Hardware in the loop simulation of a dielectric elastomer generator for oscillating water column wave energy converters

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***Abstract*— This paper presents a small-scale test-bench that can be employed for the study of a new class of Oscillating Water Column (OWC) Wave Energy Converters (WECs) with Power Take Off (PTO) unit based on Dielectric Elastomer Generators (DEGs).**

Such a test-bench is designed to perform Hardware-In-the-Loop (HIL) simulations of a small-scale DEG PTO prototype, that includes dedicated power and control electronics, with a real-time model that emulates OWC plant hydrodynamics.

The paper illustrates the theoretical model that is assumed to describe the dynamics of the OWC plant, the hardware employed to replicate the response of the DEG PTO and the algorithms for the implementation of the closed-loop controller that performs the HIL simulations. Some preliminary tests are reported considering a floating OWC collector and a simple energy-harvesting control law for the DEG PTO that is based on the measurement of the water level into the OWC structure.

Keywords*—*OWC; Dielectric Elastomer; Wave Energy; PTO;

I. INTRODUCTION

Dielectric Elastomer Generators (DEGs) are deformable variable capacitors, made of rubber-like dielectric material and compliant electrodes, that can be used to directly convert mechanical energy into direct current electricity. DEGs present several features that make them suitable for the conversion of wave energy into electricity such as: large energy densities, good energy conversion efficiency that is rather independent of cycle frequency, easiness in manufacturing and assembling, high shock resistance, silent operation and low cost.

In the last years, Wave Energy Converters (WECs) based on DEGs have attracted a lot of attention due to their potential performance.

The first prototype of a buoy equipped with a DEG has been conceived by Chiba [1]. More recently, the company SBM offshore developed a submerged tubular WEC, made by several ring-shaped DEGs, that has been tested in a wave-tank [2]. In addition, in the context of the EpoSil project [3], researchers from Bosch GmbH are studying new DEG solutions for ocean energy harvesting. In our previous works, we have proposed the concept of the Poly-OWC, that is a WEC based on an Oscillating Water Column (OWC) system equipped with a Circular Diaphragm DEG (CD-DEG) as Power-Take-Off (PTO) system [4], [5].

In this paper, we describe a small-scale laboratory test-bench that has been designed to investigate the PTO system of Poly-OWC devices at a subscale prototype level [6]. Such an experimental setup is able to impose programmed time-varying pressures on the CD-DEG, which replicate the operating conditions of the Poly-OWC air chamber, thereby making it possible to perform dry-run tests of the PTO unit. Specifically, the test-bench is employed to run Hardware-In-the-Loop (HIL) simulations of the small-scale CD-DEG PTO prototype, which are implemented by coupling it with an actuator, sensors and a model-based real-time controller that makes it possible to emulate the hydrodynamics of the OWC as excited by incoming sea waves.

Results from preliminary experiments are reported to show the test-bench functionality and measurement capabilities. Upon testing with the set-up, the obtained results can be scaled up to real system dimensions, thereby making it possible to estimate potential energy production and conversion efficiency of Poly-OWC systems.

The paper is organized as follows. Section II is dedicated to describe the working principle of the full-scale Poly-OWC system and the general architecture of the down-scaled HIL simulation system. Section III provides a description of the hydrodynamic model that is employed in the HIL simulation, while Section IV illustrates the details of the employed hardware. Section V shows an example of a preliminary test.

The work presented in this paper is developed in the context of the project PolyWEC (www.polywec.org), a FP7 FET Energy project. The research leading to these results has received funding from the European Union Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 309139.
The work has been partly supported by the Project "Studi e valutazioni sulla produzione di energia elettrica dalle correnti marine e dal moto ondoso" funded by the Italian Ministry of Economic Development.

