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Advances for dielectric elastomer generators: Replacement of high voltage supply by electret

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Dielectric generators require an external circuit with a high bias voltage source to polarize them. To drastically reduce this circuit and to avoid external polarization, we propose here original transducers combining electrets and dielectric elastomer. Two operating modes have been studied and electromechanical analytical models have been developed from the combination of electrets theory and dielectric model. These concepts are applied on e-textile application: scavenging energy during human motion. An energy density around 6 mJ g^{-1} is expected on an optimal load of 10 MΩ. More generally, the flexibility, the lightness, the absence of high-voltage supply open many fields of applications beyond e-textiles.
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Dielectric elastomer generators (DEG) offer an attractive potential of applications because of their flexibility and high energy density up to 2.8 J g^{-1}, 100 times greater than those available with piezoelectric ceramics.[1–3] These scavengers are light, compliant, adopt complex 3D geometry, can convert linear or rotational motion, and work on a wide frequency range. Some wearable applications were realized demonstrating the ability of DEG to scavenge mechanical energy from ocean waves,[1,4] wind, or human motion.[2,5] In 2001, Pelrine *et al.* proposed a DEG embedded in a shoe, able to scavenge up to 0.8 J per step (energy density of 0.3 J g^{-1}), with a bias voltage of 2500 V.[1] In 2008, Jean-Mistral *et al.* developed a patch located behind the knee scavenging 100 μW under a bias voltage of 210 V and up to 1.74 mW under a bias voltage of 1000 V.[2] More recently, McKay *et al.* proposed a soft conic generator for powering mobile devices, achieving an energy density of 10 mW g^{-1} with a high bias voltage of 2000 V.[5] In spite of all these advantages, DEG are based on energetic cycle and require an external high-voltage generator and/or a complex electronic circuit: pump charge, bidirectional flyback converters[5,6] (Figure 1).

To date, the development of wearable dielectric scavengers is slowed down owing to the rigid and cumbersome power circuit. These circuits significantly contrast with the softness of the DEG. The challenge is thus to produce a transducer with the simplest and reduced power circuit and without any external bias voltage, either high or low voltage source. This generator must also be integrable, deformable, adaptable, and able to produce enough energy to supply a low consumption system (100 μW). Some efforts have been done in this direction by combining two dielectric elastomers with a self priming integrated circuit.[7] Nevertheless, this relevant solution must be initially charged by an external supply and needs many seconds to start. In the present work, we propose an innovating solution consisting in using an electret in order to replace the upstream external supply voltage (i.e., the bias voltage and charge circuit in Figure 1). Thus, this letter introduces two operating modes for the combination of dielectric elastomer and electret. The associated electromechanical models are presented. Finally, a fruitful comparison of these two modes is proposed on a specific wearable application.

An electret is an insulator, holding a quasi-permanent electric charge and developing a high stable surface potential, available for a long time. This electrostatic voltage source could be used to polarize a DEG and thus to replace the external bias voltage as already said. This mode will be named "dielectric mode" in this study (Figure 2(a)).

One can underline that this electrostatic voltage source is currently used in electrostatic generator, named "electret generator," to scavenge mechanical vibration.[8,9] Generally, these transducers are rigid resonant structures, consisting of a mass maintained to a fixed frame thanks to a spring. This mode can be adapted to our soft structure and is called "electret mode" in our work (Figure 2(b)). The structures in Figures 2(a) and 2(b) are similar but their operating modes are rather different.

In the "dielectric mode" (Figure 2(a)), classic energetic cycles are achievable.[10] The electret is basically used to replace the external voltage source. The challenge is to electrically combine these two materials (electret and dielectric elastomer) and to mechanically stack them in order to obtain an optimized thin deformable structure. In our study, the electret is used to create an electric field to polarize the dielectric elastomer and not as a capacitor for the storage of electrical charges. It cannot be simply and directly connected to the dielectric elastomer, thus requiring a specific design for the realization of the structure. As the electret and the dielectric elastomer suffer from various deformations, we adopt a textured structure to realize the device. This 3D form allows the electret not to be strained, keeping perfectly its polarization. In Figure 2(a), the generator is still composed of a dielectric elastomer sandwiched between two compliant electrodes, one connected to the ground and the other is with a floating potential. At rest, the dielectric elastomer is not polarized because the electret, represented by a capacitor C_E and a voltage source V_E, is too distant from this elastomer. When the dielectric elastomer is stretched, it is thus nearer to the electret. The floating potential increases by zero to a

