Loading system mechanism for dielectric elastomer generators with equi-biaxial state of deformation

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ABSTRACT

Dielectric Elastomer Generators (DEGs) are devices that employ a cyclically variable membrane capacitor to produce electricity from oscillating sources of mechanical energy. Capacitance variation is obtained thanks to the use of dielectric and conductive layers that can undergo different states of deformation including: uniform or non-uniform and uni- or multi-axial stretching. Among them, uniform equi-biaxial stretching is reputed as being the most effective state of deformation that maximizes the amount of energy that can be extracted in a cycle by a unit volume of Dielectric Elastomer (DE) material.

This paper presents a DEG concept, with linear input motion and tunable impedance, that is based on a mechanical loading system for inducing uniform equi-biaxial states of deformation. The presented system employs two circular DE membrane capacitors that are arranged in an agonist-antagonist configuration. An analytical model of the overall system is developed and used to find the optimal design parameters that make it possible to tune the elastic response of the generator over the range of motion of interest. An apparatus is developed for the equi-biaxial testing of DE membranes and used for the experimental verification of the employed numerical models.

Keywords: Dielectric Elastomers Generators, Equi-biaxial stretch, Impedance control

1. INTRODUCTION

Dielectric Elastomers (DEs) are highly deformable non-conductive materials that can be employed as insulating layers to conceive variable capacitance transducers. DE transducers have been largely studied for actuation and sensing applications[1,2]. In the last decade, several researches have demonstrated that they can be successfully employed as electricity generators[3]. The working principle of DE Generators (DEGs) is based on a variable capacitor whose dielectric and conductive layers are deformed, resulting in large variations of its capacitance. Such a variable capacitor works as a charge pump and makes it possible to directly convert the introduced mechanical energy into usable electrical energy.

A very promising application field for DEGs is the wave energy sector. At present, Wave Energy Converters (WECs) are based on hydraulic and mechanical components made of bulky, heavy, costly and corrosion-sensitive materials. DEGs show several positive attributes, that suit the requirements of the wave energy sector, such as: large energy densities, good energy conversion efficiency that is rather independent on cycle frequency, easiness in manufacturing and assembling, high shock resistance, silent operation and low cost. Introducing DE-based Power-Take-Off (PTO) systems, that directly convert oscillating mechanical energy into electricity, could largely simplify WEC technology. Several studies that focus on this particular application field of DEGs have already been conducted [4–8].

The performance and the effectiveness of a WEC equipped with a DE-based PTO may depend on several factors. Among them, there are two fundamental issues that have to be considered from the early design phases: 1) how effectively the dielectric elastomer material is employed, 2) how efficient is the hydrodynamic interaction between the waves and the energy capturing system.

As regards the first issue, the dielectric material employed in a DEG is exploited at best when it is subjected to uniform equi-biaxial deformation and when generation cycles bring the material close to electromechanical rupture limits [9,10]. In this working conditions the energy produced by a unit mass of material is maximized; that is, the energy that can be

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produced with the same investment for the acquisition of DE material is maximized. The maximum theoretical energy density that can be reached is limited by electromechanical rupture and buckling conditions of the considered DE material. As an example, for an acrylic DE material, energy density up to 1.7 J/g has been estimated [9] and a maximum energy density of 0.56 J/g has been experimentally obtained for a limited number of cycles.

As regards the hydrodynamic interaction between WEC and wave motion, it is not straightforward to determine optimal solutions for the DE-based PTO. Generally, it is required for the PTOs to show a prefixed value of mechanical impedance against the external exciting force. Additionally, it is highly desirable to posses the ability to modify in real-time such a mechanical impedance over a wide range of values, making it possible to optimally control the response of the WEC according to the actual frequency content of the wave excitation forces[11].

In this paper, we introduce a Dual-Membrane Equi-biaxial DEG (DuME-DEG), which makes it possible to exploit the advantages of equi-biaxial stretch states as well as to work under optimal impedance control. This is obtained through a linkage mechanism with linear input motion that alternatively deforms two circular DE membranes, arranged in an agonist-antagonist configuration, in a way to transfer elastic energy between them. Through a proper choice of the design parameters, the mechanical stiffness against the input force can be tuned in a wide range including positive, negative and quasi-null values. When the mechanical stiffness is set to a very small value, the DEG response is solely controlled by the electrical activation and the resulting impedance can be digitally programmed in real-time.

In the second section of the paper, we describe the working principle of the DuME-DEG and propose an analytical model for predicting and optimizing its performance in terms of energy output and force input response. The third section is dedicated to the presentation of a case study in which a specific device that employs a natural rubber DE membrane is analyzed. In the fourth section, the results of a set of experiments made on a test fixture for the implementation of equi-biaxial states of stretch are reported in order to provide a validation of the proposed DuME-DEG model.