978-1-4799-8736-8/15/$31.00 ©2015 IEEE

II. SYSTEM ARCHITECTURE

A. Full-scale Poly-OWC system

A Poly-OWC is a partially submerged hollow structure (usually referred to as "collector") featuring an immersed part opened to the sea action, and an upper part closed by a CD-DEG membrane and forming an air chamber. The structure partially encloses a column of water that is exposed to the incident wave field at the bottom and to the chamber air pressure at the top. As the waves break on the Poly-OWC structure, wave-induced pressure oscillations at the underwater interface cause the reciprocating motion of the water column, with a concomitant compression-expansion of the air entrapped in the upper chamber, and the resulting inflation-deflation of the CD-DEG membrane. To generate electricity, electric charges are put on the CD-DEG electrodes when the membrane is maximally inflated (namely, when it is expanded in area). As the membrane deflates, CD-DEG capacitance decreases, which makes the charges increase their electric potential, thereby converting the work done by the air-chamber pressure on the DEG membrane into direct current electricity.

The potentialities of Poly-OWCs have been theoretically investigated with reference to different types of collector suitable for onshore [5] and nearshore/offshore [8] applications respectively (see Figure 1).

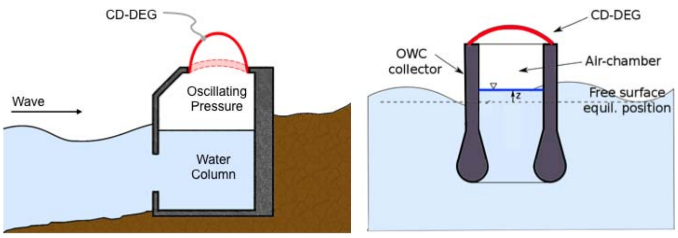

Figure 1. Schemes of possible implementations of the Poly-OWC: onshore (left) and nearshore/offshore (right).

B. Architecture and control of the HIL simulator

With the aim of testing the potentialities of Poly-OWC systems and, in particular, for the assessment of their CD-DEG PTO and the related energy harvesting controller, a HIL simulator has been developed. As depicted in Figure 3, the simulator comprises a cylindrical air chamber with variable volume that is closed at the top with a fully-functional CD-DEG (with power and control electronics included) and at the bottom with a movable piston. This latter is properly actuated and controlled so as to emulate the reciprocating motion of the water column inside the OWC structure that is excited at the bottom by the incident ocean waves and at the top by the variable air-chamber pressure. Emulation of water column motion is performed via a real-time hydrodynamic model of the specific OWC structure in exam, which receives input from a sensor that measures the relative pressure (p) within the air chamber and outputs the reference position (z) of the emulated water column free surface that needs to be tracked by the actuated piston.

A schematic representation of the considered HIL system is provided in Figure 2. Details on the employed hydrodynamic model and of the developed test-bench are given in Sections III and IV.

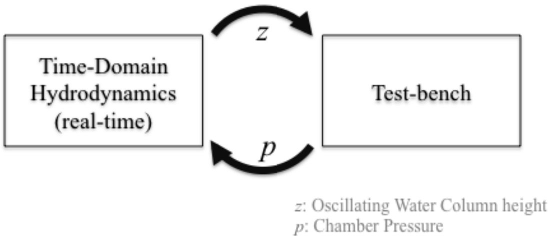

Figure 2. Scheme of the Hardware-In-the-Loop (HIL) system.

III. HYDRODYNAMIC MODEL

In this paragraph, a simplified model of OWC dynamics is presented, which relies on linear hydrodynamics and potential flow theory. The so-called "rigid piston" approximation is used; that is, the free surface of the water within the chamber is assumed to remain flat during the operation. Such free surface behaves as a rigid piston, the motion of which induces the alternate compression and decompression of the overhead air volume [9], [10].

