Preliminary study on a novel hybrid wave surge energy converter for nearshore applications

Gregorio Boccalero, Claire Jean-Mistral, Simon Chesne, Emmanuel Mignot and Nicolas Riviere

Abstract— **Nowadays, the electrical energy production by waves is limited due to technological, economic and environmental problems related to the available solutions. In this context, hybrid structures coupling electroactive materials could represent an innovative solution to design promising concepts of submerged wave converters for nearshore applications. Here, we present the development of a hybrid prototype exploiting only horizontal component of the waves, and that utilizes piezoelectric technology in synergy with electroactive polymers (Dielectric Elastomer Generators, DEG) in order to drastically increase the global efficiency of the system, while maintaining very limited production costs. Indeed, DEGs represent a high energy density technology not yet fully exploited. This approach can provide a smart, simple, cheap and robust solution for harvesting energy from coastal regions without creating encumbrances to navigation. This contribution presents the preliminary experimental studies on our small-scale models (15cmx15cm), performed in a wave flume, revealing the hydrodynamics and the electrical extraction through piezoelectric elements of bottom-hinged plates, subjected to various conditions (frequency and amplitude of waves, position of model relative to the standing waves). For the moment, piezoelectric elements scavenge few tens of nW with the dimensions adopted and the waves utilized, enough to start the hybridization with DEG. Besides, we also investigate and discuss the effect of deformable membranes integrated in the device, consisting the active materials of the DEG.**

Keywords—**electroactive polymers, hybrid energy conversion, nearshore, piezoelectric, wave surge converter.**

I. Introduction

SEA wave energy is a promising renewable source deeply investigated since the early 18th century. Many patents, conceptions and devices have been proposed, and the literature related to the reviews on this topic demonstrates the efforts in the development of solution technologically competitive to oil, coal, gas, nuclear and to other renewable source powers. However, among the many technological solution proposed, few concepts found a real application [1]. The first evident consideration is that the sea is a very aggressive chemical environment, always in movement with unexpected giant energy events. Some reasons for the limited exploitation of sea energy consist in technological, economic and environmental problems related to the available solutions, such as efficiency and robustness, investment and maintenance costs, effect on marine ecosystem, disturbance for private and commercial vessel. The energy conversion, in some cases, can also coincide with prevention of disasters, such as Tsunami emergency sensors [2], or limitation to undesirable phenomena, such as coastal erosion mitigation [3]: these are examples of applications for which there is a further technological boost. In other cases, the technology can be inspired by nature, through a bio-mimicry design based on the analogies of function, principle, shape, structure, material, process, organizational strategy, and behaviour of the various biological entities [4]. The large variety of typology of wave energy converter can be classified in offshore and nearshore solutions, comprising: single and multi-bodies heaving buoys, fully submerged heaving systems,

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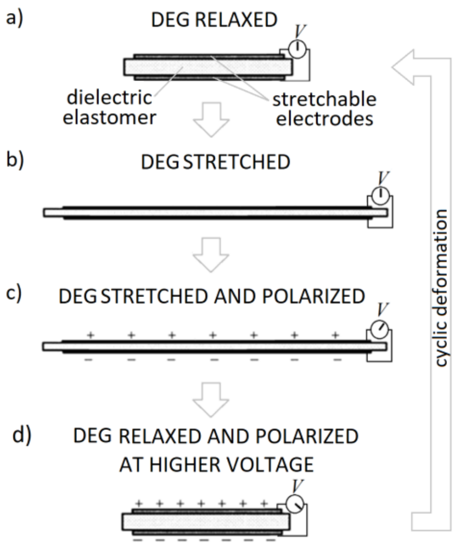

Fig. 1. Illustration of the operational generation mode of an EAP subjected to cyclical deformation: a) composite at rest, b) composite deformed by an external force, c) polarization at maximal deformation, d) voltage amplification due to the change of capacitance occurred in the relaxation. The constant charge operational condition can be represented by considering only the cases c) and d).

pitching devices, bottom-hinged, overtopping technologies and so on.

