 1, 2 and 3 for the buoy, submerged sphere
 208 and translator respectively. The surge mode is specified with the subscript
 209 1, and the heave mode with the subscript 3.

$$\begin{pmatrix} m_{\infty 11}^1 + m^1 & m_{\infty 13}^1 & 0 & 0 & 0 \\ m_{\infty 31}^1 & m_{\infty 33}^1 + m^1 & 0 & 0 & 0 \\ 0 & 0 & m_{\infty 11}^2 + m^2 & m_{\infty 13}^2 & 0 \\ 0 & 0 & m_{\infty 31}^2 & m_{\infty 33}^2 + m^2 & 0 \\ 0 & 0 & 0 & 0 & m^3 \end{pmatrix} \begin{pmatrix} \ddot{z}_1^1(t) \\ \ddot{z}_3^1(t) \\ \ddot{z}_1^2(t) \\ \ddot{z}_3^2(t) \\ \ddot{z}_3^3(t) \end{pmatrix} = \dots \quad (11)$$

210 where m_∞ 's is the added mass at infinite frequency and $\ddot{z}(t)$'s is the body
 211 acceleration. The hydrodynamic coefficients $Fe(\omega)$, $B(\omega)$ and $A(\omega)$ (the
 212 excitation force coefficient, the radiation damping coefficient and the added
 213 mass coefficient respectively), which are frequency dependent, have been
 214 obtained using the open source BEM method software called NEMOH
 215 (<http://lheea.ec-nantes.fr/doku.php/emo/nemoh/start?%E9#nemoh>). As seen
 216 on the previous section, these coefficients are used to compute the impulse
 217 response functions, which in turn work as kernels for convolution as seen in
 218 equation (4).

219 The matrix system of equations of motion is a set of differential equations,
 220 which have been integrated over time in order to obtain the displacements
 221 and velocities of the system. The commercial software Matlab[®] has been
 222 used, applying a fourth order ODE solver based on Runge-Kutta's method.
 223 Some practical problems arise when using this approach, the main drawback
 224 is the high computational cost of the simulation. This is mainly due to the
 225 internal convolutions of the wave excitation force and radiation effect, which
 226 have to be pre-calculated at each time step. Indeed, this fact forces the
 227 algorithm to run in a fixed time step, rising even more the computational
 228 cost.

229 By means of the Prony's approach the computational time has been ap-
 230 proximately halved. This method avoids the use of the convolutions by
 231 adding N virtual DoFs ($I_i(t)$) to the system, where $i = 1 \dots N$ and then as-
 232 suming that the summation of all these new DoFs approximates the product
 233 of the avoided convoltuion, as in eq. (12) shows:

$$F_{rad} = \sum_{i=1}^N I_i(t) \quad (12)$$

234 Despite the increase of the size of the system, which in turn implies a
 235 growth of the computational time, the benefits are by far larger than the
 236 drawbacks. More insight on the Prony's method can be found at [29–31]

237 The viscous drag of the device has been modelled for all degrees of free-
 238 dom, with some particularities. The vertical drag component corresponding
 239 to the heave mode of the cylinder is negligible according to [32], since the
 240 relative velocity of the body with respect to the fluid is very small. The
 241 velocity of the fluid around submerged body has been considered equal to
 242 zero since the sphere is placed at a sufficient depth where the disturbance of
 243 the wave field is of insignificant relevance, according to [20].

244 3. Description of the study sites

245 The presented device has been tuned for wave conditions typical of closed
 246 seas, characterized by short waves and intense storms. In order to estimate
 247 the Annual Energy Production (hereinafter AEP) two specific sites off the
 248 Italian coasts have been selected, where wave data are available and where
 249 the wave energy converter is supposed to be deployed. The selected sites,
 250 Alghero and Mazara del Vallo are located, respectively, on the West side of
 251 Sardinia's and Sicily's coasts. The wave potential in Alghero is 9.1 kW/m
 252 and 4.7 kW/m in Mazara del Vallo, [9]).

253 The characterization of the wave climate and the wave energy potential
 254 in terms of sea states is presented in [20]. Original data is provided by the
 255 Italian Buoy Network (<http://www.idromare.it>), operatively collecting wave
 256 data since 1989. Wave climate data shows that the prevalent sea states are
 257 characterized by relative small waves: in Alghero and Mazara H_S is below 1
 258 m during approximately 60% of the year. The peak periods with the highest
 259 probability of occurrence are around 6 s, confirming that short waves prevails
 260 in the Mediterranean climate, as the results of [20].

261 The model takes irregular waves as input. The spectrum that best repre-
 262 sents the current sea states is the JONSWAP with a γ parameter set equal
 263 to 2, as shown in [18]. Furthermore, in order to account for the spectral
 264 energy associated with the frequencies lying outside the simulation range, an
 265 algorithm applying energy compensation has been used. It is based on the
 266 ratio of the theoretical m_0 related to the theoretical spectrum ($S(\omega)$) and
 267 the value m_0^* that comes from the numerical integration of the truncated
 268 JONSWAP spectrum, ($S^*(\omega)$). The aim is to generate a modified truncated
 269 JONSWAP spectrum ($S^+(\omega)$) which has the same total energy (m_0^+) as
 270 the analytic one. Equations 13 - 16 describe the approach, while in Fig. 2
 271 an example for a JONSWAP spectrum ($H_S = 5$ m - $T_P = 10$ s - $\gamma = 2$) is
 272 presented.