2. DUAL MEMBRANE EQUIBIAXIAL DIELECTRIC ELASTOMER GENERATOR

Machines and mechanisms for the equi-biaxial stretching of polymeric membranes are commonly employed in industrial production processes of thin films[12]. For DE transducers, the stack of DE membranes and electrodes that form the variable capacitance (hereafter called "active membrane") can be deformed in an equi-biaxial fashion according to one of the following methods: 1) by inflating the active membrane that usually has an initial circular shape [13,14] 2) by expanding the active membrane through a number of clamps that are equally spaced along the membrane perimeter and that move according to prefixed trajectories [10]; 3) by compressing the active membrane with a uniform pressure[15].

The proposed DuME-DEG concept is a generator with linear motion employing two active membranes that are equi-biaxially stretched, in a reciprocal manner, by a multi-clamp circular expansion systems. A schematic of a DuME-DEG is represented in Figure 1 (on the left). The expansion system is featured by two opposing sets (an upper one and a lower one) of n circumferentially-spaced identical slider-crank mechanisms sharing the same slider. Connection between expansion system and each active membrane occurs circumferentially at the free end of the couplers belonging to the same set of slider-crank mechanisms. In Figure 1, the i-th connection point of the upper and lower sets of the slider crank mechanisms are denoted with $P_{u,i}$ and $P_{l,i}$ (for $i = 1,\dots,n$), respectively. Specifically, the considered expansion system has the following characteristics:

- the links $M_{u,i}N_{u,i}$, $M_{l,i}N_{l,i}$, $N_{u,i}O_{u,i}$ and $N_{l,i}O_{l,i}$ have equal length L_2;
- the links $M_{u,i}P_{u,i}$ and $M_{l,i}P_{i,l}$ have length L_1;
- the joint pivot points $M_{u,i}$, $M_{l,i}$, $O_{u,i}$ and $O_{l,i}$ are aligned on a line parallel to the axis of rotational symmetry of the mechanism, at a distance $\delta/2$;
- the distance between the joint pivot points $M_{u,i}$ and $M_{l,i}$ is H;
- the joint pivot points $O_{u,i}$ and $O_{l,i}$ are fixed and their relative distance is equal to $D+H$;
- the configuration of the system is uniquely defined by the slider stroke, x, that is measured from the midpoint of the segment $O_{u,i}O_{l,i}$.

The input link of the expansion system is the common slider where the force from the external energy source is applied. During the movement of the slider, the points $P_{u,i}$ and $P_{l,i}$ move radially by keeping their position laying on a circumference of variable radius (r_u for the upper and r_l for the lower membranes).

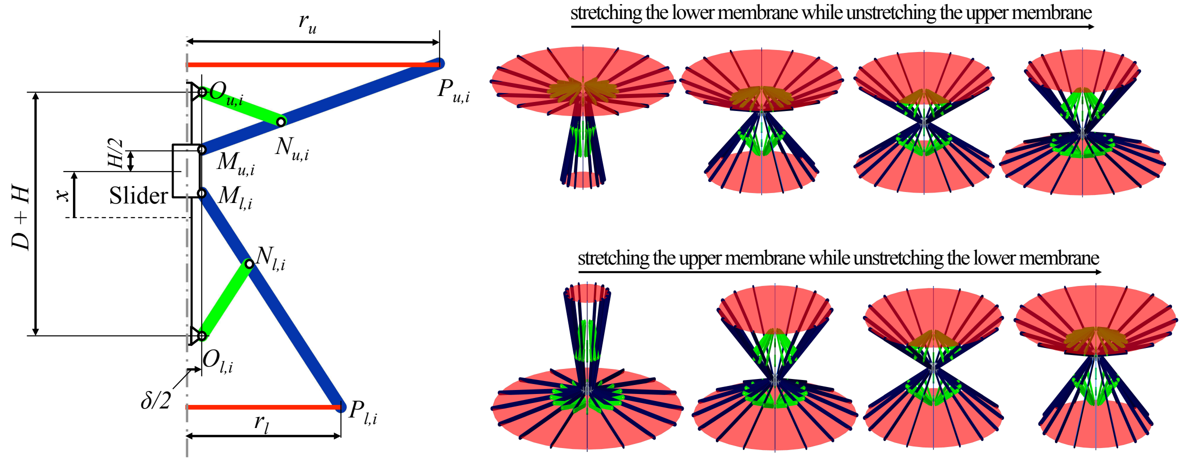

Figure 1: Schematic of the mechanisms employed for the alternative stretching of the two circular DEG membranes (on the left); Schematic sequence of deformation of the DuME–DEG during the downward movement of the slider (on the top-right) and during the upward movement of the slider (on the right-bottom).

