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Modelling and field testing of a breakwater-integrated U-OWC wave energy converter with dielectric elastomer generator

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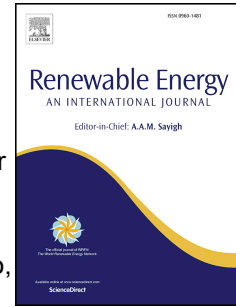
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1 **Modelling and field testing of a breakwater-integrated U-OWC**  
2 **wave energy converter with dielectric elastomer generator**

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14

15 **Abstract**

16 This paper introduces a theoretical and experimental study of a wave energy converter  
17 (WEC) that combines the two innovative concepts of U-oscillating water column (U-OWC)  
18 and dielectric elastomer generator (DEG) power take off (PTO). The U-OWC is a type of  
19 oscillating water column that features a U-shaped duct that is introduced to tune its dynamics  
20 to a certain wave period without active means of phase-control. The DEG is a compliant  
21 polymeric generator that makes it possible to convert mechanical energy into electrical  
22 energy by exploiting the large deformations of elastomeric membranes.

23 A lumped-parameter mathematical model of the proposed WEC has been set-up and a small-  
24 scale model/prototype has been preliminary tested in a benign real-sea environment. During  
25 experiments, relevant experimental data have been collected and used for assessing the  
26 reliability of the modelling approach. Beside the model validation, specific experiments have  
27 been conducted to test a simple but yet effective load shedding system based on the  
28 progressive opening of an air valve. Finally, a preliminary design of a full-scale U-OWC  
29 equipped with DEG-PTO has been studied through wave-to-wire analysis. The obtained  
30 numerical results show an overall performance that is comparable with that of more  
31 conventional, expensive and complex PTO technology.

32  
33 *Keywords:* electroactive polymers; system dynamics; resonant systems; oscillating water  
34 column; U-OWC; sea test

35

## 36 **1. Introduction**

37 Among possible wave energy converter (WEC) architectures, the oscillating water column  
38 (OWC) is one of the most investigated both in laboratory and prototypal tests [1]. The OWC  
39 is composed by a chamber with a water column that is opened to the wave field in the bottom  
40 part and topped by an air chamber in the upper part. In its conventional configuration, the air  
41 chamber has an air flow intake (e.g., an orifice) that connects the chamber to a power take-off  
42 (PTO) system. The incident waves excite the water column and induce its oscillating motion  
43 leading an alternating compression and decompression of the air in the chamber, that in turn  
44 produce an air flow through the chamber intake. The mechanical energy of the pressurized air  
45 flow is converted by the PTO device into electrical energy.

46 The OWC and PTO are the key elements of this WEC and they have been deeply investigated  
47 in literature [1–4].

48 Regarding OWCs, several systems have been proposed and developed as stand-alone  
49 solutions [5,6], breakwater integrated [7], floating [8] and in arrays [9]. In this context, in the  
50 recent years, the concept of U-OWC system has been introduced in [10]. This type of OWC  
51 features a narrow vertical U-shaped duct that connects the water column to the open wave  
52 field. This element is introduced for tuning the natural period of the water column oscillations  
53 with that of the incident waves. It was originally proposed in combination with marine  
54 structures for coastal protection. Indeed, it is integrated either in submerged breakwaters or in  
55 vertical breakwaters. A direct comparison with a classical OWC showed that it gives better  
56 performance in wind-generated seas and in swells because of the mentioned possibility of  
57 tuning conveniently its natural period and because of the larger exciting wave pressure  
58 amplitudes [11]. The most recent researches on this device provided a theoretical model used  
59 for estimating the system response in the time domain, which was validated by small scale

60 field experiments and a first prototype test used for further validating the model and  
61 evaluating the system performance at full scale [12–16].

62 As regards the PTO, the dominant technologies are the air turbines, such as Wells, impulse  
63 turbines, or the recently proposed biradial turbine [17], which share the common feature of  
64 rotating always in the same direction irrespective of the air flow direction. These elements  
65 were revisited in the last twenty years, in order to improve the efficiency of the whole system,  
66 overcome drawbacks of the existing technologies and take advantage of recent new findings.

67 Recently, dielectric elastomer generators (DEGs) have been proposed as a possible  
68 alternative technology for the implementation of PTO [18,19]. DEGs are deformable  
69 capacitors based on multifunctional dielectric polymeric materials, referred to as dielectric  
70 elastomers (DEs), originally conceived for robotic applications [20,21]. DEGs exploit  
71 deformation-driven capacitance variations to perform direct conversion of an input  
72 mechanical work into direct-current electrical energy [22]. In the past, DEGs have been  
73 implemented according to a diversity of layouts, such as annular membranes subject to out-  
74 of-plane deformation [23], inflating diaphragms [24], and tubular membranes [25].

75 It has been suggested that DEGs can be efficiently employed to harvest energy from different  
76 sources, such as human walk, sea currents, and waves [25]. Previous studies indeed  
77 demonstrated that DEGs can convert energy densities of up to 780 J/kg (per unit dielectric  
78 material mass) [26] and power densities over 200 W/kg at operating frequencies similar to the  
79 wave frequencies [24].

80 Compared to more conventional PTO systems for wave energy harvesting, DEGs are free  
81 from rigid/metallic moving parts, they are made of cheap rubber-like materials that are  
82 corrosion-resistant and resilient [27,28]. In the past, several DEG PTO implementations for  
83 different WEC concepts have been proposed and demonstrated at the scale of laboratory  
84 prototype or wave-tank model [18,29–32]. One of the most interesting layouts is the circular

85 diaphragm DEG (CD-DEG), whose promising performance has been demonstrated by initial  
86 theoretical analyses [19] and by further studies on the optimization of the CD-DEG control  
87 aimed at maximising the wave power extraction [33]. Furthermore, experimental  
88 characterisation of the CD-DEG PTO was accomplished by some of the authors of the  
89 present paper through dry-run laboratory tests [34] and wave-tank tests on small-scale OWC  
90 prototypes [35], with rated power in the range 1-4 W. Those seminal experiments  
91 demonstrated DEGs capability to operate in dynamical conditions in combination with  
92 OWCs, converting a significant fraction of the input wave power into electrical power.  
93 However, those works were always conducted in controlled laboratory environments and  
94 validated against simulated waves. None of the previous works have presented  
95 experiments/validations conducted via real sea trials.

96 In this paper, we present a first set of preliminary real sea-tests based on a comprehensive  
97 theoretical investigation/design of a novel WEC that combines an U-OWC system [36] with  
98 a set of CD-DEGs as the PTO system. As the first step toward realistic operation at sea, the  
99 experiments considered in this article take into account the purely mechanical response of the  
100 U-OWC/DEG system, i.e. a passive system that is not include the capability of generating  
101 electrical power. The obtained data have been employed to validate a time domain  
102 mathematical model of the system response, and they are expected to serve as a basis for  
103 future testing. Additionally, a full-scale design for the proposed WEC is presented, which  
104 relies on the mechanical model validated in this paper and on experimental outcomes on CD-  
105 DEGs power generation obtained in the framework of previous works [35].

106 The paper is structured as follows. Sect. 2 describes the coupled layout of a U-OWC with a  
107 set of CD-DEGs as the PTO and it introduces a mathematical model for the system dynamics.  
108 Sect. 3 presents the experimental results and provides a validation of the proposed model.

109 Sect. 4 proposes and evaluates a concept design of a larger scale U-OWC/DEG wave plant.

110 Sect 5 finally presents the conclusions.

111

## 112 **2. Modeling of U-OWC with DEG PTO.**

113 This section describes the mathematical model of a system composed by a U-OWC caisson  
114 embodying a CD-DEG PTO system that is hereafter referred as U-OWC-DEG. First, a  
115 general description of the plant is given. Then, the equations of motion of the system are  
116 provided.

### 117 *2.1. U-OWC with DEG PTO: layout and features.*

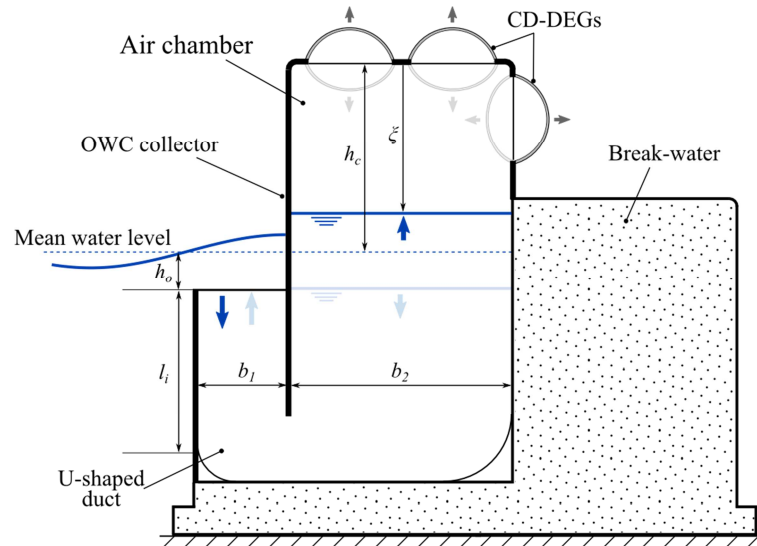
118 Figure 1 shows a schematic representation of the U-OWC-DEG concept. The system includes  
119 a U-OWC caisson that is made of a submerged U-shaped collector that is open to the action  
120 of the waves through a horizontal aperture on one side (left side in the picture), and encloses  
121 a hollow chamber on the other side. Such a chamber houses an oscillating water column with  
122 a volume of air on its top, and presents some circular apertures in the upper walls that make it  
123 possible to accommodate the CD-DEGs PTO.