$$m_0 = \int_0^\infty S(\omega) d\omega \quad (13)$$

$$m_0^* = \int_0^{f_u} S^*(\omega) d\omega \quad \text{where} \quad f_u = 3.3 \frac{2\pi}{T_p} \quad (14)$$

$$S^+(\omega) = S(\omega) \frac{m_0}{m_0^*} \quad (15)$$

$$m_0^+ = m_0 = \int_0^{f_u} S^+(\omega) d\omega \quad (16)$$

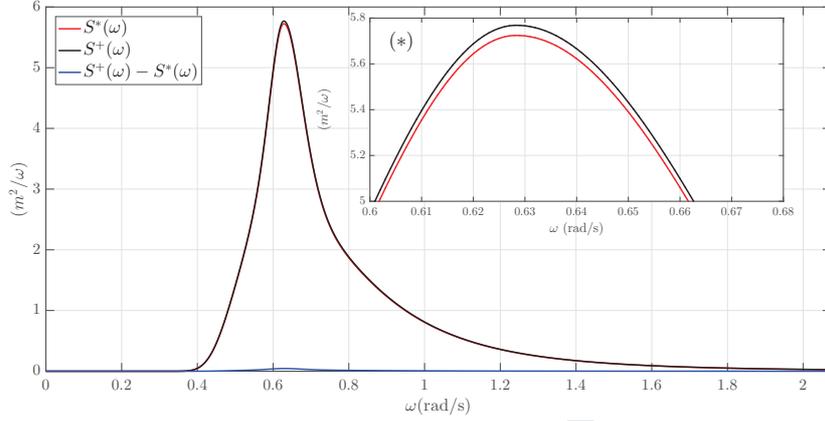


Figure 2: Comparison between the theoretical and the numerically integrated JONSWAP spectra. (*) Zoom at the spectra's peaks

273 Furthermore, in order to perform an effective analysis of the device di-
 274 mensioning a new indicator has been used; the climatic spectrum. It is
 275 computed as the weighted average of each JONSWAP spectrum that char-
 276 acterises the wave climate matrix at the selected locations; adopting the
 277 frequency of occurrence as the weighting parameter. Equations 17 and 18
 278 expose the procedure followed to compute the climatic spectrum.

$$S_C(\omega) = \sum_{j=1}^P \sum_{i=1}^N f_{ij}^{oc} S_{ij}(\omega) \quad (17)$$

$$f_{ij}^{oc} = \frac{OC_{ij}}{\sum_{j=1}^P \sum_{i=1}^N OC_{ij}} \quad (18)$$

279 Where $S_{ij}(\omega)$ is the JONSWAP spectrum with $\gamma = 2$ given an H_S class
 280 indexed i and T_P class indexed j , f_{ij}^{oc} is the frequency of occurrence of the
 281 aforementioned spectrum and OC_{ij} is the actual occurrence in hours. The

282 data used to compute the wave climates have been obtained from the mea-
 283 surements given by the RON (Rete Ondametrica Nazionale) [33]. The cli-
 284 matic spectrum aggregates two different time scales, giving a good insight
 285 on which are the most energetic frequencies at both sites globally and thus,
 286 is used to tune the device performance.

287 4. Dimensioning & Tuning

288 In first approach, the device has been modelled only in heave and with
 289 the PTO translator built-in with the floater. Influence on the floater's shape
 290 and draft has been analysed using three different geometries. A cylinder and
 291 two composed geometries, a cylinder with a conical base and a cylinder with
 292 spherical base. The optimal configuration has been found to be the regular
 293 cylinder with $\varnothing = 5m$ and draft of $d = 2.75 m$, as described in [25].

294 4.1. Free oscillation tests

295 The aim of the submerged body is to maximize the power output by
 296 shifting the natural period of the system towards the prevailing wave periods
 297 of the study sites sea states. The shape of the chosen submerged body is
 298 a sphere. After the selection of the shape, the last characteristic to be de-
 299 termined is the radius. For floating bodies, standard procedure to identify
 300 the natural modes of the system is the free oscillating test. This, consists in
 301 varying the initial position from the equilibrium state and observe the evo-
 302 lution over time under total absence of external disturbances; in this case,
 303 represented by a flat sea. The length of the test has been set to 100 s, after
 304 this time it has been observed that the oscillations are completely damped
 305 and the system has reached back the equilibrium state. Setting the equi-
 306 librium condition at the point $(0, 0)$ of the coordinate system $(z_1^1(t), z_3^1(t))$,
 307 the initial displacement of the buoy has been established at $(-1.25, -1.25)$,
 308 hence for both, surge and heave.

309 Figure 3 shows the results of the free oscillations test for four different
 310 variants of the device, the first one without sphere, and the rest accounting
 311 with a sphere of different diameter. Figure 3.a) shows the evolution of the
 312 system over time while Fig. 3.b) shows the result of the frequency analysis.
 313 Furthermore, in black, the climatic spectra $S_C(\omega)$ of the deployment sites
 314 are shown.