Oscillating systems as buoys [5], snakes [6], water columns [7] and pendulums [8] benefited much interest, and particular attention has been focused on generators called "wave surge converters" [9], for their operation simplicity, their potential in terms of generated energy and their location facilitating installation, operation and maintenance. Several surge converters have been proposed, comprising surging top surface [10]–[13] and totally submerged devices [14]. All of these conventional systems require a Power Take Off (PTO) to extract the wave energy, such as self-rectifying air turbines, hydraulic turbines, high-pressure oil-hydraulics, and to power an electric motor. These constraints make these solutions expensive in terms of maintenance and not viable in the long term, especially in the marine environment. Recently, the technology of electroactive polymers (EAP), also named Dielectric Elastomer (DE), traditionally used for actuation in robotics, has been applied to wave energy converters [15] in order to overcome the limitation of classic rigid technologies. One can cite the structures developed in the United States in 2008 (SRI) [16], Japan [17], Italy in 2013 (Polywec) [18], Germany in 2013 (EPoSil) [19] and France in 2010 (SBM) [20]. Up to now, these soft wave energy converters develop low scavenged energy density. Thus, we present in this work a hybrid device combining two active materials in order to increase the global efficiency of the EAP device while maintaining a very simple design compared to classic rigid technologies.

II. Our concept

1) *Technology*

The hybrid solution of electrical conversion proposed for our prototype consists in the simultaneous use of piezoelectric materials and electroactive polymers.

Piezoelectricity appears in some materials such as quartz, crystalline materials with no inversion symmetry, by the internal creation of charge q under an applied mechanical force T . An electrical voltage V is thus generated according to the following relations [21]:

$$\begin{cases} T = k_p x + \Gamma V \\ I = \Gamma \dot{x} - C_p \dot{V} \end{cases} \tag{1}$$

where k_p is the stiffness of the piezoelectric material, x is the deformation, Γ is the electromechanical coupling factor, C_P is the piezoelectric capacitance and upper dot stands for the temporal derivative.

The Dielectric Elastomer (DE) represent a promising high energy density transducer technology, with many advantages with respect to more traditional ones: they are cheap, light, resistant and efficient. Dielectric Elastomer Generators (DEGs) are soft electrostatic composite materials constituted by coupling two stretchable electrodes to a high permittivity elastomer sheet. Therefore, charging the DEG at its maximal stretching (S) and discharging it after its relaxation (R), enable the amplification of an input voltage V, as shown in Fig. 1. The electrical energy E generated by this process can be simply expressed as follows:

$$E = \frac{1}{2}\left(C_S {V_S}^2 - C_R {V_R}^2\right) \tag{2}$$

where C represent the capacitance of the composite, V the electrical voltage, and the subscripts S and R indicate

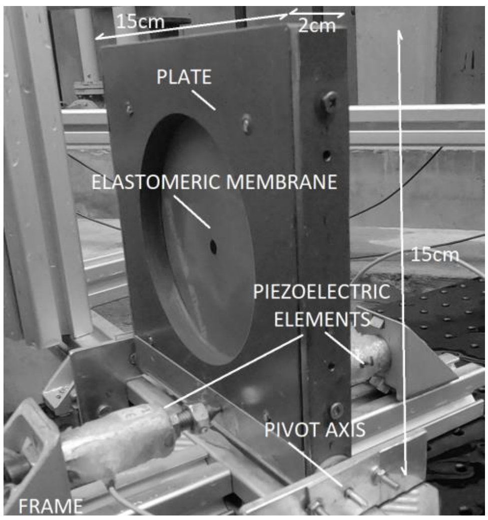

Fig. 2. Depiction of the centimetre-sized device used for the preliminary measurements. Here a passive elastomeric membrane, consisting the active material of DEG, is placed in the centre of the plate (diameter of 10 cm in this case)