The two membranes are of equal thickness and radius when unstretched, and deform in the same stretch range as the slider moves symmetrically from the central position (x = 0). By employing a sufficient number of slider-crank mechanisms, a large part of the DEG membranes deforms equi-biaxially (see Figure 1 on the right). For a given position, x, of the slider, the clamping radii r_u and r_l of the upper and of the lower membranes are obtained as

$$r_u = \frac{\delta}{2} + L_1\sqrt{1-\frac{(D/2-x)^2}{4L_2^2}} \quad ; \quad r_l = \frac{\delta}{2} + L_1\sqrt{1-\frac{(D/2+x)^2}{4L_2^2}} \tag{1}$$

In practical energy conversion applications, the linear slider is mechanically coupled with a moving body provided with reciprocating linear motion (i.e., heaving buoys for wave energy conversion applications). As the slider moves, mechanical work is done on the polymeric material against the stresses generated by both the membrane elastic deformation and by the electrostatic attraction between the capacitor plates. The stored electrostatic energy is extracted from the terminals of the membrane capacitor by means of a properly designed external electrical circuit. The electrical activation of the upper and lower membranes can be controlled independently.

For given properties and volume (namely, Ω) of the employed DE material, and for given geometry of the expansion system, the electro-mechanical state of each membrane can be uniquely described by the variable x and by the uniform electric field (namely E) acting across the DE layers.

In the next, we are generally discussing quantities and relations that are referred to the upper membrane, but equivalent relations can be found for the lower membrane by considering the anti-symmetry of the system with respect to the position x = 0. For simplicity, the subscript u is dropped in the following notation.

Owing to the incompressibility of the DE material and to equations (1), the variable capacitance C of one of the membranes of the DuME-DEG is a function of x through the membrane radius, r (which becomes r_u for the upper and r_l for the lower membranes); that is

$$C = \frac{\varepsilon \pi^2 r^4}{\Omega} \tag{2}$$

where ε is the absolute permittivity of the DE. Moreover, for any set of variables (x, E), the electric potential difference V between the capacitor terminals and the charge Q residing on the capacitor electrodes follow as

$$V = \frac{\Omega E}{\pi r^2} \quad ; \quad Q = \varepsilon E \pi r^2. \tag{3}$$

In this article, some simplifications are considered: 1) gravitational and inertial effects on the membranes and on the mechanism parts are neglected; 2) viscous mechanical losses, due to the material hysteretic behavior, are not considered; 3) electric losses, due to electrodes resistivity and to DE membrane leakage currents are neglected.

The mechanical work is done on the upper membrane by an external force F_e applied to the slider toward the positive direction of the *x*-axis. The analytical expression of F_e is found using the following energetic balance:

$$dU_e + dU_m = dL_e + dL_m \tag{4}$$

where dL_e is the electrostatic work performed on the DE membrane by the external conditioning circuit and dL_m is the infinitesimal mechanical work performed on the membrane by the slider.

$$dL_e = VdQ \quad ; \quad dL_m = -F_e dx \tag{5}$$

The quantities U_e and U_m are the electrostatic and elastic potential energies stored in the deformable membrane capacitor:

$$U_e = CV^2/2 = \varepsilon \Omega E^2/2 \quad ; \quad U_m = \Omega \Psi(x) \tag{6}$$

with Ψ being the hyperelastic strain-energy density function of the DE[16].

Here, Ψ is given by the general formulation of the Mooney-Rivlin strain-energy function[17], that is:

$$\Psi = \sum_{i=1}^{l} C_{i0} (I_1 - 3)^i + \sum_{j=1}^{m} C_{0j} (I_2 - 3)^j. \tag{7}$$

As a simplification, it is assumed here that the whole polymeric volume is subject to equi-biaxial deformation. Border effects can be included in the model if further specifications on the clamping methodology and on the number of gripping points are known. Due to incompressibility, the principal stretches of the membranes follow as

$$\lambda_1 = \lambda_2 = \lambda = r/r_0 \quad ; \quad \lambda_3 = (\lambda_1 \lambda_2)^{-1} = \lambda^{-2}. \tag{8}$$

where r_0 is the is the membrane radius in the undeformed state. Owing to equation (8), the principal stretch invariants in equation (7) take the following expressions

$$I_1 = 2\lambda^2 + \lambda^{-4} \quad ; \quad I_2 = 2\lambda^{-2} + \lambda^4 \tag{9}$$

Considering equations (1) and (8) (valid for the upper membrane), the stretch λ as a function of x is given by

$$\lambda = \lambda_p \left(\frac{\delta}{2} + L_1 \sqrt{1 - \frac{(D/2 - x)^2}{4L_2^2}} \right) \cdot \left(\frac{\delta}{2} + L_1 \right)^{-1} \tag{10}$$

where $\lambda_p = (L_1 + \delta/2)/r_0$ is the membrane pre-stretch, referred to the configuration x = D/2. This configuration may be not included in the slider motion range, but it is always possible to refer to such a position.