Indicating with z the vertical position of the free surface of water with respect to its equilibrium position, the dynamics of the water column is described by the following motion law:

$$M_{\infty}\ddot{z}+\int_{0}^{t}K(\tau-\xi)\dot{z}(\xi)d\xi+\rho gS\cdot z=-pS+F_{e}(\tau) \qquad (1)$$

where

- M_{∞} is the added mass of the water column at infinite frequency;
- the convolution integral accounts for the radiated waves generated by the water column motion;
- ρ is the water density, S is the cross-sectional area of the water column, and the product $k_b=\rho gS$ is the hydrostatic stiffness associated with the free surface displacement.
- $p=p_c-p_a$ is the difference between the air pressure inside the chamber (p_c) and the atmospheric pressure (p_a).
- $F_e(\tau)$ is the time-series of the wave-induced excitation force, which is the sum of Froude-Krylov and diffraction contributions.

The convolution kernel $K(\tau)$ expresses the radiated wave-induced force in response to an impulsive displacement of the water column and its expression in the Fourier frequency domain is

$$\hat{K}(\omega)=\hat{B}_r(\omega)+i\omega\left[\hat{M}_{add}(\omega)-M_{\infty}\right] \qquad (2)$$

where ω is the angular frequency, and B_r and M_{add} represent the radiation damping and added mass, which are a function of frequency.

Irregular waves can be described as a superposition of monochromatic regular waves, whose distribution is represented by a wave spectrum [10]. As a consequence, the general form of the wave induced force, F_e, in irregular sea waves, can be approximately expressed as a finite sum of sinusoidal addenda; namely

$$F_e = \sum_{i=1}^{n} A_{w,i} \Gamma(\omega_i) \cos(\omega_i \tau + \varphi_i) \quad (3)$$

In equation (3), Γ(ω) is a frequency-dependent wave excitation coefficient, φ_i are random phases, and $A_{w,i}$ are the amplitudes of the different monochromatic waves that are expressed as a function of the wave spectrum, $S_\omega(\omega)$, as it follows:

$$A_{w,i} = \sqrt{2\Delta\omega_i S_\omega(\omega_i)} \quad (4)$$

where $\Delta\omega_i$ is the step between the i-th and (i+1)-th considered frequency value.

The wave spectrum, $S_\omega(\omega)$, can be expressed in terms of wave parameters; for instance, the significant wave height, H_s, and the energy period, T_e. In this work, a Pierson-Moskowitz spectrum is used, according to which $S_\omega(\omega)$ reads as [10]:

$$S_\omega(\omega) = 262.9 H_s^2 T_e^{-4} \omega^{-5} \exp\left(-1054 T_e^{-4} \omega^{-4}\right) \quad (5)$$

If, instead, regular waves are considered, the wave force takes the following simple form:

$$F_e = H/2\,\Gamma(\omega)\cos(\omega\tau), \ \text{ with } \ \omega = 2\pi/T \quad (6)$$

where H (wave height) and T (wave period) are the characteristic parameters of regular waves, and the phase has been set to zero (as this does not provoke any loss of generality).

Notice that equation (1) is linear except for the term in p which, depending on the specific considered PTO, may be non-linear. Such a non-linearity makes it necessary to solve the OWC dynamics in the time domain (by using ordinary differential equations solvers) rather than in the frequency domain.

The hydrodynamic parameters involved in the described model (namely, M_∞, $M_{add}(\omega)$, $B_r(\omega)$ and Γ(ω)) can be calculated using a frequency-domain Boundary Element Method (BEM) code (for instance, WAMIT and ANSYS AQWA). The convolution integral in equation (1) is computational expensive and can be replaced with a linear state-space approximation, the parameters of which can be found with a frequency-domain identification procedure [11].

IV. Hardware Setup

The test-bench that has been developed for performing HIL simulations of Poly-OWC systems is schematized in Figure 3. Such test-bench comprises: a pneumatic piston; a small-scale CD-DEG prototype; a high-voltage (HV) electronics for CD-DEG charge and discharge; a real-time unit for overall system control and data acquisition. Specific details of each sub-system are provided below.