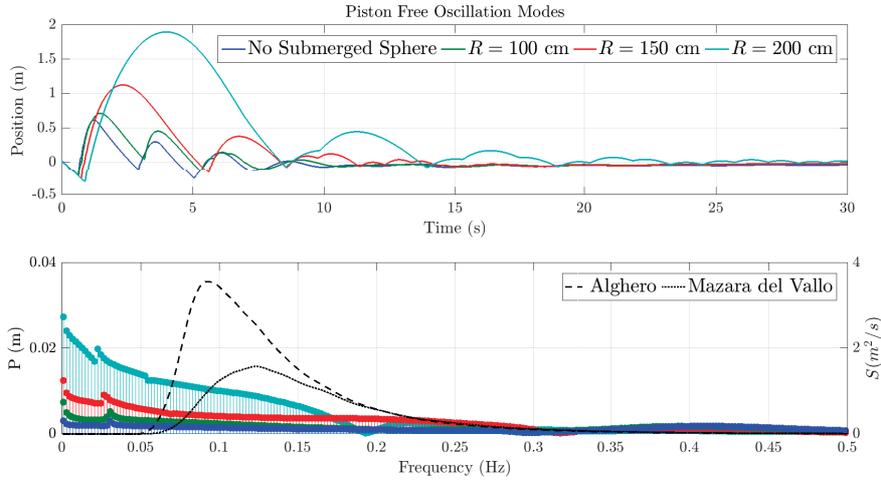


Figure 3: Free Oscillation test of the PTO's translator. a) Influence of the sphere vs. time. b) Spectral analysis of oscillations and climatic spectra from Alghero and Mazara del Vallo

315 As expected, a strong non-linear behaviour is observed in Fig. 3.a) and
 316 no clear resonance is detected in Fig. 3.b). Nonetheless, the influence of
 317 the sphere is clear on the dynamic response of the system. Oscillations in
 318 the piston increase, in period and amplitude, as the radius of the sphere
 319 grows. Judging from the area of interest (the frequency range of the climate
 320 spectra) the optimal solution appears to be the device accounting with a 2.00
 321 m radius sphere since it shows the highest amplitudes. However, not only
 322 the oscillations grow with the radius but so the non-linearities do, giving
 323 place to several undesired effects such as, slamming due to the wires, end-
 324 stop mechanism activation, translator oscillating outside the productive area.
 325 Therefore, the configuration with the sphere of radius 1.50 m delivers the best
 326 performance and assures smooth operation conditions of the device since its
 327 response is stable throughout the whole range of interested frequencies.

328 4.2. PTO's Design

329 The surge motion directly causes a variation on the oscillatory regime of
 330 the piston. An extra horizontal component is introduced at the buoy and
 331 that makes the absolute displacements larger. The absolute displacement of
 332 the buoy is then transferred to the piston through the steel wire. This causes

333 a shift of the piston mean oscillatory position (see Fig. 3.a) and causes a
 334 decrease of the energy production as the PTO is designed to oscillate around
 335 zero. In order to solve this undesired effect the PTO has been redesigned
 336 geometrically.

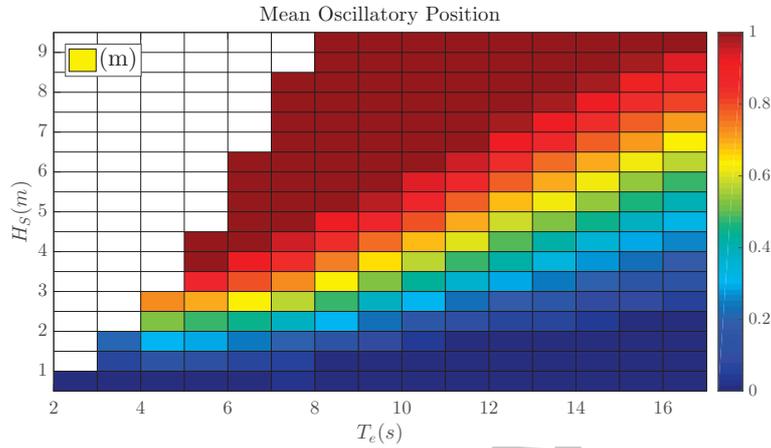


Figure 4: *Piston's Average Position at each Sea State.*

337 Figure 4 shows the mean oscillatory position of the piston for each sim-
 338 ulated condition; at the typical working conditions ($T_P = [5.5 - 7.5](s)$ &
 339 $H_S = [1.0 - 2.5](m)$), the average oscillatory position is about $\bar{x} = 0.25m$.
 340 According to such preliminary result, the piston is extended by $2\bar{x}$ and the
 341 upper part of the stator is also lengthened by \bar{x} . This combination allows the
 342 lower bound of the maximal production rate to remain untouched, whereas
 343 the upper bound of the minimal production rate is extended by $2\bar{x}$. Fur-
 344 thermore, the upper end stop position is also shifted by \bar{x} to ensure that the
 345 piston smooth motion conditions are not affected by this change.

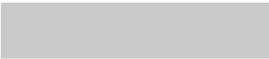


Figure 5: *PTO layout. a) Original form. b) Translator modification. c) Translator&Stator modification.*

346 The active production area is the surface of the stator, entirely or par-
347 tially, containing the translator. If divided by the total area of the stator, the
348 Active Area Ratio (AAR) is obtained. Figure 6 maps the differences in the
349 active production area of the PTO for the original and the modified PTO.
350 Figure 5 shows the differences between the original design of the PTO and
351 the optimized one.