124 Waves induce an oscillating pressure field on the opening of the U-shaped collector and  
125 produce an oscillating motion of the water enclosed in the caisson. As a result, the air volume  
126 is subject to fluctuating pressure. Such pressure variation produces the inflation and deflation  
127 of the elastomeric membrane (i.e. the variable capacitor) of the CD-DEG that, in combination  
128 with a driving power electronics, is responsible of the conversion of mechanical energy into  
129 direct current electricity [19] (more details on the working principle and layout are provided  
130 in Section 2.2.2).

131 The U-OWC-DEG system is also equipped with throttle valves in parallel with the CD-  
132 DEGs. The valve may be used for preventing overpressures in case of severe sea states.



133 Relevant geometric parameters are the width of the U-duct and of the OWC collector,  
 134 respectively,  $b_1$  and  $b_2$ ; the length of the U-duct  $l_i$ ; the inlet submergence  $h_o$ ; the distance  $h_c$   
 135 from the top of the air chamber to the mean water level; and the transversal width  $b_3$ .



136

137 Figure 1. Breakwater integrating a U-OWC with CD-DEGs.

## 138 2.2. Mathematical model.

139 The wave-to-wire model of a U-OWC with DEGs can be regarded as a chain of sub-blocks  
 140 accounting for different phenomena and/or different portions of the system, namely:

- 141 1) U-OWC hydrodynamic model, including the wave radiation-diffraction problem, the  
 142 calculation of the excitation/radiation actions on the U-OWC, and the dynamics of the  
 143 water column;
- 144 2) Compressible air chamber response;
- 145 3) DEG electro-elastic response;

146 In the following, the models are discussed separately, but it is emphasized that they constitute  
 147 a coupled system of nonlinear integro-differential equations in the time domain.

148

149 2.2.1. U-OWC hydrodynamic model.

150 The U-OWC water column oscillations are described in time domain by the unsteady  
 151 Bernoulli equation. The equation is derived by calculating the total head at the water column  
 152 inlet and the total head at the free surface of the inner water column. The unknown water  
 153 column displacement  $\xi$  is the distance from the top of the air chamber to the inner free  
 154 surface. Since energy losses along the water column and the U-duct are significant, head  
 155 losses are included in the model via the instantaneous acceleration-based method, which  
 156 accounts for steady head losses through a drag-type non-linearity and for unsteady head  
 157 losses through an inertial term. Both quantities are proportional to constants determined in  
 158 experimental tests [13,15].

159 The resulting water column equation of motion is as follows:

$$160 \quad M(\xi)\ddot{\xi} + C(\xi, \dot{\xi})\dot{\xi} + (\xi - h_c) - \frac{p}{\rho g} - \frac{1}{g} \frac{b_2}{b_1} \int_0^\tau \dot{\xi}(\tau) K(\tau - \theta) d\theta = -\frac{\Delta p^{(D)}}{\rho g}, \quad (1)$$

161 where  $\tau$  is the time;  $g$  is the acceleration of gravity;  $\rho$  is the water density;  $p$  is the relative  
 162 pressure in the air chamber;  $M(\xi)$  and  $C(\xi, \dot{\xi})$  are, respectively, time-dependent mass and  
 163 damping terms;  $K(\tau)$  is a convolution term which accounts for wave radiation loads; and  $\Delta p^{(D)}$   
 164 is the wave excitation pressure.

165 The mass and damping terms read as follow:

$$166 \quad M(\xi) = \frac{1+C_{in}}{g} \left[ \frac{b_2}{b_1} l_i + l_i + h_o + h_c - \xi \right] - \frac{b_2}{g b_1} H(\infty) \quad (2)$$

167 and

$$168 \quad C(\xi, \dot{\xi}) = \frac{1}{2g} \left\{ C_{dg} \left[ \frac{l_i}{R_{h1}} \left( \frac{b_2}{b_1} \right)^2 + \frac{l_i + h_o + h_c - \xi}{R_{h2}} \right] + 1 \right\} |\dot{\xi}| \quad (3)$$

169 where  $H(\infty)$  is an equivalent length accounting for the infinite frequency added mass,  $C_{in}$  and  
 170  $C_{dg}$  are coefficients accounting for the U-duct head losses, and  $R_{h1}$ ,  $R_{h2}$  are hydraulic radii of  
 171 the U-duct and inner chamber horizontal sections.

172 In the previous set of equations, the wave pressure at the inlet section has been taken into  
173 account by utilizing Cummins' representation of the radiated wave field under the assumption  
174 that the surrounding wave field can be described by potential theory [38,39]. In particular, the  
175 total wave pressure has been regarded as the sum of two contributions: 1) the excitation  
176 pressure  $\Delta p^{(D)}$  representing the wave pressure in a diffractive wave field; 2) and a second  
177 contribution related to the wave field radiated by the U-OWC. This second contribution  
178 further comprises two terms: a term accounting for the effect of infinite-frequency added  
179 mass,  $H(\infty)$  (included in the definition of  $M(\xi)$ ), and a convolution integral accounting for  
180 the hydrodynamic memory effects. Both  $H(\infty)$  and the kernel of the convolution integral  $K(\tau)$   
181 are geometric dependent parameters determined by solving pertinent boundary value  
182 problems (see [14]).

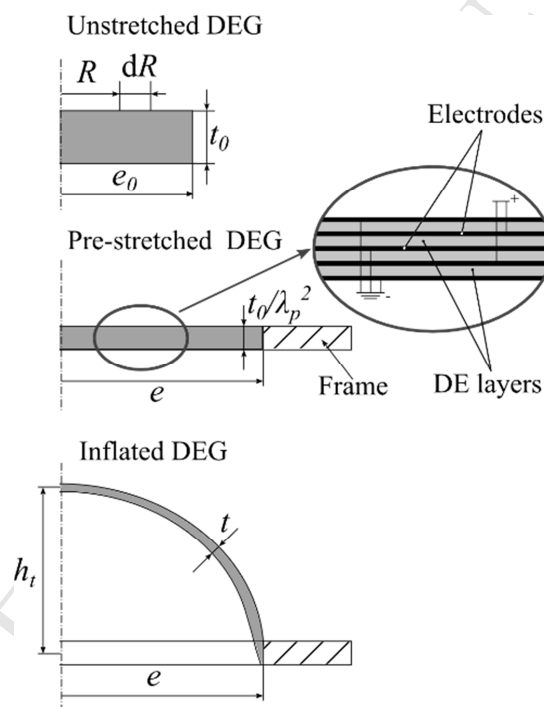
183

#### 184 2.2.2. DEG electro-mechanical model

185 The CD-DEG is an electrostatic generator that is able to convert the pneumatic work done by  
186 a pressure differential applied on its faces into electrical energy. The CD-DEG is a variable  
187 electrostatic capacitor shaped as a circular membrane. The applied pressure induces out-of-  
188 plane deformations of the membrane resulting in capacitance variations. The CD-DEG  
189 membrane is generally implemented as a stack of circular layers of DE and electrodes  
190 arranged to form a multilayer capacitor, as shown in Figure 2. Materials commonly used for  
191 the DE membranes are acrylics, natural and styrene-based rubber and silicones, which  
192 combine the electrical properties of large dielectric breakdown fields and low-conductivity  
193 with mechanical properties of large extensibility and reduced stiffness. Compliant electrodes  
194 are made of layers of electrically conductive materials that have to maintain low-resistivity  
195 even under large stretches. Compliant electrodes are usually implemented as thin metallic  
196 films sputtered on the DE substrates or carbon-loaded conductive elastomeric films [37].

197 In terms of the constitutive model, the DE material can be described as a non-linear  
 198 hyperelastic continuum (i.e., an elastic solid with non-linear stress-strain response) [40] with  
 199 dielectric behaviour. Modelling the CD-DEG using local continuum electro-elastic  
 200 formulations [41] is rather complex and computationally expensive. In order to provide a  
 201 practical formulation, suitable for design and preliminary analysis, a reduced lumped-  
 202 parameter model is provided in [19]. In this work, we use a further reduced model, as  
 203 presented in [18]. The model exploits some simplifying assumptions, previously validated  
 204 [18,33] and shortly recalled in the following.

205



206

207 Figure 2. Schematic view of a CD-DEG in its undeformed state (top), pre-stretched mounting  
 208 configuration (centre) and inflated configuration (bottom). The inset shows the detail of the  
 209 dielectric-electrode layers.

210

211 The geometry of the CD-DEG stack is schematically described in Figure 2. The symbols  $e_0$   
 212 and  $t_0$  denote the stack radius and total thickness in the undeformed state. The DEG is

213 mounted on the holding frame with a certain pre-stretch,  $\lambda_p$ , which takes its radius to  
 214  $e = \lambda_p e_0$ . Rubber-like materials are incompressible (their volume does not change after  
 215 deformation), therefore, the CD-DEG diameter after pre-stretching is  $t_0/\lambda_p^2$ . Upon application  
 216 of a pressure difference  $p$  between the DEG lower and upper faces, the latter displaces from  
 217 the flat equilibrium configuration and undergoes out-of-plane expansion.

218 As demonstrated in [18], the equilibrium pressure  $p$  associated to a given geometric  
 219 configuration and a voltage difference  $V$  applied on the DE layers has the following  
 220 expression:

$$221 \quad p = \frac{dU_m}{d\Omega_c} - \frac{V^2}{2} \frac{dC}{d\Omega_c}, \quad (4)$$

222 where  $U_m$  is the elastic energy of the DE layers,  $\Omega_c$  is the volume subtended by the deformed  
 223 CD-DEG shell, and  $C$  is its capacitance.

224 Consistently with the assumptions presented in [19], the deformed CD-DEG is approximated  
 225 as a thin spherical shell with non-uniform thickness. Therefore, its configuration can be  
 226 uniquely identified by the displacement  $h_t$  of the tip element from the equilibrium plane  
 227 (positive upwards).