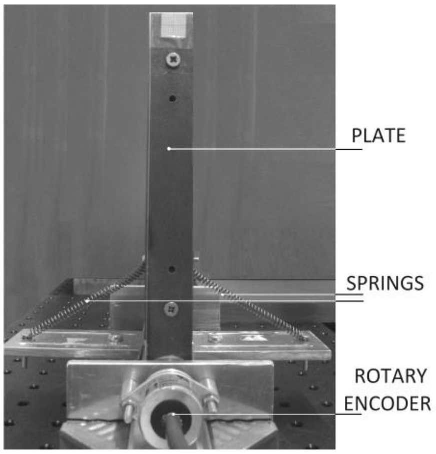

Fig. 3. Lateral view of the device equipped with two springs, instead of piezoelectric elements, utilized for investigating the dynamics. A magnetic incremental rotary encoder connected to the pivot axis is used to measure the displacement of the plate, during the characterization of the system and during the tests in the waves.

the stretched and relaxed status, respectively. Since DEG needs an external polarization source to realize their energetic cycle, this polarization can be ensured, for example, by the piezoelectric technology: this strategy brings the constitution of a hybrid device. An electronic power stage must ensure to amplify and rectify the voltage generated by the piezoelectric stage, in order to charge the DEG at the proper time. Various topologies can be adopted to realize this synchronization, such as charge pumps [22], [23] and diode rectifier [24] solutions.

2) Centimetre-sized device

The structure presented in this work represents a proof of concept, consisting in a rigid plate of dimension 15.6 cm x 2 cm x 16.5 cm pivoted to a frame. The angular motion of the plate is constrained by two piezoelectric elements, placed perpendicularly to it, and forming a lever force advantage (at 1 cm up to the pivot axis). Since the piezoelectric elements possess a very high elastic modulus, the resulting system is very stiff, thus the kind of deformation of the piezoelectric elements (in the order of tens of μm) can be assumed axial. Two iron bars screwed to pivoted part in aluminium (see Fig. 2) constitute the main plate, which hosts an interchangeable PVC part of dimensions of 15 cm x 2 cm x 13.5 cm. The presence of elastomeric membranes into the plate, constituting the active material of DEG, is also preliminary investigated, making necessary the realization of interchangeable parts equipped with circular holes (see Fig. 2).

III. EXPERIMENTAL SETUP

The experimental study is mainly carried out in a wave flume, specifically implemented for our project, in the Laboratoire de Mécanique des Fluides et d'Acoustique at INSA Lyon. It consists in a concrete tank of 8.3 m length, 70 cm width and 1 m height, filled with water until a level of 50 cm. A single-bottom-hinged flap, linked through a crank connecting rod transmission to an 80 W DC engine, equips it. The amplitude of the flap motion can be regulated by crank length adjustment, while its frequency is set through a voltage speed controller of the engine. Since for the moment no adsorbing beach was included, the flume only permits the creation of standing waves. In fact, this part of the research aims to understand the feasibility of our concept, which must operate in nearshore regions, thus partially characterized by standing wave phenomenon. The sought characteristics of the standing waves consist in wave periods of 1-2 s and wavelengths of 2-6 m. Such parameters are measured through a series of wave Gauge Controller probes, each of which having an independent monitoring circuit. A small HD waterproof camera (GoPro Hero7) is used for the video acquisition at 120 fps, from the side of the system, for each test, including the water particle trajectories and the device motion.

