Hardware in the loop test of a U-Oscillating Water Column converter coupled with a Dielectric Elastomer Generator

Andrea Scialò, Giacomo Moretti, Giovanni Malara, Marco Fontana, Alessandra Romolo, Felice Arena

Abstract— This paper deals with hardware-in-the-loop (HIL) simulation of U-OWC wave energy converters coupled with dielectric elastomer generators (DEGs). The U-OWC is a special type of oscillating water column (OWC) with a U-shaped collector suitably designed to match the device natural frequency with target wave frequencies. DEGs are polymeric variable-capacitance transducers that enable direct conversion of mechanical work into electrical energy while rejecting rigid corrosion-sensitive components. The potential of coupled DEG/U-OWC systems has been preliminarily investigated theoretically and with small scale sea tests. In this work, HIL tests are designed which combine a fully-functional scaled DEG prototype with a hydrodynamic model of a U-OWC. These tests allow to test control strategies for the system and measure the performance in terms of generated electrical energy, while requiring a remarkably lower effort than wave tank or sea tests. In the paper, a scope of the experimental test-bench and the hydrodynamic model is presented, procedures for the implementation of HIL tests are defined, and preliminary results are shown.

***Keywords*— OWC, DEG, U-OWC, hardware in the loop, wave, dielectric elastomer**

I. Introduction

WAVE energy is one of the most abundant forms of ocean energy [1]. In the last decades, several attempts were done to collect wave energy by a number of devices exploiting different working principles. The devices that leverage the working principle of the oscillating water column (OWC) proved to be among the most effective and reliable wave energy converters (WECs). The chain of energy conversion requires mainly two processes: the absorption of the incoming wave energy, and the conversion of the absorbed mechanical energy into electrical energy. In OWCs, the first task is carried out by the water column, which is enclosed in a semi-submerged hollow collector with an opening in the bottom at the sea-side. The water displacement inside the chamber is activated by the periodic sequence of wave crests and troughs, that leads to the compression and expansion of the air located in the upper part of the chamber. This mechanism can be employed to supply a power take-off (PTO) system, that implements the second task of the energy conversion chain and is responsible for electrical energy generation. Usually, the PTO for an OWC converter is a self-rectifying turbine installed in an orifice located at the top of the chamber.

In the past few years, technology breakthroughs were achieved by innovating both the OWC configurations and the PTOs.

In 2003 Boccotti proposed a new type of wave energy converter, the so-called U-OWC, by adding an external vertical duct to a traditional OWC connecting the open wave field to the inner chamber [2]. This innovation resulted in an improvement in the performance of the converter [3] by enabling to set the eigenperiod of the water column oscillations to a desired period.

Meanwhile and independently, researches were conducted on dielectric elastomer generators (DEGs) [4]. DEGs are deformable polymeric transducers that can be employed for the conversion of mechanical energy into direct current electricity. DEGs rely on cheap materials and a simple architecture/operating principle. They are free from rigid moving parts, thus providing an important improvement in terms of cost and maintainability.

Thanks to their features of high energy density, high efficiency and resistance to corrosion, they have been indicated as particularly promising for the wave energy field [5], and several WEC concepts have been developed employing a DEG as the PTO [6], [7], [8]. Recently, a number of experiments were carried out to study the

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optimal matching of OWCs and a PTO realized with dielectric elastomers [9]-[10]. Recently, an experimental activity was conducted on a U-OWC prototype equipped with several DEGs in the natural basin of the Natural Ocean Engineering Laboratory (NOEL) in Reggio Calabria (Italy) [11]. Tests were performed to investigate the mechanical response of the coupled system.

In this paper, the design of a scaled test–bench for the assessment of the coupled performance of DEGs and U-OWCs is described. Specifically, the test-bench is conceived to perform hardware in the-loop (HIL) simulations. The purpose is to assess the performance of a physical fully-functional DEG prototype coupled with a software real-time hydrodynamic model of U-OWC wave energy converter. This type of tests allows to significantly reduce the level of uncertainty and risk for the equipment compared to experiments at sea or in a wave tank, while providing significant insight into the system dynamical response and performance. Besides, HIL simulations allow testing of a same PTO in combination with different geometries of the WEC and/or different control strategies. The simulation of scenarios in which an OWC holds DEGs with a different size compared to the physical prototype can also be performed thanks to the possibility of matching/scaling the coupling variables via software.

Two different scenarios are taken into account: a large-scale scenario, based on the first full scale U-OWC prototype built in Civitavecchia (Rome, Italy), and, an intermediate-scale scenario, considering the 1:8 scale U-OWC model installed at NOEL. For the second scenario, preliminary results are reported in this paper.