228 Using the assumption of spherical deformation,  $\Omega_c$  relates to  $h_t$  as follows:

$$229 \quad \Omega_c = \frac{\pi}{6} h_t (h_t^2 + 3e^2), \quad (5)$$

230 It is also assumed that the deformation state is completely equibiaxial (i.e., the stretch is the  
 231 same in any direction tangent to the shell surface), though it is not uniform over the DEG. In  
 232 [19], it has been shown that this assumption provides a good agreement with finite-element  
 233 simulations in a wide range of DEG deformations, comprised at least between  $h_t = -e$  and  
 234  $h_t = e$ . The tangential stretch in a generic point of the DEG reads as follows:

$$235 \quad \lambda = e e_0 \frac{h_t^2 + e^2}{e^2 e_0^2 + h_t^2 R^2}, \quad (6)$$

236 where  $R$  identifies a material element lying at a distance  $R$  from the axis in the unstretched  
 237 state (see Figure 2). Notice that, owing to incompressibility, the thickness in a generic point  
 238 of the deformed CD-DEG shell is given by  $t = t_0/\lambda^2$ .

239 The deformed CD-DEG layers are parallel-plate capacitors, with total capacitance given by  
 240 the following expression:

$$241 \quad C = \frac{\pi \epsilon n_l^2 \lambda_p^2 e^2}{3t_0} \left[ \left( \frac{h_t^2 + e^2}{e^2} \right)^3 + \left( \frac{h_t^2 + e^2}{e^2} \right)^2 + \left( \frac{h_t^2 + e^2}{e^2} \right) \right], \quad (7)$$

242 where  $\epsilon$  is the DE material dielectric constant, and  $n_l$  is the number of dielectric layers in the  
 243 stack. The total thickness of the dielectric layers is assumed equal to the total DEG thickness,  
 244  $t_0$ , being the electrodes thickness negligible.

245 The DEG elastic energy is a function of the stretch. Modelling the DE material as  
 246 hyperelastic, the volumetric elastic energy density is given by a strain-energy function,  $\Psi$ ,  
 247 whose dependence on  $\lambda$  is expressed by a given constitutive model. The Mooney-Rivlin  
 248 hyperelastic model [40] is used under the assumption of incompressible solid with equibiaxial  
 249 deformation. The following expression holds for  $\Psi$ :

$$250 \quad \Psi = C_{1,0}(2\lambda^2 - \lambda^{-4}) + C_{0,1}(2\lambda^{-2} + \lambda^4), \quad (8)$$

251 where  $C_{1,0}$  and  $C_{0,1}$  are characteristic constitutive parameters. The total elastic energy,  $U_m$ , is  
 252 the result of the integration of  $\Psi$  over the total elastomeric volume:

$$253 \quad U_m = 2\pi t_0 \int_0^{e_0} R \Psi \, dR. \quad (9)$$

254 It is worth noticing that the calculation of the derivatives in Eq. (4) can be performed using  
 255 the chain rule, considering that  $U_m$ ,  $\Omega_c$  and  $C$  are functions of  $h_t$ .

256 Eq. (4) does not keep into account the mechanical inertia/kinetic energy of the DE material.  
 257 As observed in [33], the DEG dynamics is expected to be much faster than that of an OWC  
 258 (i.e., its natural frequency is much larger), thus, for the aim of this paper, the DEG response  
 259 can be assumed quasi-static.

260 The electric field in the DE layers is given by

$$261 \quad E = n_l \lambda^2 V / t_0, \quad (10)$$

262 and, since it depends on  $\lambda$ , it is not uniform throughout the CD-DEG.

263 The instantaneous electrical power output of the DEG is given by:

$$264 \quad P_u = -V\dot{Q}, \quad (11)$$

265 where  $Q = CV$  is the charge present on the electrodes.

266 The DEG operation can be ideally partitioned into control cycles, each corresponding to a full  
267 oscillation between the flat equilibrium configuration and a maximally expanded  
268 configuration (that depends on the external excitation). In fact, DEG operation involves  
269 bidirectional electrical energy fluxes: in each cycle, an amount of electrical energy is initially  
270 spent by the external circuit to charge the DEG ( $P_u < 0$ ), and a larger amount of electrical  
271 energy is successively recovered ( $P_u > 0$ ) by progressively discharging the DEG. Several  
272 control strategies have been proposed for CD-DEGs employed as the PTO in OWCs,  
273 including prediction-less controls [18,19] and advanced controllers based on a statistical  
274 knowledge of the current sea state [33].

275

### 276 2.2.3. Air chamber model.

277 The U-OWC model and the CD-DEG model are coupled by means of the air pocket model.  
278 The latter relies on the air mass and energy conservation applied to the air volume in the  
279 chamber. In this regard, the equation presented in this section considers a general case in  
280 which the device is equipped with a system connecting the air chamber to the atmosphere,  
281 like a valve, so that a certain air flow rate  $\dot{m}$  (positive if air flows out of the chamber) is  
282 included in the computation. Air compressibility is accounted for by assuming that the  
283 thermodynamic process is isentropic [42,43]. In this context, the equation describing the air  
284 chamber dynamics is,

$$285 \quad -\gamma(p + p_{atm}) \left( \frac{p+p_{atm}}{p_{atm}} \right)^{\frac{1}{\gamma}} \frac{\dot{m}}{\rho_{atm}} = \gamma \dot{\Omega}_a (p + p_{atm}) + \Omega_a \dot{p}, \quad (12)$$

286 where  $\gamma$  is the ratio of the specific heat at constant pressure and the specific heat at constant  
 287 volume;  $\rho_{atm}$  is the atmospheric air density;  $p_{atm}$  is the atmospheric density; and  $\Omega_a$  is the  
 288 instantaneous air pocket volume. The calculation of  $\Omega_a$  and its derivative leads to the  
 289 following equations:

$$290 \quad \Omega_a = b_2 b_3 \xi + \frac{\pi}{6} h_t (h_t^2 + 3e^2) N_D, \quad (13)$$

291 and

$$292 \quad \dot{\Omega}_a = b_2 b_3 \dot{\xi} + \frac{\pi}{2} (h_t^2 + e^2) \dot{h}_t N_D. \quad (14)$$

293 If the chamber is equipped with a throttle valve, the air flow rate can be calculated through  
 294 the equation

$$295 \quad \dot{m} = C_v \pi \frac{d_v^2}{4} \sqrt{2 \rho_{atm} \left( \frac{p+p_{atm}}{p_{atm}} \right)^{1/\gamma} |p| \text{sign}(p)}, \quad (15)$$

296 where  $C_v$  is an empirical discharge coefficient, and  $d_v$  is the reference valve diameter.

297

### 298 **3. In-field experimental validation.**

299 This section presents the results of field experiments aimed at validating the proposed  
 300 mathematical model of the coupled U-OWC/CD-DEG system. The experiments reported  
 301 herein are the first examples of sea trials on an OWC with DEGs. At this stage, attention was  
 302 restricted to the purely mechanical response of the system (regardless of electrical activation).  
 303 In the following, a wide scope of the experimental activity is provided, and a comparison of  
 304 experimental data and theoretical predictions is presented.



305 3.1. Set-up and data acquisition.

306 3.1.1 Experimental set-up

307 The experimental activity was carried out at the Natural Ocean Engineering Laboratory  
 308 (NOEL) in Reggio Calabria (Italy). A U-OWC caisson is installed in a benign natural basin,  
 309 where sea waves are generated naturally by the wind action. The U-OWC is incorporated in a  
 310 metallic caisson connected to a vertical breakwater serving, in this context, as a ballast for the  
 311 resulting system, while the CD-DEGs are installed on the ceiling of the air pocket (see Figure  
 312 3). The metallic caisson includes three independent chambers. Several identical CD-DEGs  
 313 are installed on one of the lateral chambers, working simultaneously as shown in Figure 3.

314



315 Figure 3. Metallic caisson incorporating the U-OWC (a) with, on the top, four CD-DEGs on  
 316 the lateral chamber (b). The U-OWC/CD-DEG is connected to a vertical breakwater serving  
 317 as a ballast for the system. One of the CD-DEGs has been painted black to facilitate post-  
 318 processing of the high-speed camera frames.

319

320 The chamber can house up to 4 CD-DEGs, though tests with a smaller number of DEGs can  
 321 be performed closing the unused DEG housings with solid steel disks and seals. On top of the  
 322 air chamber, a butterfly valve with nominal diameter of 100 mm is present, which is opened  
 323 in the presence of rough sea states to limit the DEGs deformation.

324 CD-DEG prototypes have been manufactured using a commercial acrylic film, VHB 4905,  
325 produced by 3M. This material has been chosen as it features low mechanical rigidity and  
326 large extensibility, thus, it is adequate for deploying small-scale DEG prototypes [18]. Each  
327 DEG was built by overlapping and bonding together different layers of VHB 4905 so as to  
328 form a solid dielectric layer. The unstretched thickness of the resulting layer was of 4-5 mm  
329 with a diameter of 115 mm, while the final diameter, after pre-stretching by  $\lambda_p = 3.4$  and  
330 installation on a rigid polycarbonate frame, was 390 mm.

331 In these tests, no electrodes were present on the CD-DEG prototypes, since no electrical  
332 activation was applied on the membranes and no power generation was pursued. In fact, the  
333 results of the tests were aimed at characterizing exclusively the mechanical response of the  
334 system.

335 An estimate of the power theoretically achievable with the considered CD-DEG samples (if  
336 electrical activation was applied) can be obtained based on constitutive models [19] and  
337 previous tests on CD-DEG samples made of VHB acrylic with carbon grease compliant  
338 electrodes [18,35]. According to those results, CD-DEGs can convert energy densities of 0.3-  
339 0.5 J/g per cycle. In the tests described here, the mass of dielectric material in each CD-DEG  
340 was about 40-50. Therefore, each of the employed CD-DEGs is potentially capable of power  
341 outputs of 10-25 W at an operating wave frequency of 0.4-0.5 Hz. Thus, equipping the device  
342 with four DEGs would give a theoretical rated power of 40-100 W.