The piezoelectric elements used here consist in two preloaded piezoelectric stacks, model P-844.10, acquired from Physic Instruments (PI), having dimensions of 19 mm x 19 mm x 47 mm, a Young modulus of 21 GPa, and an effective coupling coefficient of 14 mV/N. A variable resistor breadboard is also used to investigate the maximal power generated by the piezoelectric stacks under different characteristic wave climates. A pair of traction springs with radius of 2 mm, length of 40 mm and stiffness of 10 N/m substitutes, in some experiments, the piezoelectric stack. The extremities of each spring are fixed to the plate, at a higher position with respect to the point of contact of piezoelectric stacks (4 cm), and to brackets, intimately connected to the frame (see Fig. 3). This configuration, together with the use of a waterproof magnetic incremental rotary encoder (EMI22A2048S5L6S10PA from Eltra, 0.15 °/pulse) enables the investigation of the dynamics of the system and the study of the fluid-solid interactions occurring in different experimental conditions. A digital oscilloscope (Picoscope 2405A, from Pico Technology) is used both for the acquisitions of the electrical signals from piezoelectric stacks and output signals from the encoder. The membranes utilized in our prototype are made by commercial natural rubber elastomeric sheets, 20820-Red purchased from Thera-band, characterized by 0.21 mm of thickness and a Young modulus of 0.36 MPa. The elastomeric layer is hosted in an engraved window in a PVC plate that houses a circular hole, and a complementary mountable part blocks it with pressure; in

TABLE I
CHARACTERIZATION OF THE STANDING WAVES UTILIZED

Wave code (#)	Wave Period (s)	Mode number (#)	Wave length (m)	Wave Amplitude (mm)
ST1	1.21	4	2.05	89
ST2	1.46	3	2.75	42
ST3	1.46	3	2.75	56
ST4	1.46	3	2.75	80

TABLE II
MEASUREMENTS OF MOTION OF THE PLATE WITH SPRINGS

Wave code (#)	Maximum angle experienced (°)	Maximal Input force (N)	Phase motion (plate/water) (°)
ST1	11.9	5.09	190
ST2	7.1	3.3	185
ST3	10.2	4.36	195
ST4	13.4	5.56	186

this way, the membrane lays at the center of the 2 cm thick plate (see Fig.2)

IV. MEASUREMENTS

The experimental work consisted in various measurements aiming at characterizing our mechanical system and exploring various parameters.

A. *Standing waves characterization*

Being the geometry of the flume fixed, by fixing a water level of 0.5 m only some combinations of amplitude and frequency of the wave maker allowed the creation of quasi-sinusoidal waves stable in time. Still, the time evolution of wave amplitude for some experiments showed modulations between of 5 minutes to 30 minutes. We attributed this effect to the balance exchange between the provided energy and the damping one, being this latter linked to hydrodynamics dissipation, such as bottom and wall effects [25] which depend on horizontal velocity.

In order to test our device under different excitation conditions, four different stable standing waves have been individuated, characterized, and reported in Table I.

We considered the non-perfect conditions created opportune for performing the preliminary measurements of our prototype conceived for nearshore applications.

B. *Investigation of the fluid-solid interaction through moving and fixed plate*

Firstly, the plate has been fixed orthogonally to the bottom of the flume through two rigid aluminium brackets, and the affection of the presence of the device on the amplitudes of the tested waves has been checked. For all the standing waves considered, after stabilization (monitored through the probes), a decrease of the amplitudes between 10% and 20% has been measured when the device was placed below a standing wave node, keeping similar ratio of asymmetry (positive/ negative amplitude). On the other hand, no affections have been measured when the system was positioned under a wave crest. This makes sense, since at the crest of a standing wave the motion of the water particles is exclusively vertical, so parallel to the plate, while at the node, the motion is horizontal, i.e. perpendicular to the plate. Then, the system equipped with springs, a massive PVC plate (without membranes) and the rotary encoder, has been characterized in order to investigate the input forces of the waves on the plate and the dynamic of a moving plate. A quasi-static analysis, performed by applying various weight to different position of the plate, provided the estimation of the angular stiffness of the system in function of the input force applied to the plate. The angular displacements of the plate has been acquired though the encoder for all the waves, allowing the estimation of the input forces for the dynamical case (Table II). Interestingly, probably due to a particular combination of moment contributions applied to the plate, such as inertial, radiation, hydrostatic and mechanical ones [26], higher horizontal forces for ST4 than ST1 has been detected, while the wave amplitude and frequency were lower.