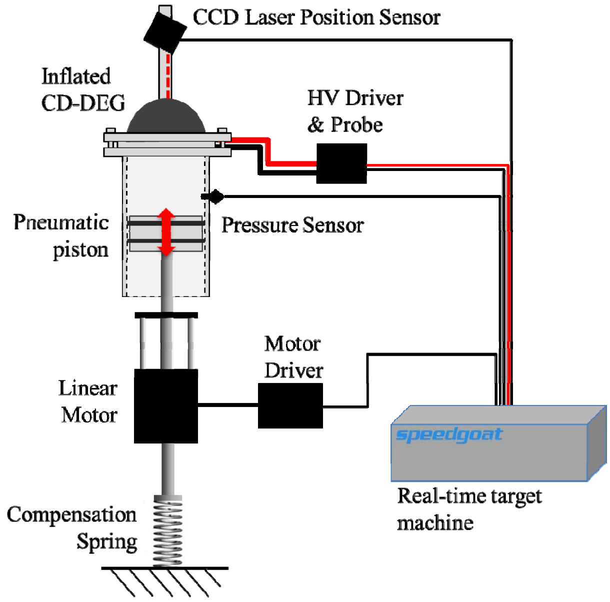

Figure 3. Schematic of the experimental test-rig.

A. *Electromechanical sub-system.*

To simulate the Poly-OWC air chamber we employ a custom made pneumatic cylinder that features: a polycarbonate cylinder tube (with internal diameter e = 130mm); a piston made of Delrin®; a clamping system on the top of the piston that is able to host interchangeable CD-DEG specimens that can be made of different materials (both for the elastic dielectric and for the compliant electrodes). Air leakages are minimized by using a planar annular gasket with a tight screwed fixture between CD-DEG and cylinder, and appropriate pneumatic circular seals between piston and cylinder. The piston is actuated via a brushless linear motor (P01-37x120F/200x280-HP by LinMot), with embedded encoder that is used to measure piston position, z. A pressure sensor (MPX12 by Freescale Semiconductor) installed on the cylinder tube is used to measure the differential pressure, p, between cylinder chamber and ambient air. A high-speed high-accuracy CCD laser displacement sensor (LK-G152 by Keyence), which is mounted on top of the cylinder head, is used in order to measure CD-DEG tip displacement, h. The pneumatic cylinder is mounted vertically and an elastic spring is introduced in order to compensate for the weight of both piston and motor slider.

B. *CD-DEG.*

The CD-DEG is a circular membrane obtained by stacking different layers of dielectric and conductive deformable materials (see the exploded scheme reported in Figure 4).

The capacitance of the CD-DEG varies when a pressure difference is applied between its compliant electrodes.

Specifically, the capacitance increase as the membrane inflates since the surface of the electrodes increases and the thickness of the dielectric layers decreases (indeed, the material used for the dielectric layers is incompressible). The maximum value for the CD-DEG capacitance is reached when the membrane is fully inflated and the minimum value occurs for its flat configuration.

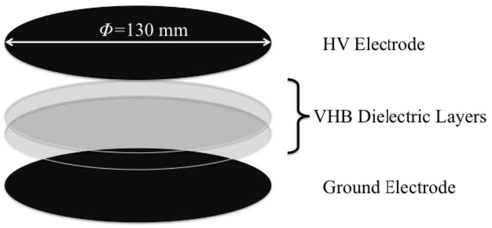

Figure 4. Schematic of the CD-DEG assembly.

C. HV Electronics.

A custom made HV driving electronics has been developed to control CD-DEG charge and discharge. As depicted in Figure 5, the considered driving electronics comprises a HV power supply (10C24-P125 by UltraVolt), three HV reed relays (HM12-1A69-150 by MEDER electronic) and two supplementary HV capacitors.

In Figure 5, C_2 is a capacitor that is permanently connected in parallel with the CD-DEG (whose variable capacitance is indicated in the figure as C_d). The capacitor C_2 is introduced to absorb and store part of the charge, i.e. limiting the rise of voltage, during the generation phase of the harvesting cycles. An appropriate choice for the value of C_2 makes it possible to increase the energy harvested in each cycle by pushing the CD-DEG to work as close as possible to its dielectric breakdown limit [12]. The capacitor C_1 is large in value and is employed to deliver the charge to the CD-DEG (and to C_2). Specifically, the charging of the CD-DEG (and of C_2) takes place when the relay S_2 is closed (with S_1 being opened at the same time).