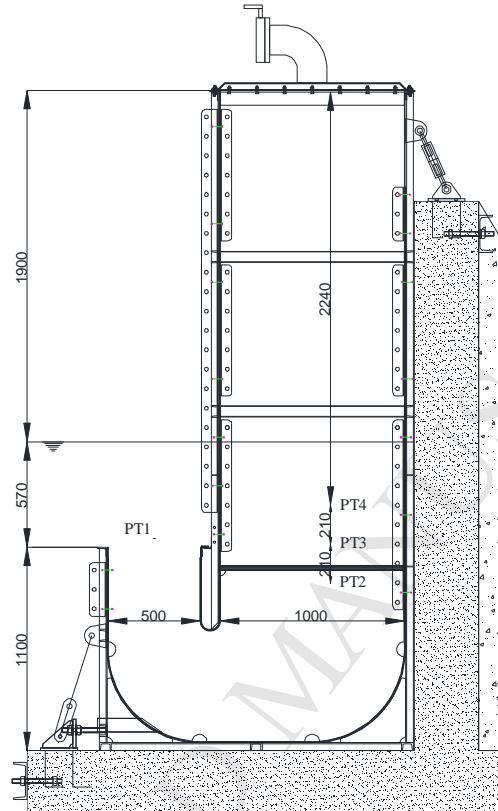
343 Relevant measurements are obtained with ATM.ECO/N pressure transducers (PT) from STS.  
344 Specifically, one PT is installed at the inlet section of the collector, while three PTs are  
345 installed within the water column and one PT is installed in the air chamber as shows in  
346 Figure 4 (in the figure, the PT installed in the air chamber is not shown). The figure and  
347 Table 1 also show the relevant geometrical parameters.

348

349 Table 1. Geometrical characteristics of the U-OWC chamber equipped with CD-DEGs.

$h_o$ [m]	$d$ [m]	$b_1$ [m]	$b_2$ [m]	$b_3$ [m]	$l_i$ [m]	$h_c$ [m]	$d_v$ [m]
0.57	1.9	0.5	1	1.23	0.8	1.9	0.10

350



351

352 Figure 4. Vertical cross-section of the U-OWC and location of the pressure transducers (PT)

353 in the water column. Lengths are in millimeters.

354

### 355 3.1.2 Data collection and post-processing

356 The PTs data were recorded with a sampling frequency of 10 Hz using a NI cDAQ-9174

357 acquisition board by National Instrument. The data were collected in short records

358 representative of individual sea states. Specifically, each record was composed by 3000

359 samples, hence, each time series has a duration of 5 minutes, which is the typical time

360 resolution of a sea state at the NOEL [44]. Globally, 102 sea states were collected, which are

361 representative of different sea conditions, spanning from wind-generated seas to mixed sea

362 states. The corresponding significant wave height and peak spectral periods ranged in the  
 363 intervals 0.15-0.45 m and 1.8-3.3 s.

364 The pressure data were used to simultaneously measure the excitation and the water column  
 365 oscillation. In particular, the PT at the inlet section provides the wave pressure,  $\Delta p_w$ ,  
 366 cumulating the contribution due to diffracted and radiated waves, while the PTs in the water  
 367 column and in the air chamber are used to measure, indirectly, the water column  
 368 displacement. For this purpose, the method described by Boccotti et al. [45] and by Malara et  
 369 al. [13] is employed. Specifically, given the simultaneous measurements of two PTs under  
 370 water (e.g., the upper and the lower one) and of the PT in the air chamber, the water column  
 371 acceleration ( $\ddot{\xi}$ ) is calculated by the equation

$$372 \quad \ddot{\xi} = g + \frac{p_u - p_l}{\rho \Delta z}, \quad (16)$$

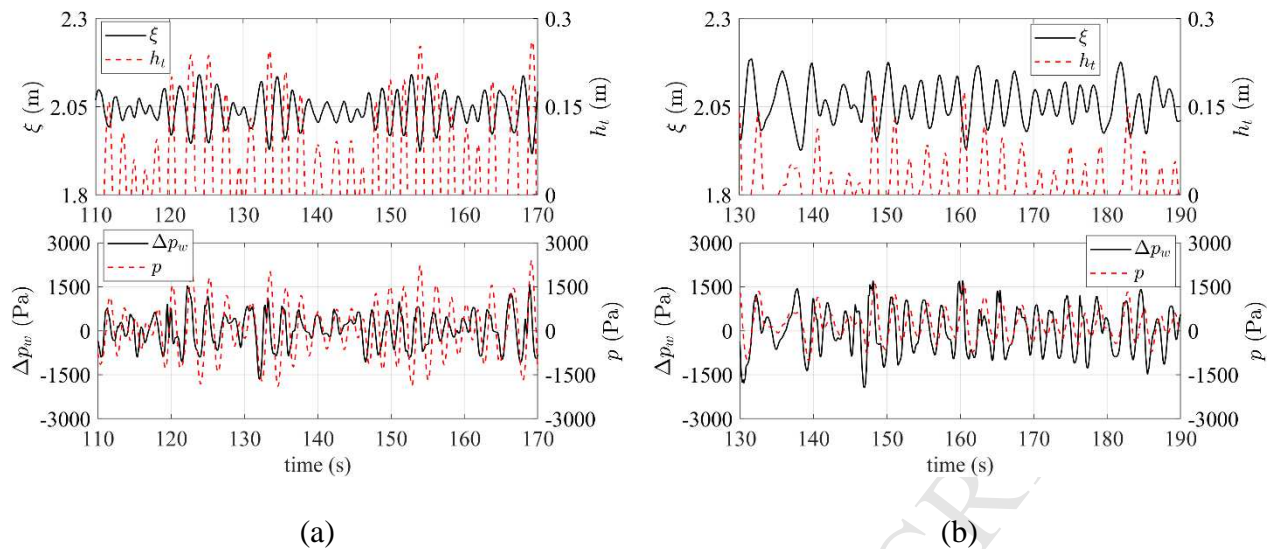
373 where,  $p_l$  and  $p_u$  are the instantaneous pressures measured by the lower and the upper  
 374 pressure transducers respectively, and  $\Delta z$  is their vertical distance. Then, the instantaneous  
 375 displacement  $\xi$  is calculated by the equation

$$376 \quad \xi = h_l - \frac{p_l - p}{\rho(g - \ddot{\xi})}, \quad (17)$$

377  $h_l$  being the distance between the lower pressure transducer and the top of the U-OWC.

378 The deformation of one of the CD-DEGs was acquired by means of a high-speed camera  
 379 (Point Grey GS3-U3-23S6M-C with lens 250F6C). The camera was placed at a distance of  
 380 approximately 2 m from the DEGs, aligned with the top cover of the U-OWC collector (i.e.,  
 381 the equilibrium plane of the CD-DEGs). Data from the camera were synchronised with the  
 382 PTs acquisitions through an external analogical trigger. Upwards deformations only were  
 383 captured by the camera, as the membrane was hidden by the air chamber walls during its  
 384 downward stroke. The acquired frames were then processed to obtain time-series of the CD-  
 385 DEG tip elevation,  $h_t$ , using the procedure described by Moretti et al. [18]. Owing to the high  
 386 sensitivity of the high-speed camera to fouling and humidity, measurement of the CD-DEGs

387 deformation was restricted to a few datasets. The effect of the DEGs on the system dynamics  
388 is however still measurable through the analysis of the time-series of  $\xi$  and  $p$ .  
389 Examples of time-series of the different measured variables are reported in Figure 5, which  
390 shows a comparison of two tests featuring similar sea conditions, 4 CD-DEGs with  $t_0 = 5$   
391 mm, and two different aperture levels of the valve (closed and fully-open). In the presence of  
392 closed air chamber, the oscillations in  $p$  are larger (since no flow is practically exhausted  
393 through the valve), while oscillations in  $\xi$  are smaller. In effect, despite introducing a  
394 damping contribution in the water column dynamics, the valve aperture causes a reduction in  
395 the mechanical stiffness of the air chamber–DEGs system. The air pressure and the DEG tip  
396 displacement are in phase, since the electrically inactive DEG behaves as a purely elastic  
397 component (except for viscoelastic dissipative effects). For the same reason,  $p$  and  $h_t$  are in  
398 phase-opposition with  $\xi$  when the air chamber is closed, whereas some small phase-shifting  
399 is present when the valve is open (due to the air chamber dynamics introduced by the valve,  
400 described by Eq. (12)). Phase shifting among  $\Delta p_w$  and the other variables is always present,  
401 as a consequence of the water column dynamics (see Eq. (1)).  
402 The oscillation amplitude of the CD-DEG monotonically increases with the air pressure, i.e.,  
403 it is smaller when the valve is open (in spite of larger oscillations in  $\xi$ ). This result suggests  
404 that a relief valve might be effectively employed as a safety device to protect the CD-DEGs  
405 in rough sea states.  
406 A wider analysis of experimental results and comparison of different operating conditions is  
407 reported in [36], where the effect of the CD-DEGs on the U-OWC dynamics is investigated  
408 through a frequency-domain approach.  
409



410 Figure 5. Time-series of water column displacement  $\xi$ , CD-DEG tip displacement  $h_t$ , wave  
 411 pressure  $\Delta p_w$ , and air relative pressure  $p$  for two tests, in the presence of 4 CD-DEGs with  
 412  $t_0 = 5$  mm. (a) Closed air chamber; (b) fully-open valve. Time-series of  $h_t$  are only relative  
 413 to upwards membrane displacement, as the membrane was hidden by the collector walls  
 414 during downward oscillations.

### 416 3.2. Model validation.

417 This section discusses a validation of the proposed U-OWC/CD-DEG coupled model.  
 418 Attention is here restricted to the coupled dynamical response of the U-OWC and the DEGs.  
 419 Therefore, attention is restricted to the following set of sub-models: the water column  
 420 dynamics, the air chamber response, and the CD-DEG elastic model, excluding the radiation-  
 421 diffraction problem and the effect of electrical activation. The latter sub-models have been  
 422 validated in the past through purposed experiments [13,35] or against numerical models [46],  
 423 and they might be further explored in the future through advanced tests including fully-  
 424 functional DEGs and U-OWC nearfield sensing.