C. *Phase motion between plate and water particles analysis*

Through the video acquisition of the device equipped with springs and operating in different standing waves, it has been also possible to clearly distinguish both the movements of the plate, and the trajectories of tracers within the water. A phase shift close to 180° between the plate and the water particles motion has been measured for the standing waves analysed (Table II), indicating that the pressure gradient, and not the velocity, mainly governs the generated force for the set of mechanical parameters used. At the wave node, horizontal particles velocity of 9 cm/s and 8 cm/s for ST1 and ST4, respectively, have been estimated through video acquisition camera.

D. *Electrical extraction through piezoelectric elements*

Experimental measurements of electrical extraction with a full plate (without a deformable membrane) have been performed in two standing waves: ST1 and ST4. We highlight that the geometrical configuration adopted for the transduction needs a very careful assemblage process in order to obtain symmetrical output voltages from the two piezoelectric stacks. Indeed, since the transducers are screwed to fixed brackets and their tips are in contact with the plate through an advantage factor of about 6 with respect to the centre of pressure, the orthogonality

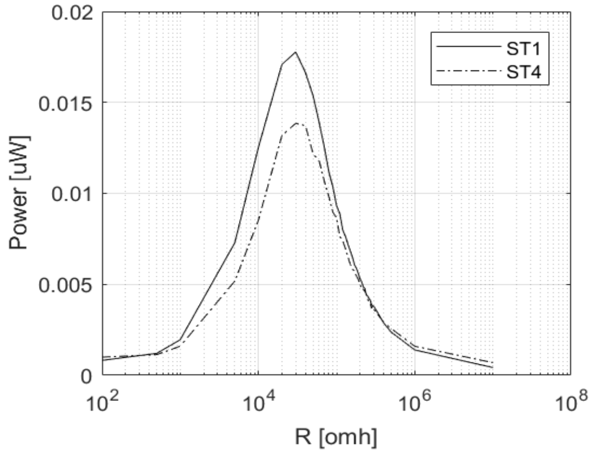

Fig. 4. Electrical power generated by the two piezoelectric elements for two standing waves characterized by different wave periods and amplitudes. Less than 1 μW is measured, at the optimal load of 30 KΩ.

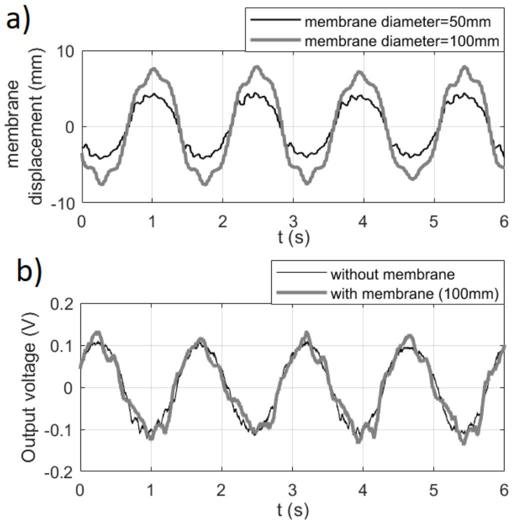

Fig. 5. Time evolution of the passive elastomeric membranes displacement (a) with two different diameters, positioned into the plate (see Fig. 2) and output voltage from piezoelectric elements (b), with and without the presence of an elastomeric membrane.

between the plate and the transducers must be ensured by the use of screw clamps and an opportune tuning.