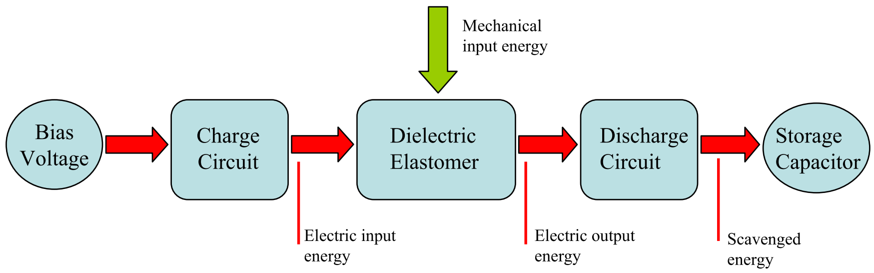

FIG. 1. Synoptic of conventional dielectric elastomer generators.

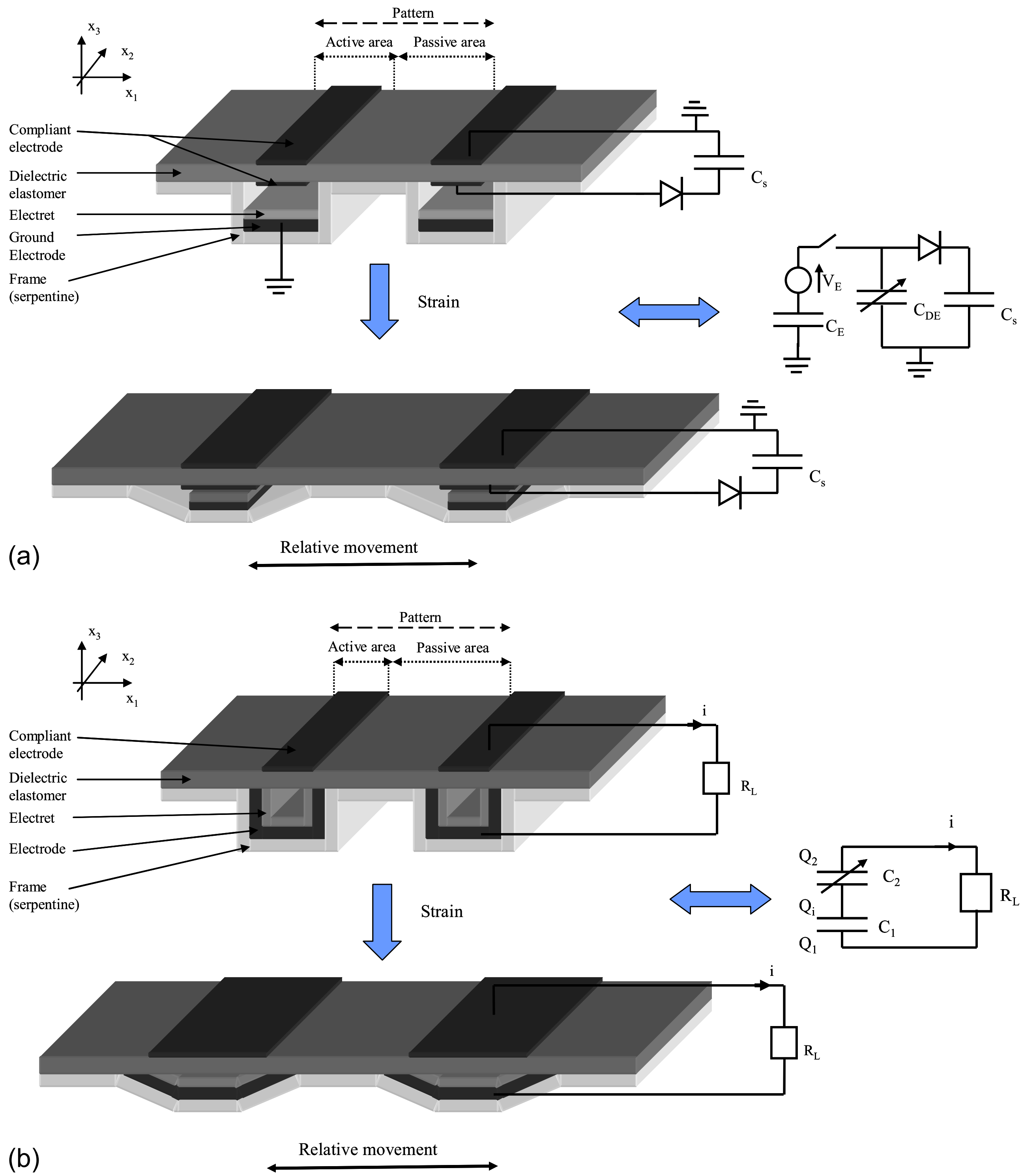

FIG. 2. Dielectric elastomer–electret coupling: Dielectric mode (a) and electret mode (b).

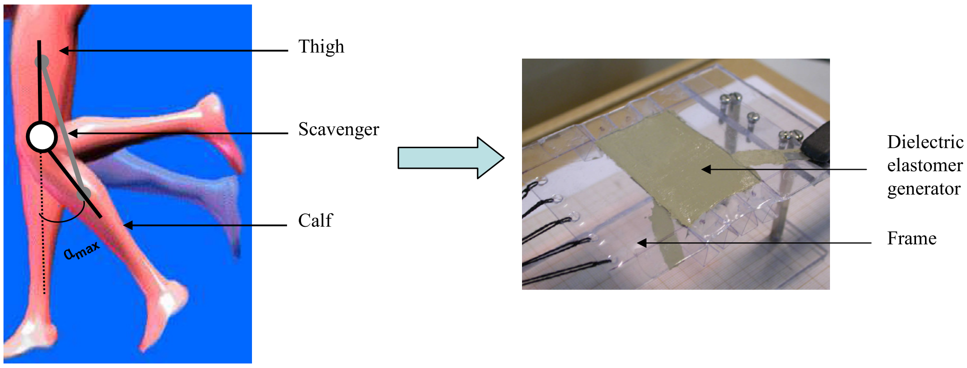

FIG. 3. Human kinetic energy scavenger—Localization and shape.

hundred volts, according to the surface potential of the electret and the gap between this electret and the compliant electrode. At this point, the capacitor is charged by a voltage V. The structure is therefore relaxed: the electret stands back and the dielectric elastomer moves to a point of equilibrium between elastic and electric stresses. This is the active phase: the variation of the expansion coefficient λ induces a decrease in capacitance, thus generating voltage boost. The input electric energy is thus amplified thanks to the mechanical strain energy (Figure 1). Finally, all charges are removed from the structure and the material returns to its initial dimensions: discharge phase. The produced energy e_{PRO} is basically the variation of the stored energy into the variable capacitor made with the dielectric elastomer (Eq. (1))

$$e_{PRO} = \frac{1}{2}(C_{\min}V_{\max}^2 - C_{\max}V_{\min}^2). \quad (1)$$

The associated power circuit is very simple and it is made up of only one external diode between the DEG and the storage capacitor C_s (Figure 2(a)). The electric representation of the movement of the electret corresponds to the switch in the case "dielectric mode."

In the "electret mode" (Figure 2(b)), a dielectric elastomer partly fills the air gap usually met in a conventional generator containing electret. C_1 is the capacitor describing the electret, C_2 is a variable capacitor describing the dielectric elastomer and air gap, and R_L is a load. The structure depicted in Figure 2(b) has the same operating principle than a classic electret generator.[8,9] The relative movement between the electrode and the counter compliant electrode generates a rearrangement of electrical charges between these two electrodes through the load resistance R_L and generates an alternative current i.