Preliminary HIL tests on a DEG PTO system coupled with a hydrodynamic model of an OWC were presented in [12], using a small-scale setup equipped with inflatable DEGs with a scale in the order of 1:80/1:70. The system was used to demonstrate the effectiveness of a control strategy for DEGs (based on instantaneous measurements of the system state, with no need for predictions) in the presence of irregular waves. Compared to that previous work, the setup described in this paper allows testing of larger scale samples, hence providing a significant contribution towards scaling up of DEG PTO technology.

II. DEG-U-OWC COUPLED SYSTEM

The performance of a Wave Energy Converter in terms of absorbed energy and, hence, convertible energy are directly related to the eigenperiod of the device with respect to the period of the incident waves. In a conventional OWC, the eigenperiod is relatively small and resonance can be achieved only by resorting to complex and expensive devices for phase control of the PTO on a wave-by-wave basis [13]. The novelty introduced by Boccotti allows to obtain a natural resonance through a proper geometrical design of the elements constituting the U-OWC, such as the width and the height of the inner chamber and of the vertical duct [2]. The scheme of a U-OWC, also known as REsonant Wave Energy Converter (REWEC3), is shown in Fig. 1. It is endowed with an external vertical duct by means of which the open wave field interacts with the inner chamber. The waves generate a pressure on the opening of the vertical duct, and induce the reciprocating movement of the water column inside the chamber, thus compressing and expanding the air pocket. In the case of a coupled system of a U-OWC and a DEG, the turbine is replaced by a set of circular membranes, called circular diaphragm DEGs (CD-DEGs), mounted on the ceiling of the caisson. The CD-DEGs are inflated outward or inward under the influence of the air pressure. A CD-DEG consists of a pre-stretched membrane of dielectric elastomer that is fixed on a circular rigid frame. The pre-stretch is given by the ratio $\lambda_p=e/e_0$, where e is the radius of the frame and e_0 is the radius of the membrane in the unstretched configuration. In order to produce electricity, the films of the membrane are covered in deformable electrodes. In terms of the operating principle, the CD-DEG is a variable (deformable) capacitor. Mechanical-to-electrical energy conversion is achieved based on an electrostatic principle, by properly controlling the voltage on the DEG as a function of its deformation.

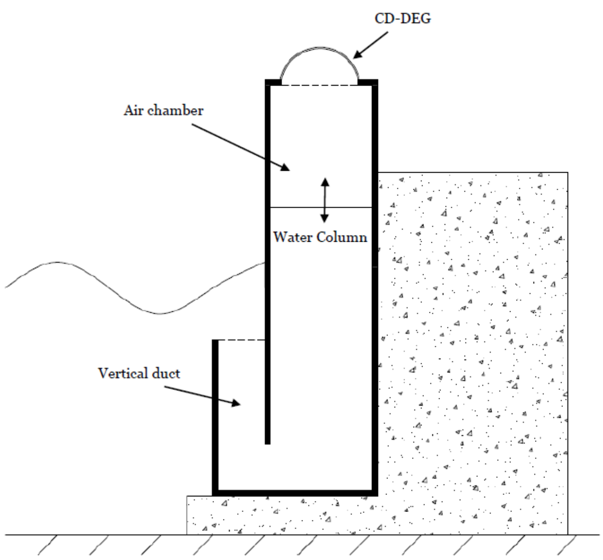

Fig. 1. Sketch of a U-Oscillating Water Column integrating a Circular Diaphragm DEG.

III. DESIGN OF HIL TEST

A block-diagram showing the key elements and variables flow in HIL tests is shown in Fig. 2. The system has the aim of simulating the dynamics of a U-OWC plant (with target dimensions) holding a CD-DEG PTO of which the physical DEG represents a scaled model.