From balance (3), the total force acting on the slider, considering the sole contribute of the upper membrane, is

$$F_e(x) = \frac{L_1 \cdot (D/2 - x)}{4L_2 \sqrt{L_2^2 - (D/2 - x)^2/4}} \Phi(x), \tag{11}$$

where the factor Φ(x) can be split into an electrostatic and an elastic term, $\Phi = \Phi_e + \Phi_m$, with:

$$\Phi_e = -\frac{2\pi r_0 t_0}{\lambda} \varepsilon E^2 \quad ; \quad \Phi_m = \frac{4\pi r_0 t_0}{\lambda} (\lambda^2 - \lambda^{-4}) \left(\frac{\partial \Psi}{\partial I_1} + \lambda^2 \frac{\partial \Psi}{\partial I_2} \right) \tag{12}$$

where t_0 is the membrane thickness in the undeformed configuration.

If both the upper and the lower membranes are considered, the overall force on the linear slider follows as

$$F_s = F_e(x) - F_e(-x) \tag{13}$$

Regarding the converted energy, the amount of electricity that is generated (or expended) by a single membrane for an infinitesimal motion dx of the mechanism is:

$$dU_e - dL_e = -\frac{2\varepsilon\Omega E^2}{r}dr. \tag{14}$$

When this expression is positive, electricity is generated. Since r_u increases with increasing x, the upper membrane generates electricity only when the slider moves downwards (toward negative x direction). Conversely, the lower membrane generates electricity if the slider moves upwards. In this article, it is assumed that each membrane is electrically activated (namely, $E \neq 0$) only in the half cycle in which it expands in area. As a result: when the slider moves downwards, only the upper membrane is active; when the slider goes upwards, only the lower membrane is active.

3. CASE STUDY

In this section, the model proposed for DuME-DEGs is illustrated through a case study, considering a commercial Natural Rubber (NR) elastomer, namely OPPO Band Red 8012, whose main relevant physical properties were measured by Vertechy et al.[18] and are resumed in the following:

- Dielectric strength: the breakdown electric field of the OPPO Band 8012 NR is estimated in E_{BD} = 80 MV/m if the area expansion of the membrane is upper limited by the condition:

$$\lambda_1\lambda_2 = \lambda^2 \le \Gamma = 9. \tag{15}$$

  In fact, if this condition is violated, the breakdown electric field is subjected to a drastic reduction. Since equi-biaxial loading is considered, condition (15) is simply expressed as $\lambda \le \lambda_{\max} = 3$. This constraint is also conservative with respect to the mechanical rupture of the considered DE material. The mentioned value for E_{BD} is an average result that comes from multiple experiments. Values up to 120 MV/m have been reached with some samples. The dielectric strength is largely affected by local microscopic defects, such as inhomogeneity in the local chemical and physical properties.

- Dielectric constant. Vertechy et al. [18] observed that the relative dielectric constant of the material varies with the stretch in the range between 1.6 and 2.4. In this article, a constant average value ε_r = 2.0 is assumed.
- Hyperelastic model. The model shown in equation (7) (with l=4 and m=1) has been fitted to the experimental data presented by Vertechy et al.[18]; the resulting parameters are given in Table 1.

i	**1**	**2**	**3**	**4**
C_{i0} [Pa]	1.64e5	-8.51e2	-3.45e1	1.07
C_{0i} [Pa]	1.35e4			

Table 1: Hyperelastic parameters for the reference elastomer.

In the considered case study, the DuME-DEG prototype is assumed with the following geometric ratios L_1/L_2=2.5, δ/L_2=0.25, and a parametric analysis is performed for different values of D. The maximum allowed value for D is $4L_2$, that corresponds to a singular configuration of the mechanism with both the membranes having radius equal to δ/2. The plots in Figure 2 show the force-displacement curves for different choices of the pre-stretch, λ_p, and of D. The curves show the mechanical response of the DE membranes only (no electric activation is considered). For each choice of the parameters, an operative interval for the variable x is identified, on the basis of the following considerations:

- the operative range of x is assumed within the interval [-D/2, D/2];
- if $\lambda_p > \lambda_{\max}$ the constraint $\lambda > \lambda_{\max}$ puts a further limitation on the stroke, preventing the linear slider from reaching the limit positions, $x= \pm D/2$ Due to this condition, if a value of D is fixed, an operative range for the DuME-DEG exists only if

$$\lambda_p \le \lambda_{\max} \frac{\delta + 2L_1}{\delta + 2L_1\left(1 - D^2/16L_2^2\right)^{1/2}} . \qquad (16)$$

If this requirement is not met, no allowed configurations, x, exists, since at least one of the two DE membranes results as being overstretched;