The effect of positioning our device under a crest of the standing waves was firstly investigated, confirming what we obtained for the device equipped with springs: no output voltage was measured in this condition. Then, a series of electrical measurements by placing the system under a node of the standing waves, applying variable external resistive loads in parallel with the piezoelectric stacks, and measuring the output voltage through a digital oscilloscope, have been performed.

This allowed us to find the maximal power generated by calculating the average delivered power dissipated P on the various resistive loads R, calculated from the root mean square of the voltage V_{RMS} as follows:

$$P = {V_{RMS}}^2 / R \quad (3)$$

As can be noted in Fig.4, that report the curves obtained by the experimental measurements led for two standing waves, the output power dissipated reaches very low values (18 for ST1 and 14 nW for ST4, both on a resistive load of 30 KΩ); rough calculations estimated mechanical input powers of the order of mW.

Since as a piezoelectric element consists in a resonant capacitance C, the characteristic resistive shunt time constant τ depends on the external resistance load R following the relation [21]:

$$\tau = RC \quad (4)$$

Therefore, adopting very different mechanical characteristic times, one can expect to measure different optimal resistive loads. In this case, since the characteristic times of the two waves considered are closed (wave periods of 1.21 s for ST1 and 1.46 s for ST4), the values of the optimal loads appeared the same (see Fig. 4).

Despite in the preliminary measurements very low powers have been obtained, the amount of energy produced is considered enough to start the hybridization with DEG, thus providing a proof of concept of the completed device.

As it can be observed in Fig 5, the values of the output voltage obtained in these measurements remains low (0.1V), close to the common voltage thresholds of diodes or MOSFETs used to rectify the electrical energy, and far away from the voltage needed for the polarization of DEG (conventionally KV) [24]. These aspects can be simply solved by the use of electronic integrated circuits able to store small output voltages signals [27], [28], and the use of charge pumping and step-up converter approaches [23].

E. Elastomeric membrane placed into the plate

The deformation of soft elastomeric membranes clamped into the plate, and its effect on the performance of the piezoelectric elements, have been investigated for one representative wave, ST4 (see Table I). An underwater video acquisition of the device located under a wave node, equipped with membranes of diameter of 50 mm and 100 mm allowed the measurement of the vertical displacement of the centre of the membrane, marked as shown in Fig.2.

At the same time, the movement of the water particles has been deduced from the movies, and the measurement of the electrical voltage from the piezoelectric elements, through the oscilloscope, too. As can be observed in Fig. 5a, the time evolution of the displacement of the two membranes appear not sinusoidal, but characterized by periodic and structured deformation sequences. The membrane of 100 mm of diameter has shown a two-steps deformation, addressed to complex fluid-solid interaction dynamics due to elastic, inertial and pressure gradient contributions; those of 50 mm has shown even more peaks, and a smaller deformation. Furthermore, by increasing the diameter of the membrane, the effective elastic constant in the direction of deformation has decreased, but the force exerted on the membrane has increased.

A phase between the deformation of the elastomer and the water particles very close to 180° has been measured, suggesting, again, the role of the pressure gradient in the system proposed.

The output voltage from piezoelectric elements in presence and in absence of the elastomeric layer of 100 mm of diameter has been measured (Fig. 5b). Small differences have been found out between the two cases, besides the presence of the membrane produced an appreciable structuration attributable to the two peaks observed in the deformation: this sensibly increased the V_{RMS}.

V. CONCLUSION

The centimetre-sized proof of concept tested herein represents a simple and robust bottom-hinged wave surge converter solution conceived for nearshore large-scale applications. The exploitation of soft electro-mechanical transducer composites, instead of traditional rigid PTO mechanisms, could show a pathway towards the reduction of costs of wave energy, through a lower capital investment and lower maintenance costs of the plants, since such cheap and soft promising high energy density materials can resist the aggressive sea environments.

The preliminary studies reported in this work partially demonstrate the feasibility of the concept based on hybrid energy scavenging solution composed by piezoelectric materials and electroactive membranes for nearshore areas.