425

### 426 3.2.1. Model set-up and calibration.

427 The time domain dynamical model of the U-OWC with DEGs has been implemented in a  
428 Matlab & Simulink environment. The numerical model combines: the U-OWC dynamic  
429 equation (Eq. (1)), the dynamic equation of the air chamber with throttle valve (Eq. (12)) and  
430 the mechanical model of the CD-DEGs (Eq. (4), considering only the first term relative to the  
431 purely elastic response).

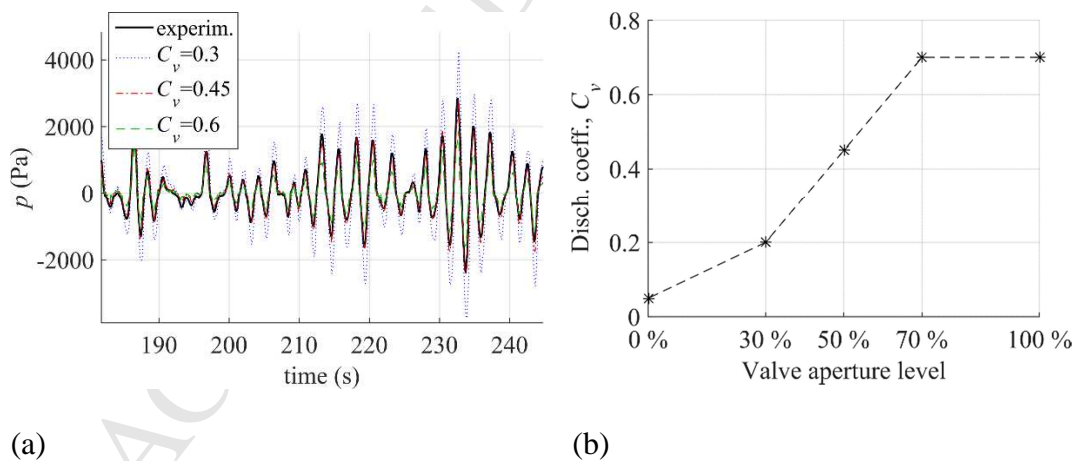
432 Simulations make use of the experimental datasets of the wave pressure  $\Delta p_w$  (i.e., the sum of  
433 the radiation and diffraction wave pressure) as the input. The simulation output consists of:  
434 the water column displacement,  $\xi$ , the air chamber pressure,  $p$ , and the CD-DEG tip  
435 displacement,  $h_t$ .

436 The parameters used in the U-OWC dynamic sub-model are the collector dimensions given in  
437 Table 1 and the hydraulic loss parameters. Based on previous tests on the reference U-OWC  
438 collector [13], the following loss parameters were used:  $C_{dg} = 0.71$ ,  $C_{in} = 0.13$ .

439 The parameters in the CD-DEG elastic model are the Mooney-Rivlin coefficients,  $C_{0,1}$ ,  $C_{1,0}$ .  
440 Based on available tests on the VHB material [18], the following values were considered:  
441  $C_{0,1} = 3700$  Pa,  $C_{1,0} = 380$  Pa. For the air chamber model, atmospheric air density  $\rho_{atm} =$   
442  $1.2 \text{ kg/m}^3$  and adiabatic heat ratio  $\gamma = 1.4$  were assumed.

443 The throttle valve has 10 positions, corresponding to different levels of aperture (from 100%  
444 open to fully-closed). In this experimental activity, in particular, five aperture levels were  
445 tested (including the fully open and closed states) that were sufficient for detecting clear  
446 alterations in the system dynamics associated with the throttle valve aperture level. The  
447 values of the discharge coefficient,  $C_v$ , corresponding to the aperture levels employed in the  
448 tests were identified through an experimental calibration procedure. Specifically, calibration  
449 tests were carried out with the valve mounted on the U-OWC collector, exploiting the air  
450 pressure variations induced by the water column oscillation. To isolate the contribution of the

451 valve, the DEGs were removed and replaced with undeformable disks. A set of acquisitions  
 452 were performed, with the valve set to different positions. In each test, we measured the  
 453 pressure  $p$  in the chamber and the level  $\xi$  of the water column. We then solved the dynamic  
 454 equation of the air chamber (Eq. (12), with  $h_t = 0$ ) for different values of  $C_v$ , using the  
 455 measured time-series of  $\xi$  as the input, hence obtaining a set of time-series for  $p$ . We thus  
 456 identified the value of  $C_v$  that minimizes the norm of the difference of experimental and  
 457 model-based pressure time-series. Figure 6.a shows a comparison of experimental and  
 458 theoretical time-series for a specific calibration test. Repeating this operation for each  
 459 acquisition allowed the identification of a value of  $C_v$  for each of the relevant aperture levels  
 460 used in the experiments, as shown in Figure 6.b. It should be noted that the discharge  
 461 coefficient of the fully-closed valve is slightly larger than 0, as a result of the air leaks in the  
 462 air chamber connections and in the valve. Moreover, over a given level of aperture (i.e., when  
 463 the free flow passage area is rather wide), the value of  $C_v$  becomes practically constant.  
 464



465 Figure 6. Discharge coefficient calibration: (a) comparison of the experimental air pressure  
 466 time-series versus model-predicted time-series relative to different values of the discharge  
 467 coefficient for a test with valve 50 % open; (b) Calibrated values of  $C_v$  at the different  
 468 aperture levels of the valve used in the tests.

469

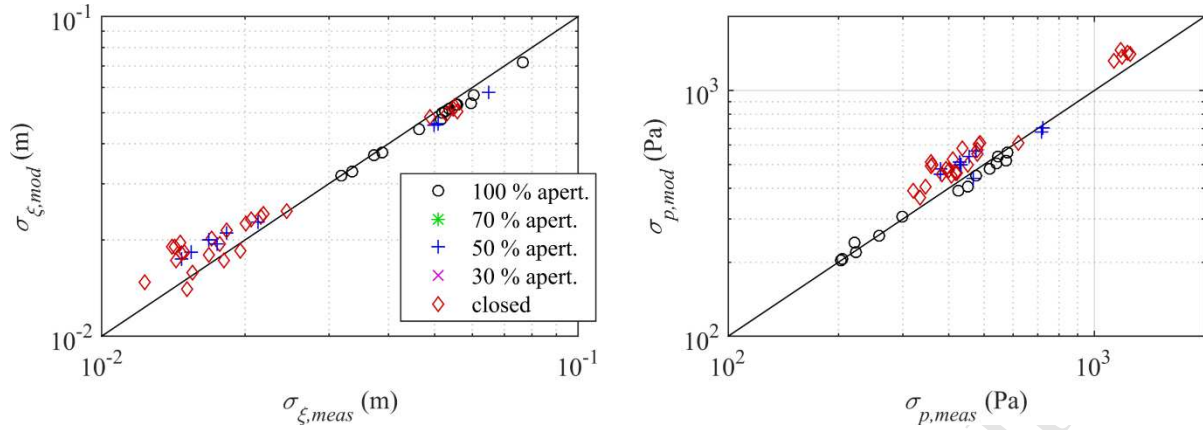


470 3.2.2. *Comparison of model and experimental data.*

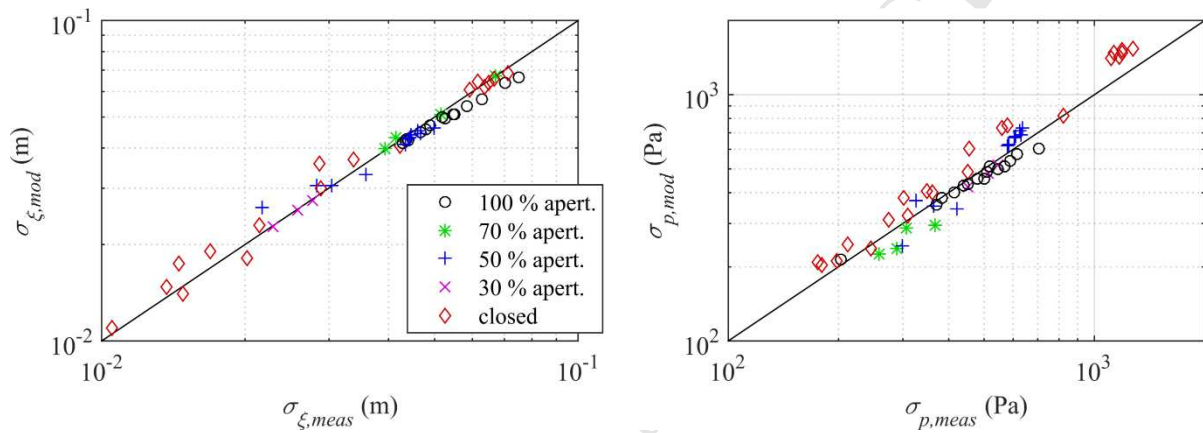
471 A set of simulations were run, using the approach described in Sect. 3.2.1. Each simulation  
472 aims at reproducing the U-OWC behaviour in a specific experimental dataset. Different  
473 records differ in terms of the following parameters (used as inputs in the simulations):  
474 measured pressure at the U-OWC inlet, number of DEGs in the chamber, DEGs thickness,  
475 discharge coefficient associated with the current valve position. An overview of the model  
476 performance against the different tests is provided in Figure 7, where we present vis-à-vis  
477 plots comparing the measured standard deviations of the water column displacement and the  
478 air chamber pressure ( $\sigma_{\xi,meas}$  and  $\sigma_{p,meas}$  respectively) and those obtained through the model  
479 ( $\sigma_{\xi,mod}$ ,  $\sigma_{p,mod}$ ). Direct comparison between modelled and experimental oscillation  
480 amplitude  $h_t$  of the CD-DEGs tip is, in contrast, omitted, as the tip height was measured only  
481 in a few tests and only during the outward stroke of the DEGs.