In the circuit, resistor R_2 (R_2 = 20MΩ) is used to provide a resistive component to the load of the power supply, whereas resistor R_1 (R_1 = 1MΩ) is used to limit the peak current that occurs during CD-DEG discharge as the relay S_3 is closed.

To measure the electric potential difference, V_d, between CD-DEG electrodes, a custom made HV probe (not depicted in Figure 5) has been implemented that features very high input resistance (nearly 50GΩ), which drastically limits the drain of charge from the CD-DEG electrodes, and large bandwidth, which is obtained thanks to a capacitor compensation network. In order to minimize the current leakage of the power electronics, all the HV wirings and components have been encapsulated via thick layers of silicone gel (Magic gel by Raytech) and acrylic tape (VHB 4905 by 3M®). A second identical HV probe is employed to measure the voltage V_1 across the capacitor C_1. This voltage reading during the charging phase of the CD-DEG (and of C_2) makes it possible to precisely evaluate the initial value of C_d.

D. Controller implementation

A MatLab® xPC Target® real-time machine (Performance real-time target machine by SpeedGoat®) is employed to run the real-time hydrodynamic model of the OWC plant, which governs the motion of the piston, and to control the charging status (charging voltage and status of relays) of the CD-DEG.

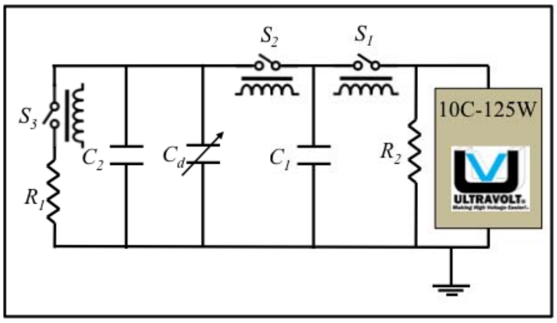

Figure 5. Simplified schematic of the HV Driving circuit.

The developed test-bench, with its sensing equipment, makes it possible to implement different algorithms for controlling the harvesting cycles of the CD-DEG. A first simple regulation strategy consists in imposing a state of electrical activation to the CD-DEG that is only a function of the actual value of its capacitance. Such a value can be directly measured or can be estimated through at least one of the following sensor readings: air-chamber pressure, position of the piston, displacement of the tip of the CD-DEG. In more advanced versions of the CD-DEG control, the acquired measures can also be employed to build suitable estimators that can further improve the energy harvesting performance of the generator.

A basic controller that can be used to conduct preliminary experiments is described in the following section.

V. Preliminary Tests

This section reports preliminary tests that have been conducted considering the hydrodynamic model of a floating Poly-OWC based on the OWC collector developed by the company Sendekia. Details of the hydrodynamic model and on the dimensioning of this WEC are reported in [8]. In order to match the diameter of the OWC collector with that of the hardware cylinder tube, a small-scale OWC prototype (with geometric scale factor of 1:77) has been considered for the computation of the hydrodynamic parameters.

The employed CD-DEG specimen is made by an active dielectric elastomer membrane, which is obtained by gluing together two layers of a commercial double-sided pressure-sensitive acrylic tape (VHB 4905 by 3M®), that is stretched onto a polycarbonate ring and coated on both sides with compliant carbon conductive grease electrodes (MG-Chemicals 846). The dimension of the internal diameter of the polycarbonate ring is e = 130mm; acrylic film pre-stretch is equi-biaxial with value λ_p = 3; the initial thickness (in the undeformed virgin condition) of the active dielectric elastomer membrane is t_0 = 1.0mm, which excludes the thickness of the compliant electrodes. A picture of the CD-DEG prototype that has been employed for this study is reported in Figure 6.

Preliminary results have been collected implementing a control law that triggers the activation status of the CD-DEG on the basis of the knowledge of the water column level z inside the chamber. Specifically, the CD-DEG is charged when z reaches a maximum (or minimum) and it is discharged when z crosses the zero.