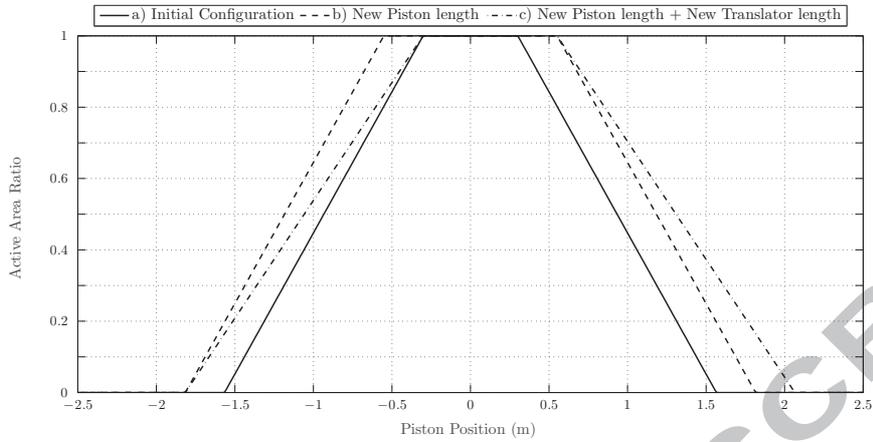


Figure 6: *PTO Active Production Area Ratio vs. Piston Displacement* .

352 To sum up, the modifications applied to the PTO regard only the geo-
 353 metrical configuration, keeping the electromagnetic properties unvaried, as
 354 described in [21]. Table 2 summarizes the geometrical and electromagnetic
 355 properties of the linear generator.

PTO Parameters	
Nominal Power (kW)	10
Nominal Speed (m/s)	0.67
Translator length (m)	2.367
Stator length (m)	1.514
Translator mass (kg)	1000
Width of stator sides (m)	0.4
Number of sides (-)	4
Pole width (mm)	50
Tooth width (mm)	8
Magnetic Field in tooth (T)	1.55
Generator Resistance (Ω)	0.3735
Generator Inductance (mH)	11.5
DC Voltage (V)	200
Efficiency μ (-)	0.791

Table 2: *Electric generator properties [20].*

356 *4.3. Duration of the Simulations*

357 In order to achieve a reliable estimate of the power absorption a standard
 358 length of the simulations needs to be defined. Due to the wide range of
 359 simulated sea states, a fixed duration of the simulations is not appropriate,
 360 as the system may reach the device production power stabilization at different
 361 times depending on the input wave characteristics. A suitable indicator of
 362 the length of the simulations was found to be the number of waves. It was
 363 determined that after 1000 waves a constant value of mean power production
 364 was reached for each of the simulated sea states. Taking into account the
 365 high level of uncertainty at this stage of the research, the authors believe that
 366 an error in power output estimation below 5% can be considered acceptable.
 367 Hence, the duration of the simulations was set equal to the number of waves
 368 necessary to obtain a value of power output differing by less than 5% from
 369 the value obtained with 1000 waves. Fig. 7 shows the deviation from the
 370 1000-wave value versus the number of simulated waves, for the system D (see
 371 Table 1). It can be noticed that the desired level of accuracy is reached for
 372 a number of waves equal to 350. The same results were found for the other
 373 WEC systems, so the duration of the simulations was set equal to 350 waves
 374 for all the studied devices.

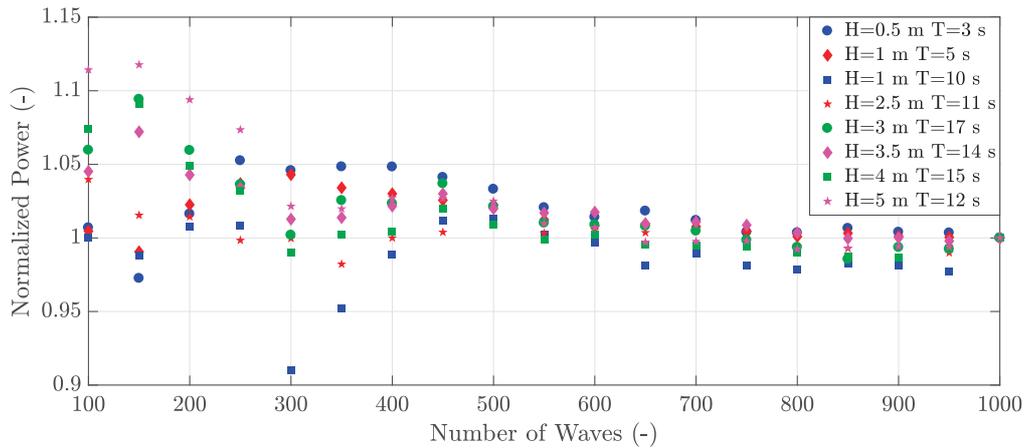


Figure 7: Power output deviation from the 1000-wave value vs Number of Waves

375 **5. Results**

376 *5.1. Generic*

377 102 simulations, corresponding to the full range of sea states that char-
 378 acterize the selected locations wave climate, have been simulated for each of
 379 the different device variants, see tab. 1. For each simulation the following
 380 parameters are extracted: displacement and velocity time-series of each de-
 381 vice part and instantaneous power. The production of the device is obtained
 382 by averaging the instantaneous power over the time-series, for any specific
 383 sea state. When combining all the output powers for each different sea state,
 384 characterised by the peak period (T_P) and the significant wave height (H_S),
 385 a two-dimensional matrix is obtained, which is commonly named power ma-
 386 trix. In order to assess the device general performance, the power matrix of
 387 each variant is shown in Fig. 8.