482 Figure 7.a shows results relative to the tests/simulations with 3 DEGs installed on the U-  
483 OWC chamber, while Figure 7.b is relative to the cases with 4 DEGs. In the plots, datasets  
484 relative to different aperture levels of the valve are denoted by different markers.

485 The plots show that, in average, tests with closed air chamber exhibit lower oscillation  
486 amplitude of  $\xi$  and larger oscillation amplitude in  $p$  than the corresponding tests with fully-  
487 open valve, as already observed in Sect. 3.1.2. Despite the broad variety of sea states and  
488 operating conditions characterising the various tests, the model is statistically capable of  
489 predicting the experimental behaviour rather effectively. In particular, data appear equally  
490 distributed above the bisector line of the vis-à-vis plots, thus confirming that the model does  
491 not provide any systematic overestimate (or underestimate) of the system oscillations.



(a) Tests with 3 DEGs



(b) Tests with 4 DEGs

492 Figure 7. Vis-à-vis comparison of experimental and model-predicted standard deviation of  
 493 the time-series of the water column oscillations (left column) and the air chamber pressure  
 494 (right column). Different markers refer to different levels of aperture of the valve. Plots (a)  
 495 are relative with tests with 3 DEGs, plots (b) refer to tests with 4 DEGs.

496

497 Similarly to Malara et al. [13], in order to quantify the model error, for each dataset we define  
 498 error metrics based on the time-series of  $\xi$  and  $p$ :

$$499 \quad \varepsilon_{\xi} = \frac{\|\xi_{meas} - \xi_{mod}\|}{\sigma_{\xi,meas}}, \quad \varepsilon_p = \frac{\|p_{meas} - p_{mod}\|}{\sigma_{p,meas}} \quad (18)$$

500

501 where the subscript *meas* denotes the measured time-series whereas *mod* denotes model  
 502 time-series, and operator  $\|\cdot\|$  is the norm of the argument function. Errors relative to the  
 503 different scenarios considered in Figure 7 (average over different datasets) are reported in  
 504 Table 2.

505

506

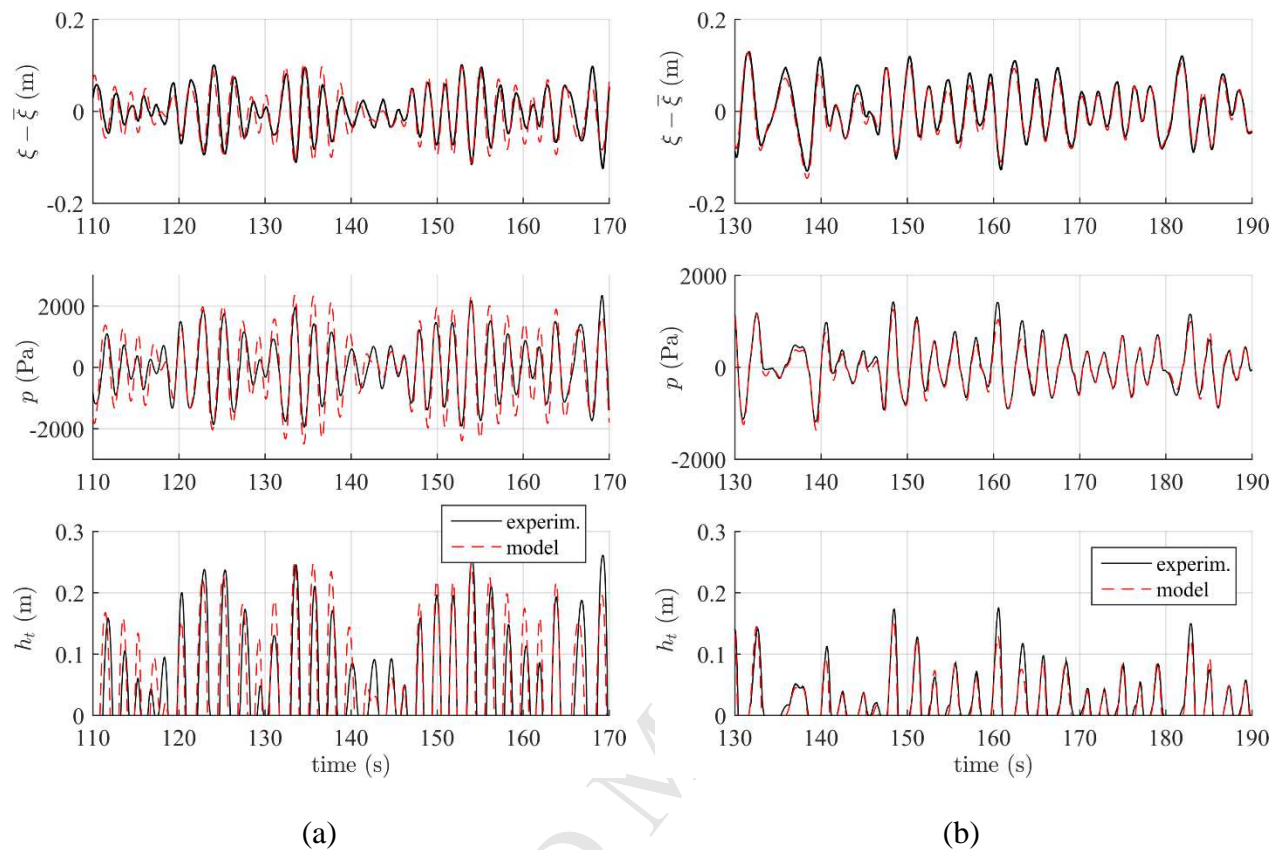
Table 2. Estimate of the model error over the time-series of  $\xi$  and  $p$ .

	$\varepsilon_{\xi}$	$\varepsilon_p$
Tests with 3 DEGs	0.41	0.42
Tests with 4 DEGs	0.33	0.34
All tests	0.37	0.38

507

508 With reference to two datasets previously considered in Figure 5, for which measurements of  
 509 the CD-DEG's tip height are also available, Figure 8 presents a comparison of experimental  
 510 and theoretical time-series. In these tests, the model tends to overestimate the oscillation  
 511 amplitudes of the different variables in the case of closed air chamber, and to underestimate  
 512 them when the valve is open. The average errors over the considered portions of the datasets  
 513 are as follow:  $\varepsilon_{\xi}=0.39$  and  $\varepsilon_p=0.50$  for the dataset shown in Fig. 8a (i.e., larger than the  
 514 average values for the different tests considered in Table 2);  $\varepsilon_{\xi}=0.22$  and  $\varepsilon_p=0.21$  for the  
 515 dataset shown in Fig. 8b (lower than the average error on the different tests). Despite the  
 516 existing discrepancies, these results confirm a remarkable ability of the model to describe the  
 517 trends and the dynamics of the relevant physical variables, including the CD-DEGs  
 518 deformation. In particular, the possible presence of rather large errors in correspondence with

519 isolated oscillations does not affect the global agreement of the theoretical and experimental  
 520 time-series on a statistical basis and the corresponding values of the average error.



521 Figure 8. Comparison of model and experimental time-series of  $\xi$  (minus its mean value  $\bar{\xi}$ ),  $p$   
 522 and  $h_t$  for two tests, in the presence of 4 CD-DEGs with  $t_0 = 5$  mm. (a) Closed air chamber;  
 523 (b) fully-open valve.

#### 525 4. Analysis and simulation of a full-scale U-OWC with DEG PTO

526 Based on the proposed model, in this section we present a theoretical analysis of a full-scale  
 527 application of a U-OWC equipped with a set of CD-DEGs as the PTO system.

528 In the analysis, reference is made to an existing U-OWC collector, installed in the port of  
 529 Civitavecchia (Italy) [47,48]. The pilot wave farm in Civitavecchia is composed by a set of  
 530 U-OWC chambers (with target power of 20 kW each) integrated on bottom-fixed  
 531 breakwaters.

532 With the aim of evaluating the potential performance of DEG PTOs in full-scale applications,  
 533 we hereby assume to replace the air turbine in one of the Civitavecchia U-OWC plant with a  
 534 set of CD-DEGs. In this regard, reference is made to DEGs made of an optimised silicone  
 535 material, specifically developed for DE application.

536 Silicone elastomers seem to be the most promising candidates for future DE applications. In  
 537 effect, compared to other DEs, they bring a number of advantages, including: large potential  
 538 for the improvement of electro-mechanical properties through the addition of compounds  
 539 [49,50]; availability of manufacturing processes for high-quality films; and the possibility of  
 540 manufacturing reliable dielectric-electrode stacks, by depositing carbon-charged silicone  
 541 electrodes on the DE layers by blade casting, spray coating or screen printing [34,51].

#### 542 4.1 Layout and assumptions

543 We consider a single U-OWC collector, the submerged part of which has the dimensions  
 544 indicated in Table 3 [48]. The upper (out-of-water) portion of the collector is equipped with  
 545 four CD-DEGs with the features listed in Table 3, installed on different (top and lateral) walls  
 546 of the collector. The values of the hydraulic loss parameters for the Civitavecchia U-OWC  
 547 chambers, provided in [15], are  $C_{dg} = 0.46$ ,  $C_{in} = 0.19$ .