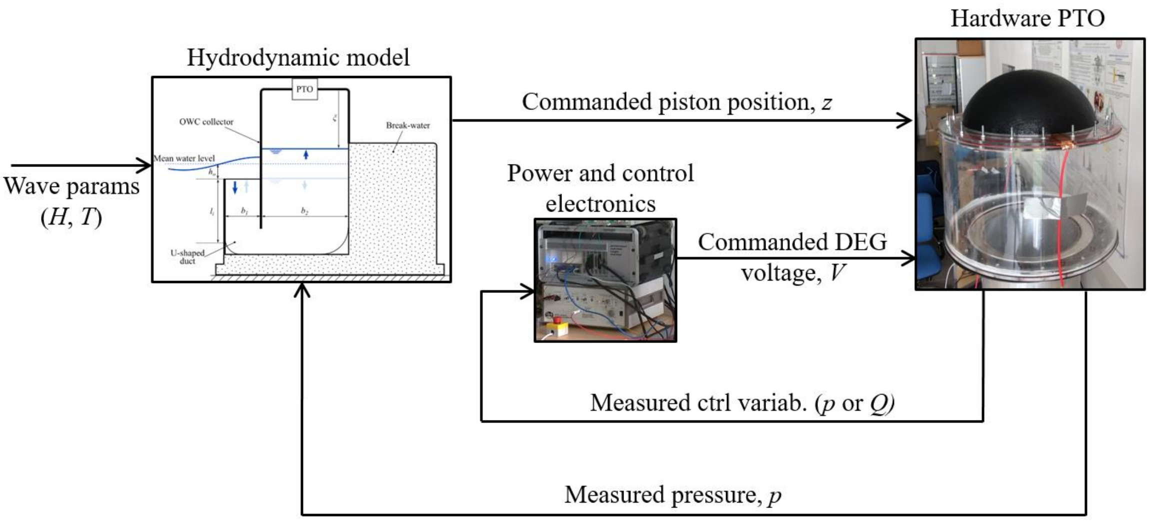

Fig. 2. Block-diagram of HIL tests combining a software hydrodynamic model of a U-OWC and a physical model of the air chamber- DEG assembly.

The simulator includes the following components:

- A custom hardware made of an air chamber with variable volume holding an actuated piston at its bottom and a holding structure for a CD-DEG at its top.
- A CD-DEG prototype, including the elastomeric unit and a set of sensors for measuring current, voltage, air chamber pressure.
- A control software that implements a real-time model of the U-OWC hydrodynamics on a target computer.

The hydrodynamic model takes the wave parameters (either regular or irregular wave parameters) as the input and solves the dynamics equation of motion. The simulated displacement of the water column inside the U-OWC chamber is used to command the motion of the hardware piston. The control loop is closed using the measured value of the relative air pressure p in the cylinder and feeding it into the model (upon appropriate scaling). The power electronics allows the implementation of energy conversion cycles by piloting the voltage V applied on the DEG as a function of the measured control variables (e.g., pressure p or DEG charge Q).

A. Setup description

A picture of the experimental setup, including the hardware for the CD-DEG driving and the power/control electronics is shown in Fig. 3.

The setup can house CD-DEGs with different dimensions, namely, diameter of 300-500 mm and thickness of up to 0.2 mm (in the pre-stretched state). Such samples represent a scaled model of hypothetical full-scale DEG PTOs, in a scale range roughly between 1:30 and 1:15 [10]. Based on state-of-the-art experimental values for the convertible energy density of DEGs (0.1-0.4 J/m^3 per unit dielectric material volume [14]) and assuming an operating frequency of 0.2-1 Hz (similar to wave tanks for prototypes testing [15]), this corresponds to a rated power in the range 1-10 W.

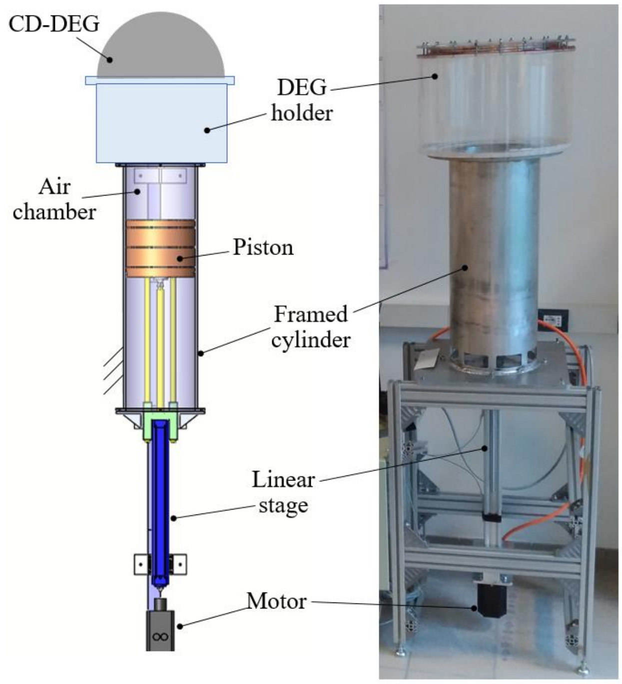

Fig. 3. Schematic drawing and picture of the experimental setup for HIL testing.

The setup includes the following custom components:

- Aluminium cylinder bored to a diameter of D_c =300 mm and length of 600 mm;
- Delrin® piston with polyurethane sealing.
- Polycarbonate cylinder on which the CD-DEG assembly can be secured through flanges. This component can be easily removed and replaced in order to match different CD-DEG diameters.