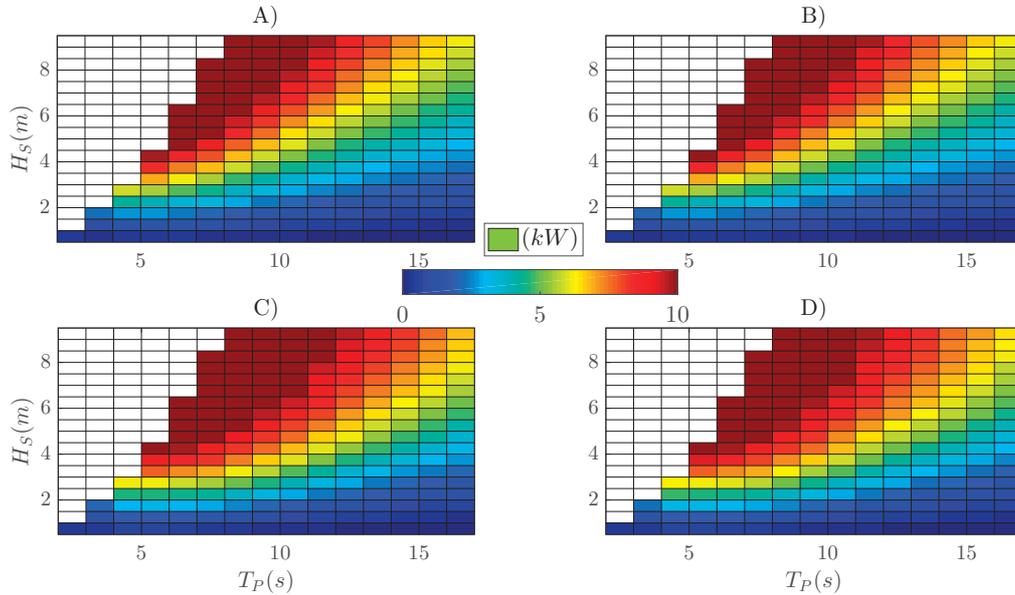


Figure 8: Power matrices for each variant of the device. A) Two bodies only heave, B) two bodies heave & surge, C) three bodies only heave and D) three bodies heave & surge. (as in table 1)

388 Figure 8.A displays the two-body variant free to move only in heave (A
 389 in tab. 1), Fig. 8.B presents the two-body variant accounting for the heave

390 and surge modes (B in tab. 1), Fig. 8.C summarizes the performance of
 391 the three-body device only in heave (C in tab. 1) and Fig. 8.D reveals the
 392 behaviour of the most complete model, accounting for three bodies and five
 393 degrees of freedom (D in tab. 1). All the power matrices show the expected
 394 behaviour. The general trend shows higher production rates at higher and
 395 steeper waves; furthermore, an increase of the produced power is noticed
 396 when the third body is added. Yet, no evident differences are observed when
 397 the surge is introduced. Therefore, a more thorough analysis is needed to
 398 study such effects in depth. In order to quantify the influence that the
 399 submerged sphere has in the power production, variants A & C, and D & B
 400 are confronted by subtracting their power output for every sea state. Such
 401 results are shown in Fig. 9.

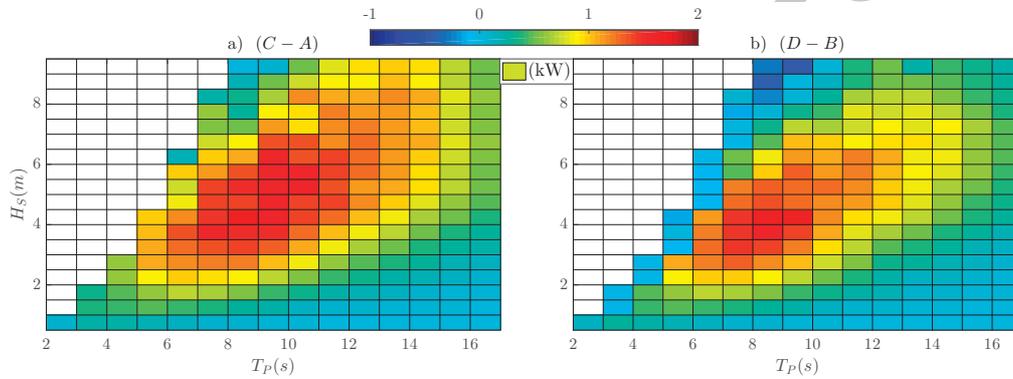


Figure 9: Power matrix difference between the two & three-body device. a) Heave only. b) Heave & surge.

402 A clear patch is observed in Fig. 9.a), having a production peak between
 403 T_P 's 7 and 9 seconds, shifting the most productive area towards higher peri-
 404 ods, just as predicted in the previous chapter. The same trend is identified
 405 in Fig. 9.b) even though the surge effect seems to mitigate it substantially.
 406 In addition, for very steep waves, this trend is even reversed and the surge
 407 effect is revealed to be counter productive because of the negative values of
 408 the production rate. This means that the addition of the submerged sphere
 409 is not always optimal, specifically if the device is to be deployed in a location
 410 where wind seas are predominant.

411 To better explore the device response, the same methodology as in the
 412 previous figure has been applied, subtracting A - B and C - D. By doing

413 so, the pure surge effect can be analysed for both, the two and three-body
 414 device. See Fig. 10.