Other standing waves will be characterized in order to extend the investigations of the prototypes to different conditions. Besides, an adsorbing beach should to be included in the flume to create progressive waves. An extended set of experiments will aim to investigate the effect of mechanical and hydrodynamic parameters, such as the use of different materials to explore the effect of the hydrostatic restoring moment on the phase between the plate motion, the water particles movement and the deformation of the membranes.

Few amount of power has been scavenged with this first prototype, and we addressed this to mechanical losses occurred in the transmission of the force to the piezoelectric stacks: other geometries and configurations have to be investigated. Moreover, a complete analytical model will be developed to optimize the electrical extraction. Anyway, the energy produced can be already considered sufficient for supplying the DEG.

Other experiments on the deformation of membranes will be led by changing position, thickness and material of the membranes, and exploring combinations of materials of the main plate. DEG have to be tested through the realization of stretchable electrodes and the use of proper electronics. The latter represents a technological challenge, since all the parts will be submerged.

The promising attempts suggest fruitful perspectives.

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REFERENCES

[1] L. Wang, J. Isberg, and E. Tedeschi, "Review of control strategies for wave energy conversion systems and their validation: the wave-to-wire approach," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 366–379, 2018.

[2] R. A. Lawson *et al.*, "From research to commercial operations: The next generation Easy-to-Deploy (ETD) tsunami assessment buoy," in *OCEANS 2011 IEEE - Spain*, 2011, pp. 1–8.

[3] B. M. John, K. G. Shirlal, and S. Rao, "Effect of Artificial Sea Grass on Wave Attenuation- An Experimental Investigation," *Aquat. Procedia*, vol. 4, no. Icwrcoe, pp. 221–226, 2015.

[4] H. Zhang and G. A. Aggidis, "Nature rules hidden in the biomimetic wave energy converters," *Renew. Sustain. Energy Rev.*, vol. 97, no. August, pp. 28–37, 2018.

[5] M. Mekhiche and K. A. Edwards, "Ocean Power Technologies Power Buoy : System-level design, development and validation methodology," *2nd Mar. Energy Technol. Symp.*, pp. 1–9, 2014.

[6] G. J. Dalton, R. Alcorn, and T. Lewis, "Case study feasibility analysis of the Pelamis wave energy convertor in Ireland, Portugal and North America," *Renew. Energy*, vol. 35, no. 2, pp. 443–455, 2010.

[7] J. M. Paixão Conde and L. M. C. Gato, "Numerical study of the air-flow in an oscillating water column wave energy converter," *Renew. Energy*, vol. 33, no. 12, pp. 2637–2644, 2008.

[8] S. P. Gunawardane, C. J. Kankanamge, and T. Watabe, "Study on the performance of the 'Pendulor' wave energy converter in an array configuration," *Energies*, vol. 9, no. 4, 2016.

[9] D. Sarkar, E. Renzi, and F. Dias, "Wave Power Extraction by an Oscillating Wave Surge Converter in Random Seas," *Vol. 8 Ocean Renew. Energy*, no. November, p. V008T09A008, 2013.

[10] E. Renzi and F. Dias, "Hydrodynamics of the oscillating wave surge converter in the open ocean," *Eur. J. Mech. B/Fluids*, vol. 41, pp. 1–10, 2013.

[11] N. Tom, M. Lawson, Y. H. Yu, and A. Wright, "Spectral modeling of an oscillating surge wave energy converter with control surfaces," *Appl. Ocean Res.*, vol. 56, pp. 143–156, 2016.

[12] T. Whittaker and M. Folley, "Nearshore oscillating wave surge converters and the development of Oyster," *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 370, no. 1959, pp. 345–364, 2012.

[13] R. P. F. Gomes, M. F. P. Lopes, J. C. C. Henriques, L. M. C. Gato, and A. F. O. Falcão, "The dynamics and power extraction of bottom-hinged plate wave energy converters in regular and irregular waves," *Ocean Eng.*, vol. 96, pp. 86–99, 2015.