- in order to prevent the material from the loss of tension condition (or "buckling"), a limitation on the minimum allowed stretch is identified, namely $\lambda \ge \lambda_{\min}$, where $\lambda_{\min}$ is calculated by zeroing the total equi-biaxial stress of the membrane (elastic term plus electrostatic contribution):

$$\sigma = \lambda_1 \frac{\partial \Psi}{\partial \lambda_1} - \varepsilon E^2 = \lambda_2 \frac{\partial \Psi}{\partial \lambda_2} - \varepsilon E^2 = 0. \qquad (17)$$

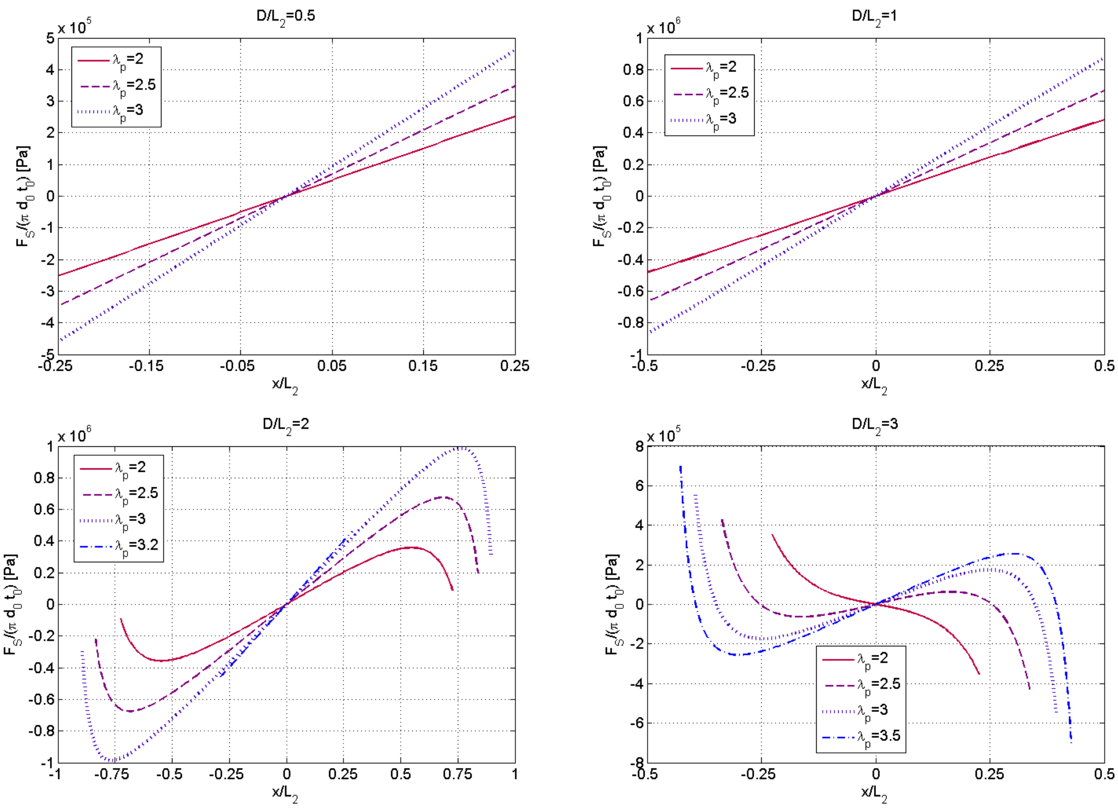

Figure 2: Mechanical force-displacement response of the DuME-DEG as a function of parameters D and λ_p.

As shown, the force-displacement profiles reported in Figure 2 are strongly affected by variations of the parameters λ_p and D. In particular:

- Low values of D originate approximately linear force profiles. For D/L_2=0.5 and D/L_2=1, the operative range for the variable x coincides with the interval x∈ [-D/2, D/2]. In this situation, the slope of the curves, representing the equivalent mechanical stiffness of the DuME-DEG, increases with λ_p.
- For D/L_2=2 and D/L_2=3, the force characteristic is visibly non-linear, showing maxima and minima, or presenting a negative slope (i.e. for D/L_2=3 and λ_p =2).
- Values of D/L_2 greater than 2 imply a progressive restriction in the operating interval of the DuME-DEG, which is due to the onset of the abovementioned restrictions (buckling and maximum stretch).

Considering electrical activation, the maximum energy that can be converted in a cycle by the DuME-DEG is calculated using equation (14), by assuming energy conversion cycles at constant electric field, E. If λ_1 and λ_2 are the minimum and maximum stretches achieved by the membranes during the full stroke of the slider, the maximal energy density (per unit volume of DE material) that can be converted in a cycle by a single membrane is

$$En/\Omega = 2\varepsilon E^2 \ln\left(\lambda_2/\lambda_1\right) \tag{18}$$

Figure 3 shows the dependence of the converted energy density as a function of D and λ_p. In order to identify the maximal energy that can be converted by the DuME-DEG, the condition $E=E_{BD}$ is assumed.