Moreover, the hardware mounts commercial components for electro-mechanical driving and control:

- Kollmorgen AKM52L brushless motor (with commercial driver), coupled to the piston through a linear actuation stage by Festo (maximum force: 4500

N) and communicating with the target control machine via EtherCAT.
- Speedgoat performance real-time target machine, operated via Matlab Realtime software environment, running the control software and the hydrodynamic model.
- High-voltage signal generator (10/10B-HS by TREK) with 10 kV maximum voltage output.

The system allows position control of the piston with an accuracy of ±0.2 mm and maximum piston speed of 1.0 m/s. Assuming a maximum force of 3500 N on the linear stage to conservatively account for friction losses in the sealing and other losses, the maximum pressure that can be generated in the air chamber is ~0.5 bar. Based on established models [10], such a pressure is a conservative value that guarantees the inflation (over the emi-spherical deformed configuration) of CD-DEGs made of different elastomeric materials [16] with the target dimensions.

In order to achieve the convertible energy densities envisaged for energy conversion applications, the CD-DEG has to be operated at large electric fields (namely, 10^1-10^2 MV/m). To achieve that while limiting the applied voltage (consistently with the power supply capacity), CD-DEG prototypes are manufactured using a multi-layered layout in which dielectric layers are separated by electrodes with alternated polarity.

B. Hydrodynamic model

The hydrodynamic response of the U-OWC is simulated numerically. The water column dynamics is described via a nonlinear integral differential equation encapsulating the effect of the system added mass and radiation damping, as well as the effects of the head losses. The model developed by Malara et al. [17] is implemented, which is based on the unsteady Bernoulli equation. In this context, the water column dynamics is described by the equation,

$$M(x)\ddot{x} + C(\dot{x},x)\dot{x} + \frac{1}{g}\frac{b_2}{b_1}\int_0^t K(t-\tau)\dot{x}(\tau)d\tau + x + \frac{p}{\rho g} = \frac{\Delta p^{(D)}}{\rho g}, \tag{1}$$

where

$$M(x) = \frac{(1+C_{in})}{g}\left(l_i\frac{b_2}{b_1} + l_i + h_o + x\right) + \frac{1}{g}\frac{b_2}{b_1}H(\infty); \tag{2}$$

$$C(\dot{x},x) = \frac{1}{2g}\left\{1 + C_{dg}\left[\frac{l_i}{R_{h1}}\left(\frac{b_2}{b_1}\right)^2 + \frac{l_i+h_o+x}{R_{h2}}\right]\right\}|\dot{x}|; \tag{3}$$

x being the water column displacement measured from the mean water level (positive upwards); the dots denote differentiation with respect to time; p being the relative air chamber pressure; g being acceleration due to gravity; b_2, b_1, l_i and h_o being width of the water column, width of the vertical duct, length of the vertical duct, and depth of the inlet section with respect to the still water level respectively; C_{in} and C_{dg} being empirical coefficients accounting for the head losses [18]; and R_{h1} and R_{h2} being hydraulic radii of the duct horizontal section and of the water column horizontal section.

The quantities $H(\infty)$ and $K(t)$ are the infinite frequency added mass and the retardation function associated with the hydrodynamic memory effect. These quantities depend on the geometry of the system, which are determined by solving related boundary value problems (see [19]). In this regard, note that the determination of the retardation function is conducted via the radiation damping of the system $B(\omega)$, which allows estimating it by the equation

$$K(t) = \frac{2}{\pi}\int_0^\infty B(\omega)\cos(\omega t)\,d\omega. \tag{4}$$

The excitation pressure $\Delta p^{(D)}$ on the system is calculated by resorting to the diffraction theory. All these quantities are determined by utilizing the semi-analytical approach proposed by Malara and Arena [20], which is based on the matching of eigen-function expansions of the related boundary value problems. The technique was developed with the aim of determining the hydrodynamic parameters of a U-OWC array and can be utilized for estimating them in case of a single U-OWC chamber of finite transversal width.

C. Coupling of the software model and the physical DEG

One of the main features of HIL tests is the possibility of simulating scenarios in which a WEC virtually holds a PTO system whose sizes are different from those of the physical PTO model. This can be consistently achieved by scaling the measured physical variables fed into the hydrodynamic model and the variables (resulting from software model) used to pilot the hardware.

In the considered application, the setup can hold a single DEG with limited dimensions and given initial volume of the air chamber. Under certain assumptions, however, the dynamics of U-OWC plants with arbitrary dimensions (and number) of the CD-DEGs and the air chamber can be consistently simulated. Coupling of the software model and the physical prototype can be implemented by properly scaling the measured air pressure to be fed into the software solver, and commanding the piston position as a convenient function of the simulated water column displacement and the air pressure.

We hereby present a procedure to identify relationships between physical and simulation parameters, with reference to the variables defined in Table 1.