Being based on the preceding considerations, we propose the first version of the human kinetic energy scavenger,[2] using an active area of 3 cm per 5 cm and a passive area of 6 cm per 5 cm (Figure 3). The dielectric elastomer thickness is about 32 μm. During walk, the angle α between the thigh and the calf varies from 5° to 60°, until awaiting 120° during the run. The goal is to transform this variation of angle in term of deformations what could be comparable to a mechanical input source for a DEG to produce electricity (Figure 1). According to geometrical consideration, a stretching of 50% can be achieved at 1 Hz (frequency corresponding to a walk).

In a dielectric mode, with an active pure share deformation of 50%, the active phase, for a cycle at constant charge Q, is described from Eq. (2)

$$mx_{10}\frac{\partial^2\lambda}{\partial t^2} = \frac{x_{20}x_{30}}{\lambda} \times \left[-2(C_{10}+C_{20})\left(\lambda^2 - \frac{1}{\lambda^2}\right) + \frac{Q^2}{\varepsilon_0\varepsilon_r\lambda^2 x_{10}^2 x_{20}^2}\right]. \quad (2)$$

Weight of the structure, the electrostriction phenomena, and the pre-stress of the elastomer are neglected in this model. Mechanical behavior of the dielectric elastomer is based on hyperelasticity with a Mooney Rivlin strain energy ($C_{10} = 0.01875$ MPa and $C_{20} = 0.03368$ MPa).[10,11] The dielectric constant of the elastomer and its variation with frequency, temperature, pre-strain, and nature of the electrode were investigated in a preceding work.[12] To compare our solution with the commonly used version (classic energetic cycle), the same total area for the scavenger was chosen: the structure is composed of six patterns (serpentine) with a length for the active zone about 0.5 cm at rest and per pattern. The width of the structure is 5 cm, the dielectric elastomer thickness is 32 μm, and that of the electret is 25 μm. With a simple square pattern for the serpentine, the compliant electrode length must be smaller than that of the active zone.

Up to now, only some electret polymers, such as Teflon sheet (25 μm thick), can satisfy a surface potential up to −2000 V with a good stability (no surface potential decrease

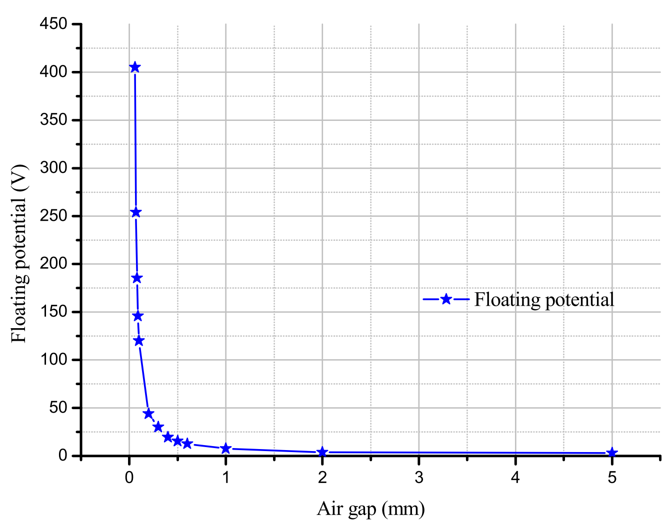

FIG. 4. Floating potential as a function of the air gap in the "dielectric mode."

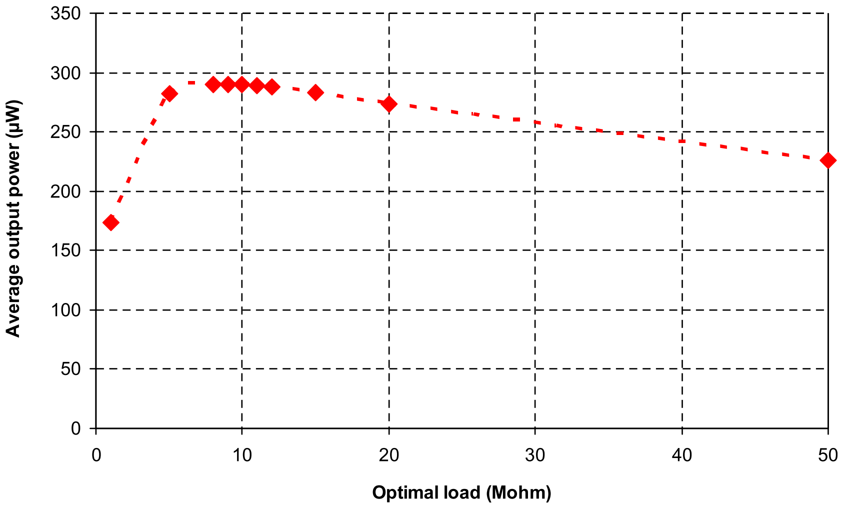

FIG. 5. Average output power as a function of the optimal load in the "electret mode."