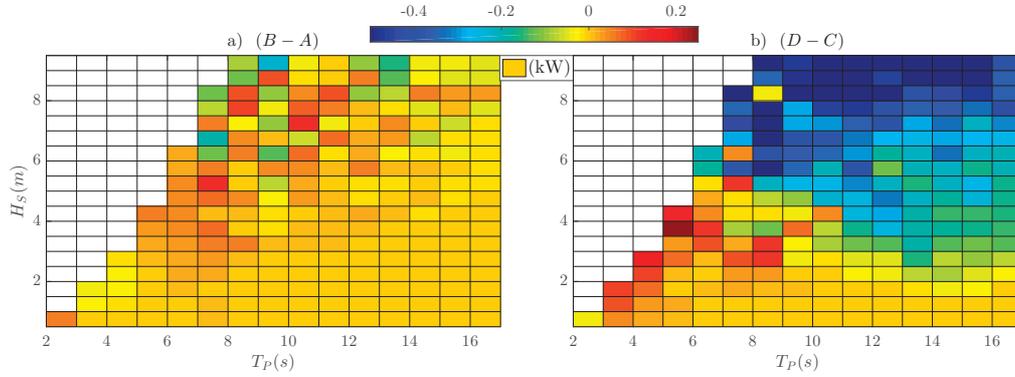


Figure 10: Power matrix difference between the heave-only mode and the heave & surge mode. a) Two-body device. b) Three-body device.

415 Figure 10 shows a different behaviour between devices when the surge
 416 mode is modelled. The three-body device shows a clear positive trend in
 417 production rates for small steep waves, typically $H_S < 4.5$ m and $T_P < 7$ s.
 418 On the contrary, a decrease of the production is detected for flatter waves
 419 and getting more intense for $H_S > 4.5$ m (Fig. 10.b). The two-body
 420 device shows no predominant trend, having the strongest variations in the
 421 steep-wave region. Hence, both devices appear to have high sensitivity to
 422 wave steepness since in both figures the most extreme values are found at
 423 the steep wave area and the minimum variation is obtained at the flat-wave
 424 area. Consequently, the difference in each device's power production has
 425 been studied according to wave steepness. See Fig. 11.

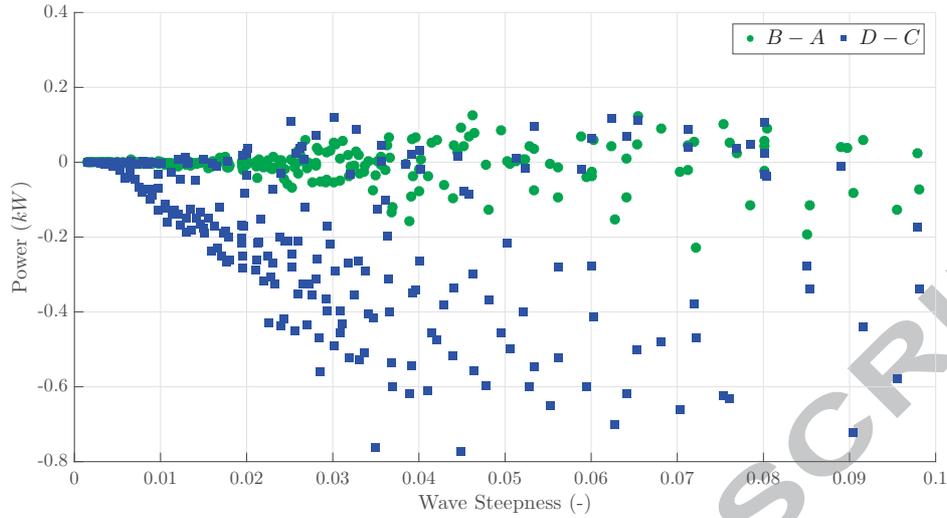


Figure 11: Power output difference vs. wave steepness for each device, green circle and blue square for two-body and three-body device respectively.

426 The two-body device reveals very low surge-related sensitivity to wave
 427 steepness, since the scatter cloud mean is approximately null and its disper-
 428 sion is rather low. On the contrary, the blue-dotted cloud has a clear wave
 429 steepness akin trend, which confirms that the inclusion of the sphere has an
 430 evident negative contribution when modelling the surge mode, as the power
 431 difference increases with the wave steepness.

432 Although the buoy is the body in direct contact with waves, the electric
 433 production is carried out by the PTO's piston. This, in the case of the three-
 434 body device, is greatly influenced by the submerged sphere. To study this
 435 behaviour, an analysis of three parameters concerning the piston's dynamics
 436 has been carried out. The aforementioned parameters are the following: the
 437 active area ratio of the PTO (described in the previous section), the average
 438 velocity of the piston and average amplitude of the piston's oscillations. The
 439 AAR gives very good insight, not only for the amplitude of the oscillations
 440 but also for the offset of the centre of such oscillations with respect to the
 441 equilibrium position. Furthermore, the average oscillation amplitude helps
 442 to complete the analysis on this regard, since a joint study of both param-
 443 eters allows to obtain a detailed picture on the piston regime. Finally, it is
 444 important to consider as well the average piston's velocity since it is directly
 445 linked to the power output through the magnetic induction laws.

446 Figures 12 and 13 have been computed following the same procedure as
 447 in Fig. 10. The values shown are AAR(B)-AAR(A) and AAR(D)-AAR(C),
 448 for the a) section of Figs. 12 and 13 respectively. The average piston run at
 449 the b) section and the average piston velocity for section c).