We consider a generic simulation scenario, in which a number N_d of CD-DEGs are installed on a reference U-OWC collector. We assume that the DEGs mounted on the simulated OWC are made of the same material as the physical CD-DEG prototype, and they are subject to the same strain and electric field time history. Real-time coupling between software model and hardware is realised, i.e., the piloting signals have the same time scale as the simulations (e.g., oscillating variables have the same frequency in the physical model and in the scenario).

TABLE 1
SYMBOLS REPRESENTING THE VARIABLES IN THE SIMULATED SCENARIO (SOFTWARE) AND IN THE PHYSICAL PROTOTYPE (HARDWARE)

VARIABLE	GENERIC	SCENARIO	HARDWARE
RELATIVE AIR PRESSURE	p	p_S	p_H
NUMBER OF DEGS	N_d	N_d	1
DEG RADIUS[a]	e	e_S	e_H
DEG THICKNESS[a]	t	t_S	t_H
AIR VOLUME SUBTENDED BY THE DEG CAP	Ω	Ω_S	Ω_H
WATER COLUMN/PISTON CROSS-SECTION	S	S_S	S_H
AIR CHAMBER INITIAL VOLUME	V	V_S	V_H
WATER COLUMN/PISTON DISPL.	x	x_S	x_H
POWER OUTPUT	$\wp$	$\wp_S$	$\wp_H$

[a]In the pre-stretched equilibrium configuration

Approximating the deformed CD-DEG as a thin spherical shell made of elastomeric material, the relative air pressure p in the chamber relates to the local stress σ in the elastomeric material as follows:

$$p = \frac{2\sigma t}{R}, \tag{5}$$

where R is the local curvature of the DEG, which depends on the local strain and is proportional to the CD-DEG radius e [21]. The stress σ is a function of the local strain, the strain rate, and the electric field [22], therefore it assumes the same values in the simulated scenario and in the prototype. Based on that, the air pressure used in the software model and the measured one must relate as follows:

$$\frac{p_S}{p_H} = \frac{t_S e_H}{t_H e_S}. \tag{6}$$

In particular, the right hand side of (6) provides a scaling factor to be applied on the measured pressure p_H in order to obtain the pressure p_S to be fed in the software model.
In order to identify a similar relationship between the modelled water column displacement x_S and the commanded piston position x_H, it is assumed that the air in the U-OWC chamber follows adiabatic transformations. Since the air chamber volume variations (due to DEG and water column displacements) are reasonably small compared to the initial volume, the following linearised model for the air chamber response can be employed:

$$\frac{p}{p_{atm}} = \frac{\gamma}{V}(Sx - N_d\Omega) \tag{7}$$

where p_{atm} is the atmospheric pressure and γ is the air's adiabatic exponent. The volume Ω subtended by the DEG is considered positive for outward expansions and negative otherwise, and it depends on the DEG strain and radius [21], so that the following relationship holds:

$$\frac{\Omega_S}{\Omega_H} = \frac{e_S^3}{e_H^3}. \tag{8}$$

Using (6)-(8) leads to the following relationship:

$$x_H = \frac{1}{N_d}\frac{S_S}{S_H}\frac{e_H^3}{e_S^3}x_S + \left(\frac{V_H}{\gamma S_H} - \frac{t_S e_H^4}{t_H e_S^4}\frac{V_S}{\gamma N_d S_H}\right)\frac{p_H}{p_{atm}}. \tag{9}$$

In practice, the displacement x_H to be commanded to the piston is the sum of two contributions: a geometrical contribution proportional to the simulated water column displacement x_S, and a contribution due to the air chamber compressibility.

The possible mismatch between the number and dimensions of the CD-DEGs in the simulated scenario and in the hardware setup leads to a mismatch between the electrical power generated by the prototype and that virtually produced in the scenario. The electrical power converted by a DEG solely depends on the time sequence of the strain and the applied electric field, which is the same for the physical and the virtual DEGs. The power output in the simulation scenario is thus obtained scaling the experimental one by the ratio of the total dielectric material volume in the scenario and that of the physical prototype, namely:

$$\frac{\wp_S}{\wp_H} = N_d\frac{e_S^2 t_S}{e_H^2 t_H}. \tag{10}$$

Equation (10) clearly assumes that the CD-DEG efficiency is the same in the physical prototype and in the scenario, thus neglecting possible effects that depend on the scale. This is, in general, a conservative assumption. It is indeed expected that CD-DEGs practically employed in the envisaged scenarios are the result of optimised manufacturing and assembly processes, potentially featuring better efficiency and time-stable performance compared to the physical samples used in the tests.

D. CD-DEG control

The control of a DEG PTO consists in a regulation of the voltage trajectory applied on its electrodes through the power electronics. In principle, the applied voltage profile can be regulated according to control strategies aimed at maximising the power production based on a real-time prediction of the incoming wave profiles [23]. Nonetheless, simpler control strategies are most often suggested/implemented, which do not require any prediction of the system response and only rely on instantaneous measurements of the DEG state [10].