548

549 Table 3. Features of the considered full-scale U-OWC chamber with DEG PTO.

U-OWC dimensions		DEG PTO features		DE material properties	
$h_o$	2 m	$N_D$	4	Hyperelastic parameters	$C_{1,0} = 230$ kPa; $C_{0,1} = 0$
$d$	14.2 m	$e$	1.4 m	Dielectric constant	$\epsilon = 3.9 \cdot 8.85 \cdot 10^{-12}$ F/m
$b_1$	1.6 m	$t_0$	0.05 m	Rupture stretch	$\lambda_u = 8.8$
$b_2$	3.2 m	$\lambda_p$	1.3	Break-down electric field: $E_{BD} = E_0 \lambda^{r_e}$	$E_0 = 100$ MV/m
$b_3$	3.87 m	$n_l$	80		$r_e = 1$
$l_i$	5 m				

550

551 The DEGs are made of a silicone material with the properties described by Madsen et al.  
552 [49]. This material is obtained blending a commercial silicone elastomer (ELASTOSIL  
553 LR3043/50) with a silicone oil (30 phr of LMS-152) so as to enhance the dielectric properties  
554 of the original elastomer while reducing its elastic stiffness. Although that material has been  
555 only investigated in the laboratory and is not a commercial product yet, we believe that it is  
556 representative of upcoming materials conceived for use as dielectric elastomer. The operating  
557 limits of the material are the ultimate rupture stretch,  $\lambda_u$ , expressing the maximum  
558 extensibility of the elastomer, and the maximum admissible value of the electric field, namely  
559 the break-down electric field,  $E_{BD}$ . Though in [49] the break-down field in the unstretched  
560 state only is measured (namely, 130 MV/m), based on literature results on different DEs [24],  
561 we assume that  $E_{BD}$  increases proportionally with the stretch  $\lambda$  to the power of  $r_e$  (see Table  
562 3), with the value at unitary stretch conservatively taken equal to 100 MV/m. The considered  
563 silicone material is stiffer than the VHB acrylic considered in Sect. 3, therefore, the chosen  
564 pre-stretch is rather small. The total volume of DE material (over the 4 DEGs) is  $0.74 \text{ m}^3$ .  
565 The number of layers,  $n_l$ , guarantees that the DEG output voltage is below 50 kV.

566 The response of the U-OWC with DEG PTO is investigated in a set of typical sea states at the  
567 Civitavecchia site. The average wave climate at the installation site is characterized by sea  
568 states with JONSWAP spectral distribution [52] (standard peak enhancement factor of 3.3)  
569 whose peak period,  $T_p$ , and significant wave height,  $H_s$ , are correlated as follows [44]:

$$570 \quad T_p = 8.5\pi\sqrt{H_s/(4g)}. \quad (19)$$

571 In order to assess the response of the device in rough sea conditions, significant wave heights  
572 of up to 5 m are considered.

573

## 574 4.2 CD-DEGs control

575 In this work, we make reference to a simple control strategy which does not require a-priori  
 576 knowledge of the incident waves, and only relies on the measured DEG deformations. Such a  
 577 strategy has been previously discussed in [19,33]. The operating cycle of a DEG is divided  
 578 into the following phases:

- 579 1) When the DEG expands from the flat configuration ( $h_t = 0$ ) to an inflated  
 580 configuration (either inwards or outwards), no voltage is applied on its electrodes.
- 581 2) As the deformation (and capacitance) reaches a maximum, the DEG is rapidly  
 582 charged and its voltage is risen to the maximum value compatible with break-down.  
 583 During this phase (called priming), electrical energy is initially spent to charge the  
 584 DEG.
- 585 3) When the DEG moves back towards the flat position (i.e., its capacitance decreases),  
 586 the applied voltage is kept at the maximum value allowed by the break-down  
 587 condition. During this phase, the DEG outputs electrical power.
- 588 4) As the DEG reaches the flat position (minimum capacitance), it is fully discharged  
 589 and the stored energy is harvested.

590 In the simulations, the voltage rise during charging phase (1) and its decrease during  
 591 discharging phase (4) are simulated as quick first-order dynamics (with a characteristic time  
 592 much shorter than the full cycle duration).

593 Based on Eq. (10) and Table 3, the limiting condition for the voltage (applied during phase  
 594 3)) in relation to break-down is as follows:

$$595 \quad V \leq \frac{E_0 t_0}{n_l \lambda^{2-r_e}}. \quad (20)$$

596 Since the stretch  $\lambda$  is not uniform through the DEG (see Eq. (6)), the operating voltage during  
 597 phase 3) is obtained feeding the maximum stretch value (at the CD-DEG tip) into the right-  
 598 hand side of Eq. (20), namely

$$599 \quad V = \frac{E_0 t_0}{n_l \lambda_t^{2-\gamma_e}}, \quad (21)$$

600 where  $\lambda_t$  is the stretch calculated at the DEG tip (i.e., at  $R = 0$ ).

601

#### 602 *4.3 Safety mode operation*

603 We assume that the U-OWC air chamber is equipped with a safety valve with nominal  
 604 diameter  $d_v = 0.15$  m. Such a valve is closed in normal operating conditions, and it is partly  
 605 opened in the presence of rough sea states to limit the CD-DEGs deformation. We assume  
 606 that the level of aperture of the valve is adjusted on a mid-term basis, based on the knowledge  
 607 of the average wave parameters (e.g.,  $H_s$  or  $T_p$ ).

608 Though, according to Madsen et al. [49], the maximum admissible stretch  $\lambda_u$  on the CD-  
 609 DEGs is theoretically very large, we define a conservative threshold value,  $\lambda_{th}$ , that should  
 610 not be surpassed but for a reduced amount of time. This measure is intended to increase the  
 611 technical lifetime of the DE material, which, similarly to rubber, is expected to depend on the  
 612 amplitude of the cyclic stretch variations to which it is subjected [53]. Here, we use  $\lambda_{th} = 2$ .

613 The level of aperture of the valve (i.e., the discharge coefficient  $C_v$ ) in each sea state is  
 614 chosen accordingly, so as to guarantee that the stretch does not surpass  $\lambda_{th}$  for more than 5%  
 615 of the simulation time horizon. In statistical terms, this is equivalent to set an upper bound to  
 616 the probability that the DEG deformation surpasses the chosen threshold.

617 In a real application, extensive analyses should be performed in order to choose meaningful  
 618 values for  $\lambda_{th}$  and the corresponding limit percentage of occurrence. Such analyses should  
 619 keep into account fatigue tests on the selected DE materials and should realize a compromise  
 620 between an increase in DEG lifetime and a reduction in the energy production due to the  
 621 stretch limitation. Moreover, dedicated analyses should be conducted in order to identify  
 622 possible ageing effects due to electrical activation.



623

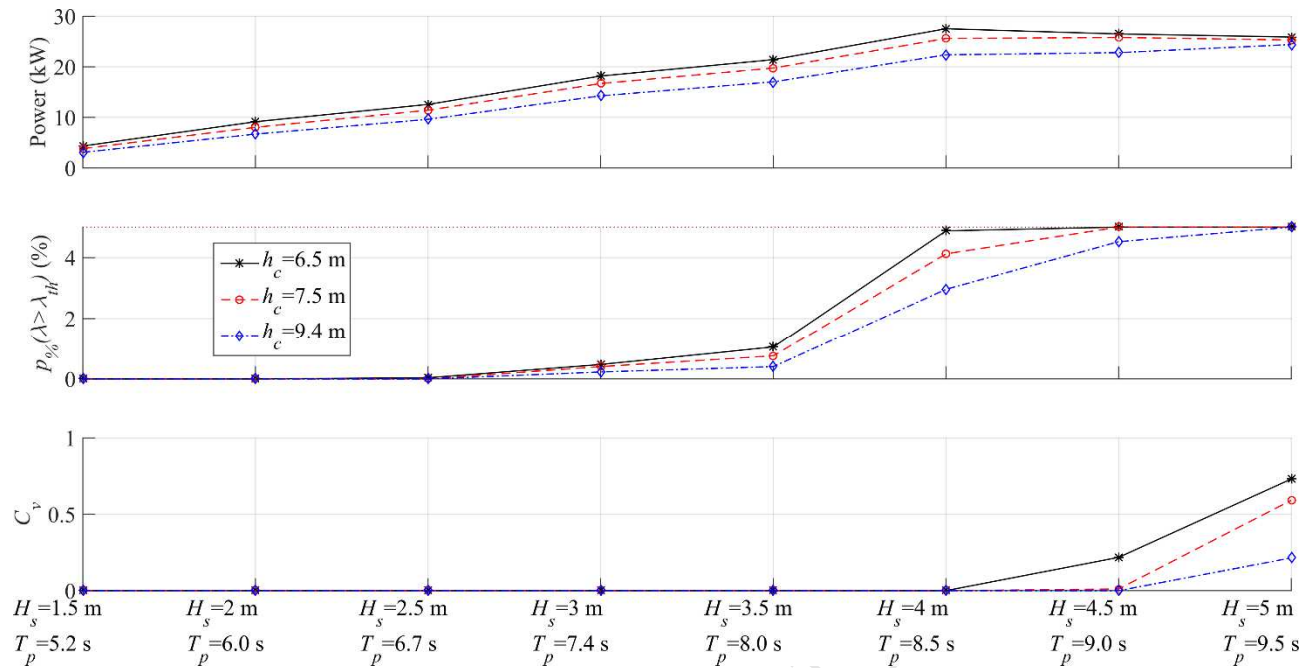
624 *4.4 Results and discussion*

625 The performance of the full-scale U-OWC has been simulated in a Matlab & Simulink  
626 environment. The U-OWC hydrodynamic parameters and the exciting pressure have been  
627 computed via the two-dimensional semi-analytical approach of Malara et al. [14]. The  
628 convolution integral involved in the computation of the radiation forces (see eq. (1)) has been  
629 approximated with a state-space model in order to reduce the computational burden [54]. In  
630 the simulations, different values of the emerged height  $h_c$  of the collector were considered.

631 Eight sea states with  $H_s$  between 1.5 and 5 m were considered. For each sea state, a  
632 simulation with a duration of 200 times the peak period was run, and the average power  
633 output was calculated from the DEG instantaneous power,  $P_u$  (see Eq. (11)). For the roughest  
634 sea states, in which aperture of the security valve is required, the calculation of the power  
635 output and the valve aperture was carried out through an iterative procedure. The iterative  
636 procedure was initiated by setting  $C_v = 0$ . Then, the coefficient was increased by steps of 0.1  
637 until the percentage occurrence of stretches larger than the threshold value  $\lambda_{th}$  was  
638 statistically reduced below 5%.