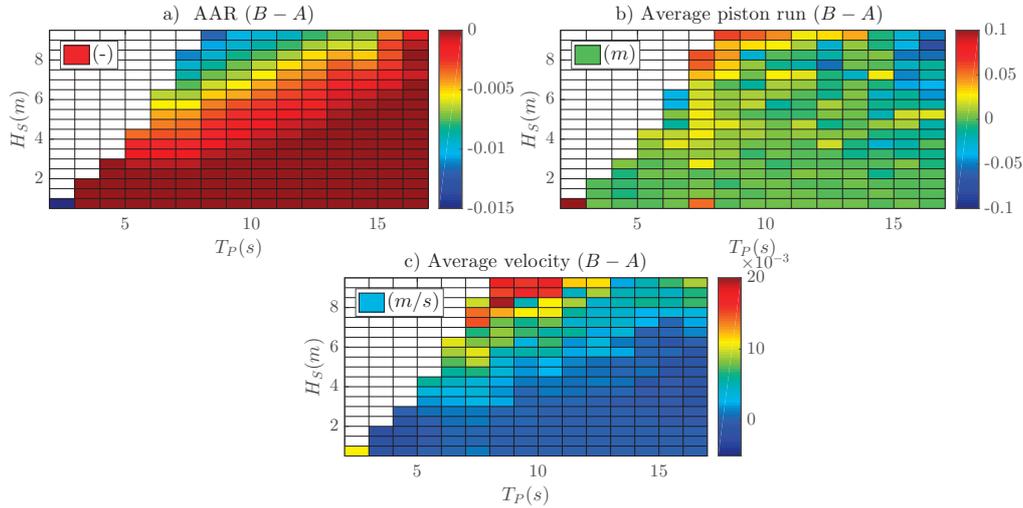


Figure 12: Two-body device difference matrices between heave-only mode and heave & surge mode. a) Active Area Ratio, b) Average amplitude of the piston's motion, c) Average piston's velocity

450 The combination of positive average piston run and negative AAR dif-
 451 ferences given at the top-left corner of the matrix (high and steep waves)
 452 means that the piston presents larger oscillations when the surge is taken
 453 into account but, it is doing so outside the range where electricity is effec-
 454 tively produced. However, the velocity differences are also positive at the
 455 same area, meaning a higher electricity production. Considering the values,
 456 it can be realized that differences are actually very small. This, brings about
 457 high uncertainty upon the dominance of a specific parameter over the other.
 458 As a matter of fact, this was already observed in Figs. 10.a) and 11, where
 459 no clear conclusion can be drawn whether the surge effect is either positive
 460 or negative for the two-body device.

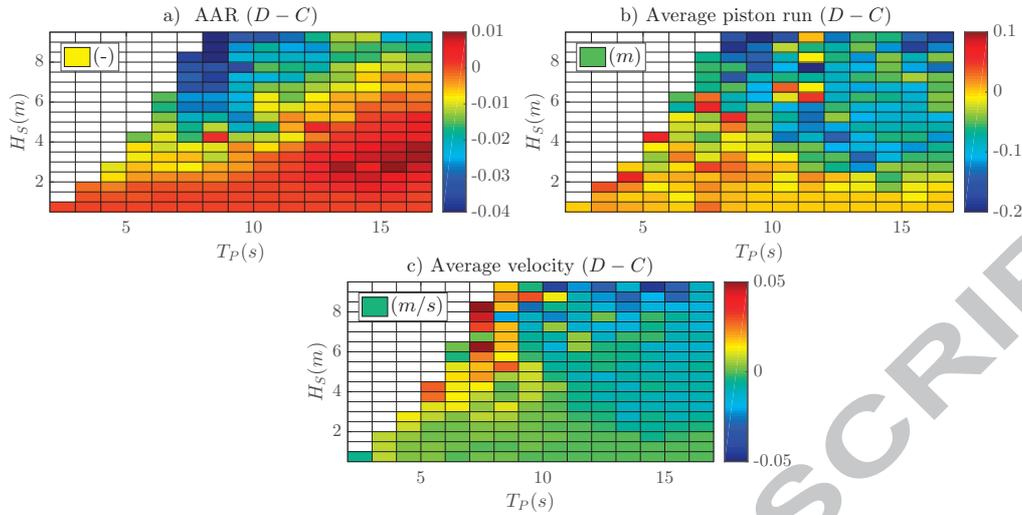


Figure 13: Three-body device difference matrices between heave-only mode and heave & surge mode. a) Active Area Ratio, b) Average amplitude of the piston's motion, c) Average piston's velocity

461 For the three-body device instead, a clear pattern can be distinguished for
 462 steep waves. The AAR difference is negative for steep waves, which implies
 463 that the piston oscillates less effectively when the surge mode is taken into
 464 account. Nevertheless, the velocity differences are positive, which means it
 465 oscillates slightly faster. The piston run is negative for high waves, indicating
 466 a more frequent activation of the end-stop mechanism, leaving no doubt to
 467 the negative influence of the surge at that region of the matrix, as already
 468 confirmed by Figs. 10.b) and 11. For the other regions of the matrix no
 469 substantial difference is encountered other than a slight increase of the piston
 470 run and AAR for smaller waves.

471 5.2. Site-Specific

472 The average energy production of the simulated devices has been com-
 473 puted for the two selected sites, Alghero and Mazara del Vallo. A 20 year
 474 long data record provided by the RON [33] has been used to compute the
 475 climate matrices of the deployment sites. These, are then crossed with the
 476 power matrix of the device to obtain the average energy production. Results
 477 are shown in table 3.