CD-DEGs are traditionally controlled based on a four-phase control cycle, corresponding to a full oscillation of the DEG between the flat and the maximally inflated/deflated configuration:

1) As the CD-DEG expands (either outward or inward), it is kept electrically uncharged.
2) When the DEG deformation (and capacitance) reaches a maximum, the DEG is quickly charged, hence spending an amount of electric energy.
3) While the membrane deformation decreases, pressure makes work against the charges and mechanical energy is converted into electrostatic energy. During this phase, the DEG voltage trajectory (as a function of the deformation) can be chosen following different strategies.
4) Finally, when the device capacitance is minimum (i.e., in the flat position), the CD-DEG is quickly discharged and the stored electrostatic energy is recovered.

Triggering between the different phases and voltage profile control during phase 3) require measurement/estimate of the CD-DEG capacitance. This can be achieved by directly measuring the current produced by the DEG, integrating it to obtain the DEG charge, and thus estimating the capacitance from charge and voltage. Nonetheless, since the current amplitude varies by orders of magnitudes throughout the cycle (i.e., it is large for short time intervals during phases 2) and 4), and low during the time span of phase 3)), such a procedure might lead to inaccuracies, unless special equipment for current sensing is employed (e.g., isolation amplifiers). Alternatively, an estimate of the CD-DEG deformation/capacitance can be obtained indirectly, e.g., by measuring the air chamber pressure or the DEG central point displacement. Such an indirect estimate also leads to possible inaccuracies due to the CD-DEG dynamics and viscoelasticity.

At laboratory scale, a simple implementation of the described control cycle can be achieved by piloting the CD-DEG through a bidirectional high-voltage signal generator, capable of piloting the voltage profile as a function of the estimated CD-DEG capacitance. In a real installation, in which storage and delivery of the generated energy is required, the implementation of the control cycle requires suitable bidirectional DC-DC power converters [24].

Since no storage of the generated energy is implemented at laboratory scale, the electrical energy generated in each cycle should be measured from the applied voltage and the measured current. In order to improve the estimate of the generated energy, rejecting mentioned inaccuracies due to current measurements, dedicated circuits have been proposed in the past, which are suitable for laboratory testing and can be straightforwardly integrated in the presented HIL setup [10].

E. DEG-U-OWC simulation scenarios

HIL tests will be performed with the aim of simulating the following scenarios:

- Large-scale U-OWC chamber equipped with a set of CD-DEGs as the PTO.
- Intermediate-scale U-OWC chamber operating in a mild wave climate and equipped with a set of CD-DEGs as the PTO.

For the first scenario, reference is made to the dimensions of the U-OWC plant installed in Civitavecchia [25]. The U-OWC chambers in the plant are installed in a water depth of 15 m, subject to waves with significant height of up to 5 m and peak periods in the range 5-10 s. The target power is approximately 20 kW per chamber.

For the second scenario, reference is made to a U-OWC scaled model installed in the Natural Ocean Engineering Laboratory (NOEL) in Reggio Calabria (Italy) [18]. The device is installed in 2 m-deep water and it is subject to natural waves with the typical size of a laboratory tank, (heights of 0.15-0.45 m and peak periods between 1.8 s and 3.3 s).

A scope of the U-OWC chamber and the DEG PTO features in the two scenarios is presented in Table 2.

TABLE 2
U-OWC COLLECTOR DIMENSIONS AND APPROXIMATE DEG PTO DIMENSIONS IN THE CONSIDERED SIMULATION SCENARIOS

	SCENARIO 1	SCENARIO 2
U-OWC CHAMBER DIMENSIONS		
h_o	2 m	0.57 m
d	15 m	1.9 m
b_1	1.6 m	0.5 m
b_2	3.2 m	1 m
b_3	3.87 m	1.23 m
l_i	5 m	0.8 m
DEG PTO FEATURES		
N_m	4	4
e	1.5 m	0.2 m
t	30 mm	0.4 mm

Though the first scenario is more relevant, since it represents a large-scale plant, it relies on a significant mismatch between the physical CD-DEG sizes and those hypothesized in the scenario, leading to uncertainty on the actual scalability of the obtained energetic performance.

In contrast to the target DEG PTO for the envisaged applications, the physical CD-DEG installed on the HIL setup has a diameter of 0.4 m and a thickness (in the pre-stretched configuration) of 0.15-0.25 mm. The samples will be manufactured using acrylic elastomer VHB 4905, which is particularly convenient to produce CD-DEGs with the target dimensions through simple manufacturing procedures. Due to its poor durability and large viscosity, this material is not a suitable candidate for employment in real installations. Nonetheless, since its dielectric properties are similar to those of other dielectric elastomer materials, its employment in HIL tests still provides meaningful indications on the possible performance of DEG PTOs in the considered scenarios.