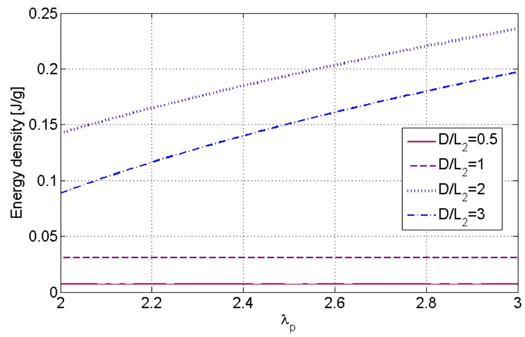

Figure 3: Convertible energy density (J/g) as a function of D/L_2 and λ_p.

Notice that:

- For D/L_2=0.5 and D/L_2=1 the energy density does not depend on the pre-stretch, because the motion range is independent of λ_p (provided that $\lambda_p< \lambda_{max}$).
- For D/L_2=2 and D/L_2=3, if λ_p increases, the motion range enlarges since the system is less sensitive to buckling. Consequently, the convertible energy density increases with λ_p.
- The maximum convertible energy density is obtained when D/L_2=2 since, as already mentioned, larger values of this parameter bring to a reduction in the operating range of x.

The plots in Figure 2 suggest that the mechanical response of the DuME-DEG can be regulated by a proper choice of the design parameters. In particular, if the elastic response of the generator is nearly cancelled, the force generated by the DuME-DEG can be fully controlled acting on the electric field, E. For a given choice of the pre-stretch λ_p, this can be obtained by adjusting the ratio D/L_2. For λ_p=3,Figure 4.a shows the variation of the device force characteristic with the ratio D/L_2. For an appropriate choice of D/L_2, the force characteristic can be flattened around the central equilibrium point, x=0. In particular, in Figure 4.b, we report the DuME-DEG mechanical response for the value of D/L_2 that minimizes the integral mean value of the force module (D/L_2=3.18).

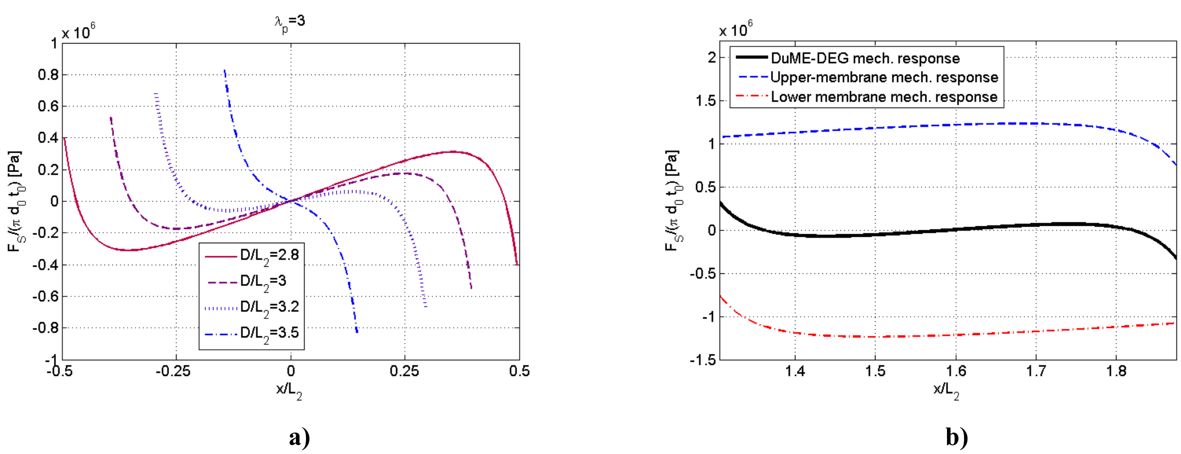

Figure 4: Elastic response of the DuME-DEG with λ_p=3 with: a) varying D; b) D/L_2=3.18 (minimum force integral value)

In Figure 4.b, the DuME-DEG elastic response is split into two contributions, due to the upper and lower membrane respectively. The use of a combined dual membrane mechanism clearly provides a compensation effect of the DuME-DEG force response, and allows to strongly reduce the elastic component of the force in an interval around the configuration x=0.

The force response of a DuME-DEG with D/L_2=3.18 is shown in Figure 5 for different values of E_u and E_l that are, respectively, the control electric field of the upper and lower membranes. Values of the electric field up to 120 MV/m have been considered. By varying the value of the activation electric field, the DuME-DEG behaves as a dual-effect generator, capable of providing bi-directional controllable forces in a position interval around configuration x = 0.