Variant	N. of Bodies	Surge	Alghero	Mazara del Vallo
A	2	X	12.89	9.34
B	2	✓	12.91	9.35
C	3	X	17.00	12.28
D	3	✓	17.04	12.38

Table 3: Annual Energy Production for the four variants (tab. 1) at the selected locations. All units are MWh/y.

478 The three-body device has a higher electricity production, the increase is
 479 about 30% for Alghero and 32% for Mazara del Vallo, stating the shift in the
 480 resonance frequency induced by the submerged sphere towards more common
 481 sea state conditions. The surge has no influence on the long-term electricity
 482 production, results are almost identical either for Alghero or Mazara del
 483 Vallo, denoting that the major differences in power production identified in
 484 section 5.1 occur for rather improbable sea states at these locations. The
 485 differences in annual energy production depending on the number of bodies
 486 will affect the resulting cost of the electricity of the two technical solutions,
 487 as shown by [34].

488 6. Conclusions

489 With the aim to estimate the feasibility of wave energy conversion in
 490 the Mediterranean Sea this paper thoroughly analyses the body dynamics,
 491 with particular focus on the surge effect and in the energy production of a
 492 point absorber WEC. The model runs in the time domain, uses irregular
 493 waves, is able to handle multi-body systems with various degrees of freedom
 494 and delivers the instantaneous electric power, which is later used to obtain
 495 both, generic and site-specific performance indicators. In order to increase
 496 its computational efficiency, the code has been parallelized and the prony's
 497 method has been adopted, reducing the total simulation-time by an order of
 498 magnitude.

499 A sensitivity analysis on the dimension of the submerged body has been
 500 performed by running several free oscillation tests. These, have confirmed
 501 that the optimal submerged body size is $R = 1.50m$. Figures 3 and 9 show
 502 that the resonant frequency of the system is shifted towards the most per-
 503 sistent sea state period range. On the one hand, the presence of the sub-

504 merged body increases the electric production, which goes up to approx-
505 imately 30% when tanking into account both, heave only and heave and
506 surge modes. On the other hand, it could lead to undesired effects from the
507 technical/operational point of view, such as the increase of the working time
508 of the end-stop survival mechanism or the slamming effects occurring in the
509 interconnecting lines due to its large inertia. For all the stated above, it
510 is reasonable to worry about the technical/economical feasibility of a point
511 absorber with a submerged body disposed in such configuration, particularly
512 when considering the surge, as no increase of the electricity production is
513 found.

514 Slamming phenomena occurring in extreme wave events have been con-
515 sidered in the mathematical modelling by means of the end-stop mechanism
516 and the steel wire modelling, see section 2.1. Nevertheless, their effect has
517 not been deeply analysed due to their negligible contribution on mean annual
518 energy production. Slamming effects have a major relevance in the reliabil-
519 ity and survivability of the devices and hence should be adequately taken
520 into account in WEC design. A relevant work including slamming restraint
521 constraints in WEC modelling has been recently published by [35].

522 Another remarkable conclusion that can be drawn from the previous sec-
523 tion is that considering the surge shows no relevant contribution to the elec-
524 tricity production, as presented in table 3. Therefore, the surge mode may
525 be neglected at early stages of development when modelling numerically the
526 behaviour of a heaving point absorber for pure energy production assessment
527 purposes. This, allows to use a simpler and more computationally efficient
528 model that brings in more flexibility from the research point of view.

529 The shift of the piston not only affects the electric production directly,
530 but also some technical aspects. Since the piston offset makes it easier to
531 reach the limit position for survival of the device. Hence, for the same wave
532 conditions, when considering the surge, the end-stop mechanism is activated
533 sooner; and consequently, the electric production utterly decreases. Further-
534 more, the more the end-stop mechanism is working the higher the probabil-
535 ity of breakdowns (slamming effects and high tensions in wires and springs).
536 Consequently, it is reasonable to think that a shorter lifespan of the device
537 and higher maintenance tasks mean higher costs in general. A possible way
538 to reduce such an undesired effect and capsize this trend would involve the
539 implementation control strategies, for instance, a moving stator which adapts
540 to the mean oscillatory position of the translator.

541 However, it is crucial to acquire deep knowledge on how all the effects

542 introduced by the surge influence the device.

543 The average annual production, is rather low for the single device. There-
544 fore, the exploitation concept for this kind of the devices lies in the wave
545 energy farm. Deploying a substantially elevated number of devices in ar-
546 rays. Some studies [36, 37] conclude that, if well spatially distributed, a
547 wave energy farm can produce at a higher rate than the single device. Since
548 the available wave power resource in the Mediterranean Sea is much lower
549 than in other areas of the planet, nowadays the only way to make wave en-
550 ergy exploitation feasible with point absorbers is by means of multiple-device
551 plants.

552 7. Acknowledgments

553 We would like to acknowledge Professor Giuseppe Passoni for the very
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Highlights

- Point absorber WEC modeled with several degrees of freedom per body.
- A 2-body and a 3-body device modeled in, irregular waves, heave and surge.
- Coupling of mechanic (hydrodynamic and lines) and electromagnetic forces (PTO).
- Comparison between only heaving device and heaving and surging device.
- Comparison and analysis of the production between the different configurations.
- Production assessment in the Mediterranean Sea, Sardinia and Sicily.

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