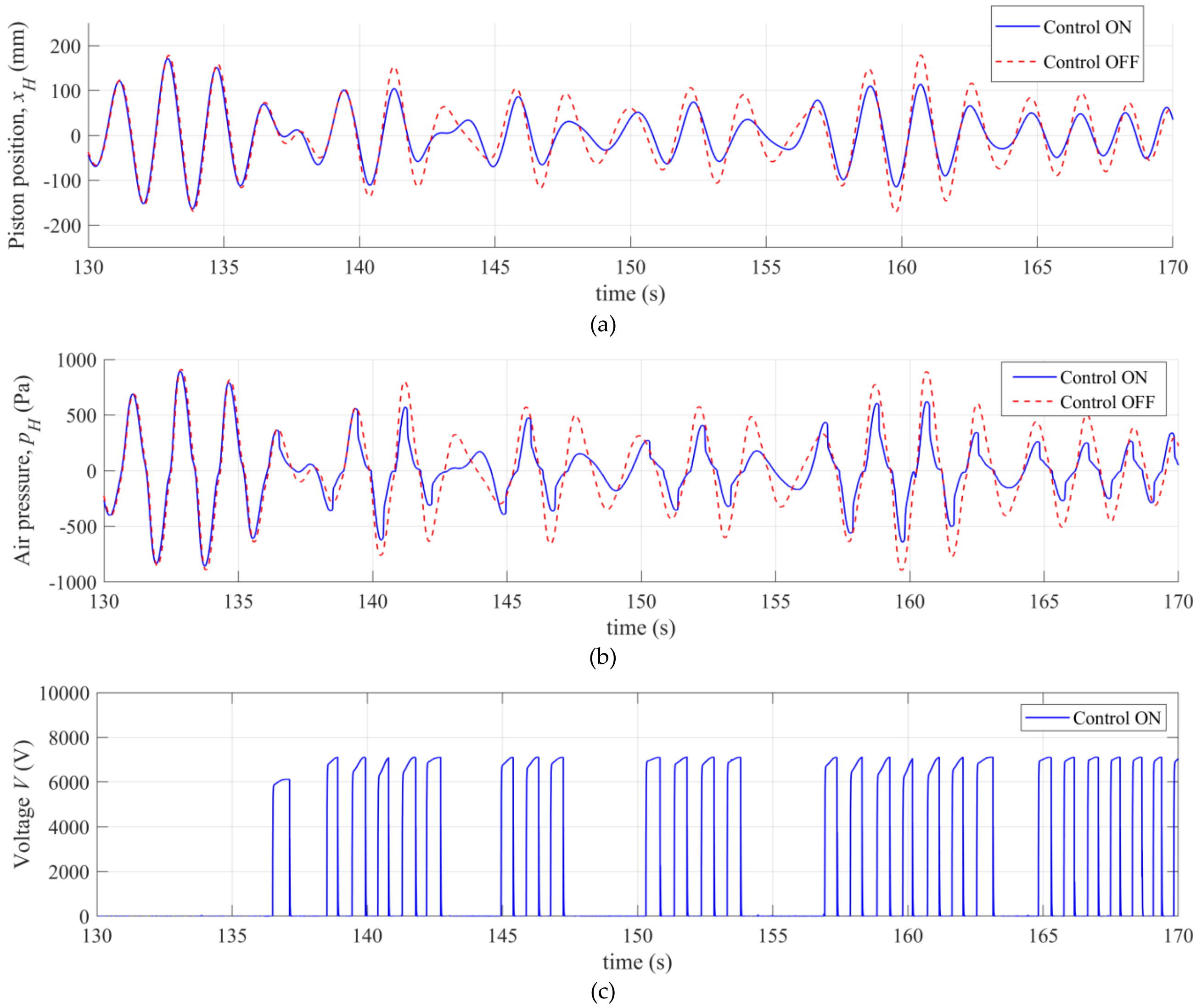

Fig. 4. HIL simulation of an intermediate-scale U-OWC model coupled with a CD-DEG prototype. The dataset shows two test runs: a purely mechanical test (in the absence of electrical signal on the DEG), and a test with electrically controlled DEG, in the presence of a same train of irregular waves (H_s = 0.15 m, T_p = 1.65). (a) Hardware piston elevation, (b) Air chamber pressure, (c) Voltage (in the test with actively controlled DEG).

IV. PRELIMINARY EXPERIMENTAL RESULTS

In this section, we report preliminary experimental results relative to Scenario 2 (i.e., simulation of an intermediate scale U-OWC) introduced in the previous section.