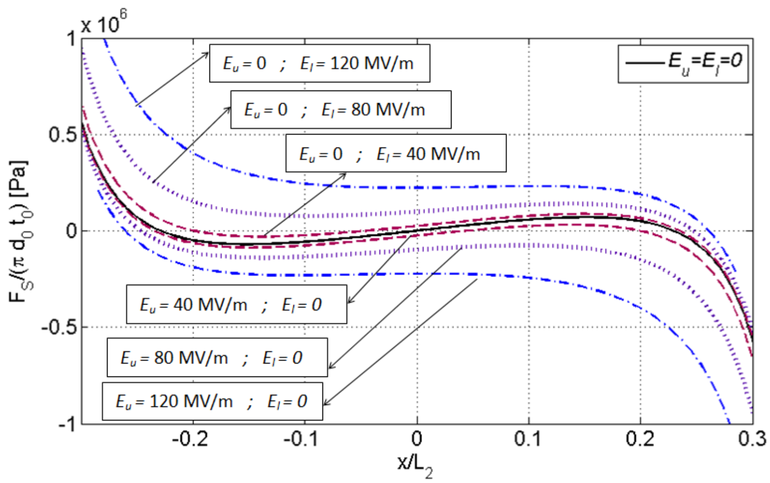

Figure 5: Effect of electric activation on DuME-DEG force response in presence of different electric field values.

4. EXPERIMENTAL TESTS

A set of verification experiments has been conducted with the aim validating the model developed for the estimation of the input force-stroke response. A test fixture has been developed to induce equi-biaxial state of deformation to a circular specimen of OPPO Band-Red 8012.

4.1 Setup

Specimens. Circular specimens made of Natural Rubber OPPO Band Red 8012 were cut with a diameter of 59mm. The thickness of the membrane t_0 = 0.18mm was measured using high-accuracy CCD laser displacement sensor (Keyence LK-G152) according to the procedure described by Vertechy et al.[18].

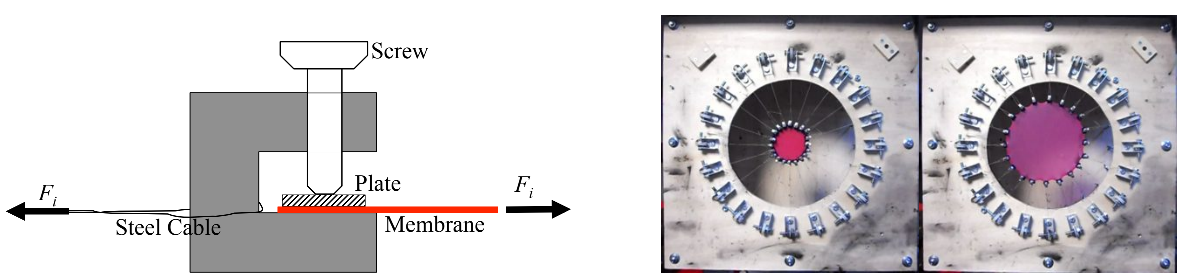

Figure 6: Schematic of the clamping system (on the left) and picture of the clamped specimen in unstretched and stretched configurations.

Mechanical stretching system: The stretching mechanism is similar to the one adopted by Huang[10]. The circular specimen is clamped at 20 points equally spaced along its perimeter using special designed clamps (see Figure 6) that enables tests with different kinds of DE materials including natural rubbers (NR), silicones and acrylics. The equi-biaxial deformation of the specimen is achieved applying traction forces with 20 iron cables (Carl-Stahl CG 012024) arranged along radial directions according to the scheme represented in Figure 7. Each cable is deviated by a ball-bearing supported idle pulley and is attached to a central plate (cable plate) through an adjusting-screw that enables the fine tuning of the initial tension. The cable plate is connected to the output stage of the linear motor (LinMot P01-37x120F/200x280-HP) through a load-cell (DSEUROPE 535QD-A1) to measure the total applied force.

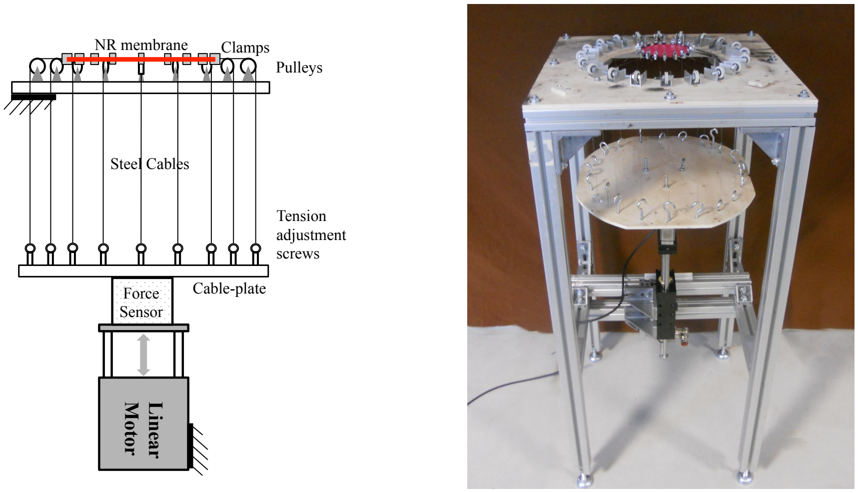

Figure 7: Schematic (on the left) and picture (on the right) of the of the text fixture employed for the experimental verification of the numerical model.