with time).[13] Finite element simulation predicts the value of the floating potential as a function of the air gap for an electret with a surface potential of -1000 V (Figure 4).

One observes that in "dielectric mode," the value of the floating potential raises sharply with the decrease of the air gap. These results show that an air gap of 75 μm ensures a floating potential around 240 V on the compliant electrode, which allows scavenging 100 μW at 1 Hz.

In the "electret mode," due to the configuration of the generator, the dielectric elastomer supports a pure shear deformation along the x_1 direction. The intrinsic equations of the scavenger, based on electret generator theory and on dielectric model, are given in Eq. (3)

$$m x_{1d0}\frac{\partial^2\lambda}{\partial t^2} = -\left[2\frac{x_{20}x_{30}}{\lambda}(C_{10}+C_{20})\left(\lambda^2-\frac{1}{\lambda^2}\right)\right] + \left[\frac{\partial}{\partial\lambda}\left(\frac{Q_2^2}{2C_{eq}}\right)\right]+f_{ext},$$
$$\frac{\partial Q_2}{\partial t} = \frac{V}{R_L}-\frac{1}{C_{eq}}\frac{Q_2}{R_L}. \tag{3}$$

V is the surface potential of the electret. C_{eq} is the equivalent capacitance made up of the electret capacitor C_1 in series with the variable capacitor C_2. C_2 consists of the dielectric elastomer and the air with an equivalent dielectric constant obtained from mixing rule. The structure has the same geometry (six patterns). The output power will be maximal for an optimal load (Figure 5).

The soft electret generator develops a high output voltage (400–450 V) under a low current (50–100 μA). For cycle at 1 Hz, the average output power is about 290 μW on an optimal resistance of 10 MΩ and the density of produced energy is 6 mJ g^{-1}. The power circuit associated to that operating mode is a simple diode rectifier.

To compare the performances of the two structures, we arbitrarily chose a maximal output voltage around 400 V for the both. Under these limitations (size and voltage), the first structure is able to scavenge up to 100 μW with a bias voltage of 240 V, and the second one is able to scavenge up to 290 μW with an electret having a surface potential of -1000 V. Thus, with a consideration of maximal output voltage, the "electret mode" is the most appropriate for energy scavenging applications. Nevertheless, with a maximal input condition, the "dielectric mode" is most powerful in term of scavenged energy. One can underline that due to the texture of the structure, the classic energetic cycle allows scavenging more energy. Thus, the optimization of the serpentine pattern (shape, size, gap) will induce an increase of the produced energy density.

In this letter, we presented scavengers combining a dielectric elastomer and an electret in two distinguishes operating modes: "dielectric mode" and "electret mode." These generators present the following advantages: not resonance, total flexibility, lightness, and deformation, allowing a whole integration in a lot of applications such as e-textile. In addition, the other undeniable advantage in the use of electret as power source is the removal of external high-voltage supply and/or electric circuit (pump charge). Moreover, we proposed analytical models of the structures combining the theories of dielectric elastomers and electrets generators. The optimized structure in "electret mode" is expected to scavenge up to 290 μJ at 1 Hz, with a potential surface of -1000 V for the electret. The energy density is about 6 mJ g^{-1}. This value is hundred times that obtained with a piezoelectric polymer (60 μJ g^{-1}) and twenty that obtained with an electrostrictive polymer (0.3 mJ g^{-1}). One can note that piezoelectric ceramics and electromagnetic devices harvest in theory up to 100 μW cm^{-3} from vibrations and about 10–50 mJ cm^{-3} from deformations. This power density is about 2.1 mW cm^{-3} for human walking motion.[14]

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