The described HIL setup has been equipped with a CD-DEG sample made of VHB acrylic, with thickness t = 0.25 mm (in the pre-stretched flat state) and pre-stretch λ_p = 3.4. The CD-DEG sample is a multi-layer structure with two dielectric layers and three carbon-grease electrodes: two grounded electrodes on the stack outer faces, and a high-voltage electrode between the two dielectric layers. The voltage on the DEG is driven according to the cycle described in Sect. D, using a driving circuit with the layout and features described in [26].

In Fig. 4, we analyse the response of the system (i.e., the software U-OWC model and the hardware PTO) in a reference irregular sea state. In this test, the simulated U-OWC is subject to a wave train generated according to a JONSWAP spectrum, with significant wave height H_s = 0.15 m, peak period T_p = 1.65 s, and shape parameters χ_1 =3.3 and χ_2 =0.08 respectively [27]. This represents a realistic mild sea state at the NOEL test site. The figure compares the results of two test runs, namely: 1) a purely-mechanical test (with no voltage applied on the DEG); and 2) a generation test (with electrically controlled DEG), with the aim of assessing the effect of electrical activation on the dynamics of the U-OWC. The figure includes the following plots: piston displacement (Fig. 4a), air pressure (Fig. 4b), and DEG voltage (only in the test run with electrical activation – Fig. 4c).

The time-series relative to the two datasets (with and without electrical activation) present an initial overlap, as no voltage is initially applied on the DEG in both cases. Following that, the application of a voltage on the DEG causes a significant modification in the dynamics, including the following effects:

- Each time that the CD-DEG is charged (phase 2 of the control cycle), a drop in the air pressure occurs. This is due to the electrically-induced relaxation of the DEG stress, which causes a further moderate expansion of the CD-DEG with a consequent decrease in the air chamber pressure. The piston/water free surface, in contrast, has a continuous and smooth dynamics, given by the inertial response of the system.

- The oscillation amplitude of both the pressure and the piston motion decreases in the presence of an electric activation. This demonstrates that, when electrically controlled, the CD-DEG is able to damp the system dynamics, hence converting an amount of mechanical energy into electrical energy.

The time series of the voltage (relative to the dataset with electrically controlled CD-DEG) shows that the employed circuit and control strategy are able to effectively pilot the DEG in the presence of different wave pulses. In particular:

- In the phases in which electrical activation is present on the DEG (phase 3 of the control cycle), the voltage has an increasing trend, hence confirming that the DEG charging/discharging (phases 2, 4) are properly synchronised by the controller with the instants in which the CD-DEG capacitance is maximum/minimum.
- In the cycles in which the deformation is rather small (i.e., when the pressure module is below 200 Pa), the DEG is not activated, since in these cases electrical losses would overcome the generated energy.

In this test, the average generated power was 0.5 W, with peaks (in the cycles with maximum deformation) of up to 1.2 W. Based on Eq. (10) and the dimensions envisaged in Table 2, this corresponds to a power of 3.2 W (with peak of 7.7 W) for the considered scenario. Given the mild sea state under investigation, this represents a good fraction (over 15 % in average) of the available input power. Moreover, this figure represents a significant power target for a DEG prototype at the state of the art (most DEGs developed to date in laboratories have a rated power below ~1 W). Larger power outputs may be pursued with the considered UOWC plant in energetic sea states, but this would require larger CD-DEGs, including larger volumes of dielectric elastomer material, that would be difficult to implement with the manufacturing techniques used in the described experiments. The considered scenario and the present results set, in contrast, a feasible target for future sea tests of DEG systems at the NOEL test site.

V. Conclusion

This paper described a test – bench setup designed to study the control of U-Oscillating Water Column systems coupled with Circular Diaphragm Dielectric Elastomer Generator (CD-DEG) power take-off (PTO). The possibility to perform hardware in the loop simulations allows to investigate real operating conditions of these wave energy converters in a controlled environment compared to the experiments at sea or in wave tanks. The development of two different simulations scenarios, a full scale and a model scale case, is going to be performed and for each of them a scaling procedure of the physical PTO model and input and output dimensions is proposed. Specifically, numerical simulations are conducted for predicting the wave exciting pressure. Then, the water column oscillation is numerically calculated by integrating the associated equation of motion. Next, such oscillations are transferred and reproduced in the test – bench. In this context, different control strategies of the CD-DEG PTO are identified in order to estimate and maximise the energy production of U-OWC devices equipped with CD-DEG in further tests. Preliminary tests are described which provide evidence of the functionality of the proposed HIL test-bench and set a target (in terms of DEG dimensions/rated power) for future sea trials on a U-OWC with DEG PTO.

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