4.2 Tests and results

A series of 3 data acquisitions has been carried out on a specimen of OPPO Red in order to determine the force-displacement characteristics of the membrane. Experiments have been repeated with three different strokes of the linear motor: 40, 50 and 60 mm respectively (corresponding to stretch of 2.50, 2.85 and 3.18). Experimental curves were acquired at a low stretch rate of $66.7 \cdot 10^{-3}$ [s^{-1}] in a way to limit the viscoelastic effects.

Experimental results are reported in Figure 8 together with the theoretical forecast provided by the hyperelastic model described by equation (7) with parameters given in Table 1. In the calculation of the theoretical response, two different approaches have been adopted for the calculation of the equi-biaxial stretch.

- Approach 1. The stretch is defined as the ratio between the outer diameter of the membrane in the deformed configuration (estimated as the sum of the initial diameter and two times the actual stroke of the motor) and the undeformed (initial) outer diameter of the sample (59 mm).

- Approach 2. Since the clamps have a width of 4 mm along the membrane radial directions, they identify a circular region, within the membrane, whose diameter is 51 mm (in the initial configuration). In any deformed configuration, the equi-biaxial stretch is calculated as for Approach 1, but considering 51mm as undeformed (initial) diameter.

In both cases, the force is calculated referring to the whole DE volume, using equation (7) with different values of $\lambda_1 = \lambda_2 = \lambda$.

Approach 2 provides a better match between theoretical force and experimental data. This approach introduces an overestimation of the stretch that takes into account the increased stiffness due to the peculiar deformation of the material close to the sample clamping points.

As shown in Figure 8, theoretical curves adequately match the experimental ones. In particular, the curve calculated according to Approach 2 provides a better estimation of the experimental results.

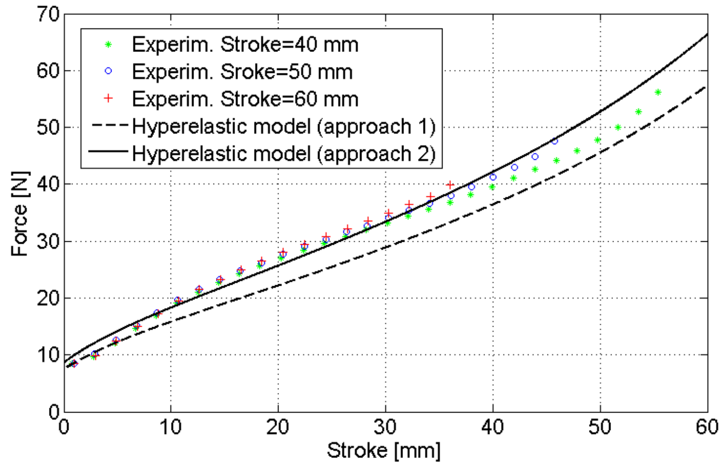

Figure 8: Experimental measurements and theoretical estimation of the total force performed by the steel cables on the membrane (due to the motor force plus the cable plate weight)

5. CONCLUSIONS

In this paper, we have introduced a novel architecture for a Dielectric Elastomer Generator (DEG) with linear motion. The generator, called Dual Membrane DEG (DuME-DEG), has been specifically conceived for Wave Energy Converter (WEC) applications. The proposed generator employs a linkage mechanism, which makes it possible to equi-biaxially stretch two circular deformable membranes made of sandwiched dielectric and conductive layers (namely "active membrane" or "DEG membrane").

The DuME-DEG mechanical architecture is conceived in a way to have a bidirectional force response which can be tuned by a proper choice of the design parameters. In particular, different levels of stiffness can be obtained including negative and quasi-null values. This makes it possible to design DEGs that provide WECs with a dynamic behavior specifically tuned to the frequency content of the external excitation force. In particular, when the mechanical stiffness of the DuME-DEG is minimized, the generator shows a resistance to the input force that is solely dependent upon the electrical activation. This provides a DEG that is controllable in real-time in a way to assume variable programmable impedance. Thus, the DuME-DEG can be potentially employed in specific types of WECs that require a fine impedance matching (such as small size buoys).

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