639 Simulation results are shown in Figure 9. The top plot shows the U-OWC power output for  
640 the different sea states (carrying increasing incident power). The central plot shows the  
641 percentage of the simulation time,  $p_{\%}$ , during which the DEGs stretch  $\lambda$  stays above the  
642 threshold  $\lambda_{th}$ . The bottom plot shows the minimum level of aperture of the security valve  
643 (expressed by  $C_v$ ) required to keep  $p_{\%} \leq 5\%$ :  $C_v = 0$  indicates that  $p_{\%} \leq 5\%$  is achieved  
644 keeping the valve completely closed.

645



646  
 647 Figure 9. Response and performance of a full-scale U-OWC with DEG PTO in a set of  
 648 reference sea states. Top plot: power output. Central plot: expected percentage of operating  
 649 time during which the DEGs stretch surpasses the threshold value,  $\lambda_{th}$ . Bottom plot:  
 650 Discharge coefficient expressing the required level of aperture of the security valve in the  
 651 different sea states.

652

653 The proposed design of the DEG PTO results in a rated power output between 20 and 30 kW,  
 654 consistently with simulation results relative to the scenario in which an air turbines is  
 655 employed as the PTO [55]. For instance, a similar analysis conducted via Monte Carlo  
 656 simulations was proposed by Malara and Arena [56], that provided power output estimations  
 657 for four different turbine models (monoplane with/without guide vanes, biplane and contra-  
 658 rotating). A comparison of the data produced in sea states with comparable significant wave  
 659 height and peak period shows that the obtained converted powers are similar. A reduction in  
 660 the air chamber height  $h_c$  (with respect to the nominal value of the Civitavecchia collectors,  
 661 namely  $h_c = 9.4$  m) results in an increase in the power output. Reducing  $h_c$  indeed causes a  
 662 reduction in the air chamber compressibility, which in turn leads to larger DEG deformations.

663 In practice, the value of this design parameter should represent a compromise between the  
664 converter performance and safety requirements for the port infrastructure.

665 The trend of the power output is monotonically increasing with increasingly energetic sea  
666 states, up to  $H_s = 4$  m. In rougher sea states, the power output experiments a saturation as a  
667 result of the partial aperture of the security valve. The required level of aperture of the valve  
668 increases with the incident wave power and with decreasing values of  $h_c$ . In practice, despite  
669 representing a limiting factor for the performance, an air chamber with large compressibility  
670 guarantees robustness in the presence of rough sea states, as it allows the achievement of a  
671 dramatic reduction in the DEGs deformation with relatively small diameters of the throttle  
672 valve. It is worth noticing that, in the mildest sea states,  $p_{\%}$  is equal to 0 as the maximum  
673 deformation of the DEGs is permanently below the threshold value.

674 The presented results demonstrate that DEGs are a promising PTO solution for the U-OWC,  
675 as they potentially enable performance equal or better than that achievable with air turbines,  
676 despite their greater architectural simplicity. Moreover, simulation results suggest that safe  
677 plant operation can be achieved even in relatively rough sea states through the employment of  
678 a simple throttle valve.

679

## 680 **5. Concluding remarks**

681 This paper deals with the assessment of a U-oscillating water columns (U-OWCs) wave  
682 energy converter equipped with a dielectric elastomer generator (DEG) power take-off  
683 system. The mathematical model proposed in the paper has been obtained by combining a  
684 one-dimensional model based on the unsteady Bernoulli equation with an isentropic  
685 thermodynamic model for the air chamber dynamics, and a lumped-parameter electro-  
686 mechanical model of the DEG. The model reliability has been assessed against field data  
687 obtained from a small-scale experiment conducted in the NOEL (Natural Ocean Engineering

688 Laboratory) benign natural basin in Reggio Calabria (Italy). The presented experimental  
689 activity served as a first pilot investigation of a U-OWC with DEGs at sea. In this regard, the  
690 purely mechanical response of the system was investigated.

691 Based on the collected experimental data, it has been demonstrated that the model is able to  
692 capture the crucial features of the system dynamics in a variety of sea states, without  
693 systematic over- or under-estimations of the relevant physical parameters.

694 The validated model has been used for predicting the performance of a full-scale plant. For  
695 this purpose, the plant constructed in the port of Civitavecchia has been considered as a case  
696 study. The proposed mathematical model has been applied, assuming that one chamber of the  
697 plant is equipped with circular diaphragm DEGs (CD-DEGs) instead of turbines. Power  
698 output data have been obtained by running numerical simulations starting from spectrum  
699 compatible realizations of different sea states. It has been shown that a system integrating U-  
700 OWC and CD-DEGs may provide an average power output comparable to that of a U-OWC  
701 with turbines. Further, it has been shown that the presence of the CD-DEGs does not affect  
702 the reliability of the system, as the use of throttle valves prevents the inception of excessive  
703 pressures in severe sea states.

704 The results presented in this article pave the way for different future activities aimed at the  
705 advancement of the U-OWC with DEGs. The gathered data and numerical models will  
706 primarily allow the development of dry-run experiments aimed at evaluating control  
707 strategies and power output performance of DEG prototypes subject to loading histories  
708 similar to those recorded at sea. Furthermore, building upon the experience of this pilot  
709 activity, sea tests on DEG prototypes capable of actively extracting electrical power from the  
710 presented U-OWC plant will be carried out in the future.

711 **List of symbols**

712

**Physical constants**

<i>Symbol</i>	<i>Unit</i>	<i>Description</i>
$g$	$\text{m/s}^2$	Acceleration of gravity
$p_{atm}$	Pa	Atmospheric pressure
$\gamma$		Adiabatic exponent
$\rho$	$\text{kg/m}^3$	Sea water density
$\rho_{atm}$	$\text{kg/m}^3$	Atmospheric air density

**U-OWC geometry and hydrodynamic model**

<i>Symbol</i>	<i>Unit</i>	<i>Description</i>
$b_1$	m	Width of the U-duct
$b_2$	m	Width of the main collector
$b_3$	m	Transversal width of the collector
$h_o$	m	Depth of the collector inlet section
$l_i$	m	Length of the U-duct
$C(\xi, \dot{\xi})$	s	Time-dependent damping coefficient
$C_{dg}, C_{in}$		Head loss coefficients
$H(\infty)$	m	Infinite frequency added head
$H_s$	m	Significant wave height
$K(\tau)$	$\text{m/s}^2$	Radiation convolution kernel
$M(\xi)$	$\text{s}^2$	Time-dependent Inertial coefficient
$R_{h1}, R_{h2}$	m	Hydraulic radii of the U-duct
$T_p$	s	Wave peak period
$\xi$	m	Distance of the air chamber top wall from the free surface
$\tau$	s	Time coordinate

$\Delta p^{(D)}$	Pa	Wave pressure in a diffractive wave field
<b>CD-DEG geometry and model</b>		
<i>Symbol</i>	<i>Unit</i>	<i>Description</i>
$e$	m	Radius (flat pre-stretched configuration)
$e_0$	m	Radius before pre-stretch
$h_t$	m	Tip element displacement
$n_l$		Number of layers
$r_e$		Exponential parameter for the break-down electric field expression
$t$	m	Local thickness
$t_0$	m	Thickness before pre-stretch
$C$	F	Capacitance
$C_{1,0}, C_{0,1}$	Pa	Mooney-Rivlin hyperelastic parameters
$E$	V/m	Local electric field
$E_0$	V/m	Break-down electric field at unitary stretch
$E_{BD}$	V/m	Break-down electric field
$P_u$	W	Instantaneous electrical power output
$Q$	C	charge
$R$	m	Radial coordinate on the unstretched CD-DEG
$U_m$	J	Total elastic energy
$V$	V	Voltage
$\epsilon$	F/m	DE's dielectric constant
$\lambda$		Local stretch
$\lambda_p$		Pre-stretch
$\Psi$	J/m <sup>3</sup>	Strain-energy density function
$\Omega_c$	m <sup>3</sup>	CD-DEG cap subtended volume

**Air chamber geometry and model**

<i>Symbol</i>	<i>Unit</i>	<i>Description</i>
$d_v$	m	Valve reference diameter
$h_c$	m	Air chamber height
$\dot{m}$	kg/s	Mass flow rate through the apertures
$p$	Pa	Air chamber gauge pressure
$C_v$		Valve discharge coefficient
$N_D$		Number of CD-DEGs on the air chamber
$\Omega_a$	m <sup>3</sup>	Instantaneous air pocket volume

### Experiments and simulations parameters

<i>Symbol</i>	<i>Unit</i>	<i>Description</i>
$h_l$	m	Distance between the lower pressure transducer and the air chamber top wall
$p_l, p_u$	Pa	Pressure measured by the submerged transducers
$p_{\%}$	%	Maximum percentage time (on the simulation horizon) during which the stretch $\lambda$ is allowed to be larger than $\lambda_{th}$
$\varepsilon_p, \varepsilon_{\xi}$		Errors in the simulated air pressure and water column displacement compared to the experimental data (average over a dataset)
$\lambda_{th}$		Threshold safety value for the DEG stretch
$\sigma_{p,meas}$	Pa	Measured standard deviation of the air pressure
$\sigma_{\xi,meas}$	m	Measured standard deviation of the water column displacement
$\Delta z$	m	Distance between the submerged transducers

### Operators and notation

<i>Symbol</i>	<i>Description</i>
$\dot{\varphi}$	Differentiation with respect to time of a generic variable $\varphi$
$\bar{\varphi}$	Time averaged value of a generic variable $\varphi$
$\text{sign}(\varphi)$	Sign of a generic variable $\varphi$

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723

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- Model of a U-shaped oscillating water column with dielectric elastomer generator
- Tests on a scaled prototype are carried out in a benign sea basin
- Good agreement of model prediction and experimental data over a wide set of tests
- The model is used to predict the performance of a full-scale U-OWC with DEG
- First step toward the demonstration of the feasibility of dielectric elastomer WEC

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