[14] I. F. Noad and Richard, "Wave energy absorption by submerged flap-type oscillating wave surge converters," *Proc. 11th Eur. Wave Tidal Energy Conf.*, no. SEPTEMBER 2015, 2015.

[15] G. Moretti *et al.*, "Resonant wave energy harvester based on dielectric elastomer generator," *Smart Mater. Struct.*, vol. 27, no. 3, 2018.

[16] S. Chiba, M. Waki, R. Kornbluh, and R. Pelrine, "Innovative power generators for energy harvesting using electroactive polymer artificial muscles," in *Proc.SPIE*, 2008, vol. 6927, no.

[17] Mikio Waki, Seiki A. Chiba, Z. Song, S. Zhu, and K. Ohyama, "Experimental Investigation on the Power Generation Performance of Dielectric Elastomer Wave Power Generator Mounted on a Square Type Floating Body," *J. Mater. Sci. Eng. B*, vol. 7, no. 5, pp. 179–186, 2017.

[18] R. Vertechy, M. Fontana, G. P. Rosati Papini, and D. Forehand, "In-tank tests of a dielectric elastomer generator for wave energy harvesting," *Electroact. Polym. Actuators Devices 2014*, vol. 9056, no. March, p. 90561G, 2014.

[19] B. Scherber, M. Grauer, and A. Köllnberger, "Electroactive polymers for gaining sea power," in *Proc.SPIE*, 2013, vol. 8687.

[20] P. Jean *et al.*, "Standing wave tube electro active polymer wave energy converter," in *SMS (EAPAD)*, 2012, vol. 8340, p. 83400C21.

[21] T. Hehn and Y. Manoli, "CMOS Circuits for Piezoelectric

Energy Harvesters," *C. Circuits Piezoelectric Energy Harvest.*, vol. 38, p. 204, 2015.

[22] T. McKay, B. O'Brien, E. Calius, and I. Anderson, "An integrated, self-priming dielectric elastomer generator," *Appl. Phys. Lett.*, vol. 97, no. 6, pp. 2011–2013, 2010.

[23] P. Illenberger, K. Takagi, H. Kojima, U. K. Madawala, S. Member, and I. A. Anderson, "A Mathematical Model for Self-Priming Circuits : Getting the Most From a Dielectric Elastomer Generator," *IEEE Trans. Power Electron.*, vol. 32, no. 9, pp. 6904–6912, 2017.

[24] C. Lagomarsini, C. Jean-Mistral, G. Lombardi, and A. Sylvestre, "Hybrid piezoelectric–electrostatic generators for wearable energy harvesting applications," *Smart Mater. Struct.*, vol. 28, no. 3, p. 035003, 2018.

[25] P. D. Weidman, A. Herczynski, J. Yu, and L. N. Howard, "Experiments on standing waves in a rectangular tank with a corrugated bed," *J. Fluid Mech.*, vol. 777, pp. 122–150, 2015.

[26] R. Gomes, M. Lopes, and J. Henriques, "A Study on the Wave Energy Conversion by Submerged Bottom-hinged Plates," *Eur. Wave Tidal Energy Conf.*, no. September, p. 10, 2011.

[27] L. Garbuio, M. Lallart, D. Guyomar, C. Richard, and D. Audigier, "Mechanical energy harvester with ultralow threshold rectification based on SSHI nonlinear technique," *IEEE Trans. Ind. Electron.*, vol. 56, no. 4, pp. 1048–1056, 2009.

[28] A. R. Bulsara, S. Baglio, F. Maiorca, C. Trigona, B. Andò, and F. Giusa, "Diode-less mechanical H-bridge rectifier for 'zero threshold' vibration energy harvesters," *Sensors Actuators A Phys.*, vol. 201, pp. 246–253, 2013.