Figure 7 reports the experimental results acquired during three tests of the same CD-DEG subjected to different activation voltages and excited by the same emulated set of polychromatic incident waves, generated using the spectrum of equation (5) with the following parameters: $H_s = 4.55$cm and $T_e = 0.91$s, that, at full scale, correspond to $H_s = 3.5$m and $T_e = 8.0$s according to the rules of Froude scaling [13]. The plots reported in figure are for the different variables that are measured with the set-up: the voltage (V_1) across capacitor C_1; the voltage (V_d) across the CD-DEG (and C_2); the differential pressure (p) with respect to atmosphere inside the cylinder (that emulates the pressure inside the OWC air-chamber); the position (z) of the piston (that emulates the free surface of the column of water inside the OWC). In each plot, the results of the three tests performed with different activation voltages are represented by red, blue and black solid lines.

The reported results highlight the following:

- In all wave periods and for all the three test cases, upon electrical activation, voltage V_d increases as the CD-DEG deflates. That is, irrespective of wave height and period and of the value chosen for the activation voltage, the considered control law based on the measurement of the water level inside the OWC structure is effective and makes it possible to convert pneumatic energy into electricity via the CD-DEG.
- Activation of the CD-DEG determines a drop in pressure inside the cylinder chamber, with the drop being larger as the activation voltage is higher. This pressure drop indicates that the mechanical work absorbed by the piston to deflate the CD-DEG is lower than that provided during the inflation phase, with the difference being the electrical energy that is extracted by the CD-DEG (plus the losses that are due to material viscoelasticity). As a consequence, the energy that can be harvested by the CD-DEG is larger as the activation voltage is higher.
- The motion amplitude of the piston diminishes as the activation voltage of the CD-DEG is increased. This indicates that the energy extraction performed by the CD-DEG can significantly affect the dynamics of the water inside the OWC structure. This demonstrates that the CD-DEG can extract a significant portion of the energy that is available in the incident water waves.

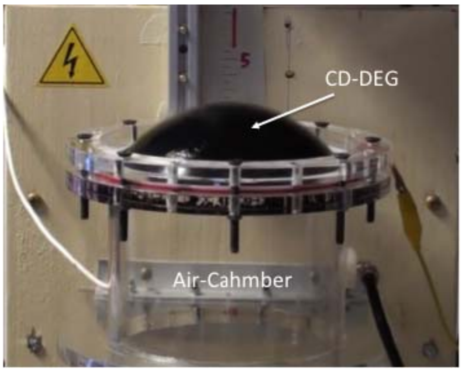

Figure 6. Picture of the inflated CD-DEG during operation.

VI. CONCLUSIONS

This paper presented an experimental test-rig that can be used to study the control of Oscillating Water Column (OWC) Wave Energy Converters (WECs) based on inflated Circular Diaphragm Dielectric Elastomer Generators (CD-DEGs).

The test-rig makes it possible to simulate the practical operating conditions of this kind of WECs by performing hardware-in-the-loop simulations.

After a presentation of the purposely developed hardware set-up and global controller architecture, an experimental case study, which is based on the emulation of a floating OWC converter, is provided to show the dynamic response and energy harvesting performance of a particular CD-DEG specimen made with acrylic dielectric elastomer membranes and carbon conductive grease electrodes.

In the future, hardware-in-the-loop simulations will be performed using the developed test-rig to optimize and assess CD-DEG power take-off systems and energy harvesting controllers for WECs that are based on the OWC principle.

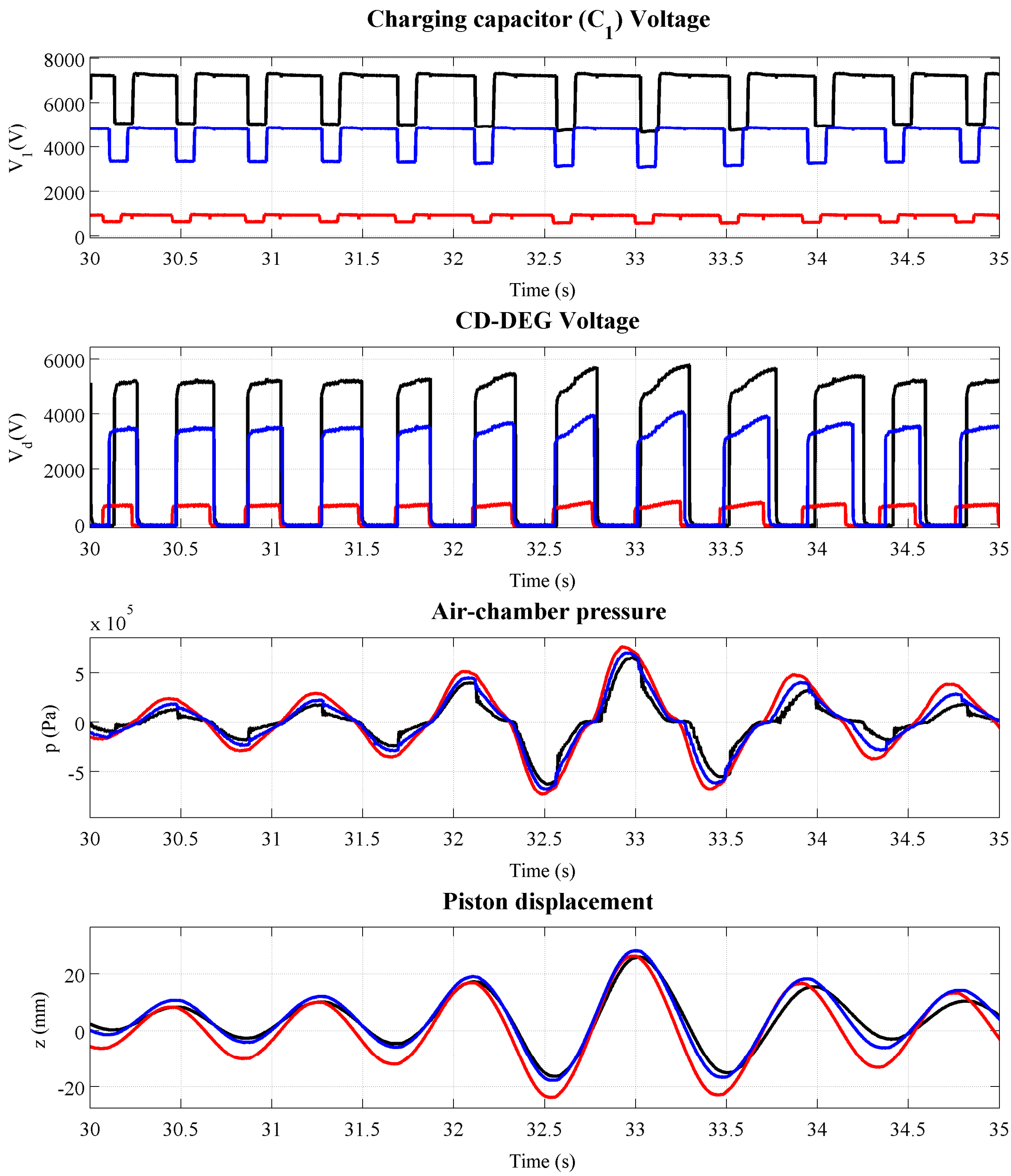

Figure 7. Example of the measured variables time-series during experiments with simulated polychromatic waves (H_s = 4.5cm, T_e = 0.91s). Data are plotted for the same incident wave and three different values of the supply voltage on the charging capacitor.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of:

- SELMAR company (Italy) for the development of the hardware setup;
- SENDEKIA company (Spain) for the concession of the geometry of their offshore OWC concept;
- Marco Alves form WavEC (Portugal) for providing the hydrodynamic parameters of the OWC collector.

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