DIELECTRIC POLYMER: A COMPLETE STUDY IN GENERATOR MODE

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Abstract: To ensure the autonomy of various sensors, a promising alternative to the batteries is to scavenge the ambient mechanical energy. Up to now, most of the developed structures are rigid and use vibration as mechanical source. For these reasons, we develop a flexible dielectric scavenger that operates in a large frequency spectrum from quasi-static to dynamic range. We report in this paper some experiments that validate our analytical electro-mechanical modeling for dielectric polymer in generator mode. We can theoretically expect to scavenge up to $1.21 J.g^{-1}$. We present some application able to harvest up to100µW, enough to supply a low consumption system.

Key Words: dielectric polymer, mechanical energy scavenger, model and experiments

1. INTRODUCTION

Dielectric polymers are a new category of emerging materials. They are generally used as actuators for artificial muscles, binary robotics or mechatronics. Dielectric polymers work as a variable capacitor, and show large deformation when submitted to an electric field. They are low cost, light, flexible, resistant and have a fast answer. But, they have also great promising performances in generator mode especially in terms of energy density ($1.5 J.g^{-1}$ according to [1]).

2. ANALYTICAL MODELLING

2.1 Scavenging cycle

To scavenge mechanical energy, the polymer follows the cycle depicted in the figure 1.

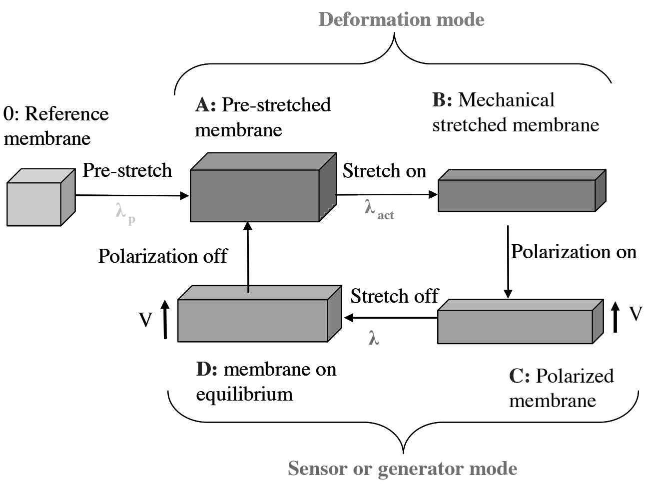

Fig 1: Scavenging cycle
With λ_p λ_{act} λ matrix expansion coefficient

The volume of the polymer is keep constant.

In phase 1 (A to B), the material is stretched under a mechanical load. In phase 2 (B to C), a poling electric field is applied to the polymer. In phase 3 (C to D), under this electric field, the material is compressed until an equilibrium between elastic (σ_e) and Maxwell (σ_m) stresses is reached. It is the active phase: the variation of capacity generates electricity. In phase 4 (D to A), the electric field is cancelled, the material returns to its original dimensions. To overcome the use of a very high poling voltage, the material can be pre-strained with an expansion coefficient λ_p (phase 0 to 1).

Various scavenging cycles can be realized: at constant voltage V, constant charge q or constant electric field E. For example, electrical energy produced during a cycle at constant charge q is reported in equation 1.

$$E_{pro} = \frac{1}{2}(C_C V_C^2 - C_D V_D^2) \qquad (1)$$

With V_c, V_d voltage at point C and D
C_c, C_d capacity at point C and D

The final scavenged energy is reported in equation 2.

$$E_{scavenged} = E_{pro} - electric\ losses \qquad (2)$$

Electric losses include losses by conduction, by diffusion on the dielectric polymer and dielectric losses function of the operating frequency.

Equilibrium between mechanical and electric stresses generates two specific areas: actuator and sensor mode. The three different scavenging cycles are also plotted on figure 2: cycle ABCD at constant electric field, cycle ABCD' at constant voltage and cycle ABCD'' at constant charge.

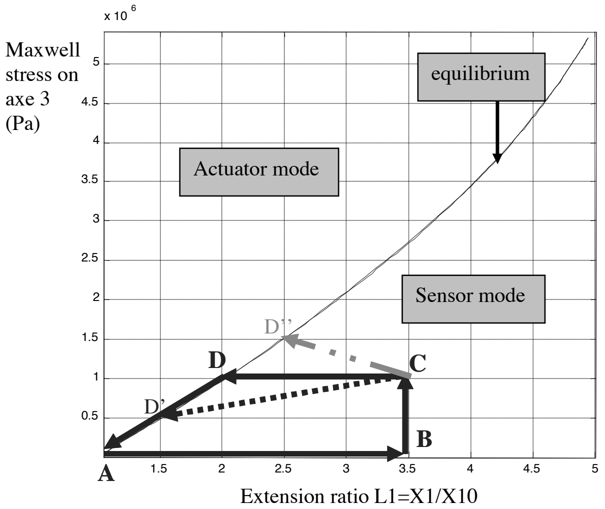

Fig 2: Actuator and Generator area

We have developed an analytical model describing all the scavenging cycle phases, in order to simulate the behaviour of simple structure in main deformations. For each phase of the cycle, electrical and mechanical stresses equilibrium is writing. Motion equation for active phase (C to D) takes care of all the different phases of the scavenging cycles.

Thermal aspects are negliged in this study.

2.2 Operating area

Failure criteria, boundaries conditions and pre-strain define an operating zone (figure 3) in which motion equation is validate.

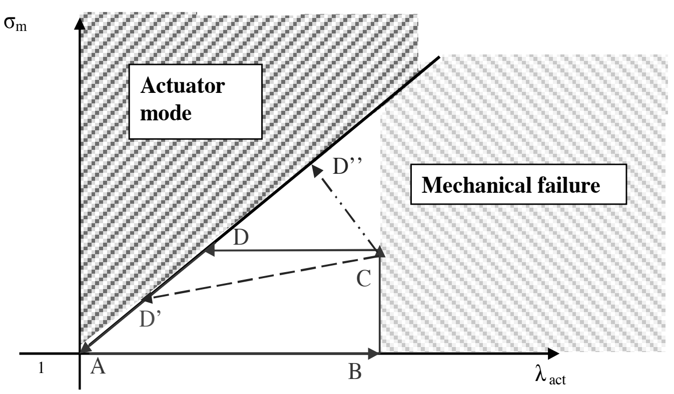

Fig 3: Operating area

Maximum electric field, voltage or charge is imposed by the thickness of the structure in point C. For a maximal mechanical deformation, namely a minimal thickness, the dielectric breakdown is $100 MV.m^{-1}$ for the chosen polymer.

2.3 Material properties

The chosen polymer is 3M VHB 4910 characterized by its large deformations (300% on average) and high dielectric constant (4.7).This polymer is modelling by a quasi-linear viscoelastic model [2].

2.3 Simulations results

Motion equation is writing for a membrane biaxially deformed (figure 4).

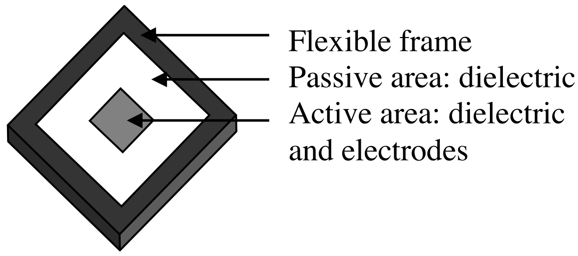

Fig.4: Dielectric generator modelled

We calculate the scavenged energy for the structure described in figure 4, according to the motion equation and operating area.

For a centimetre membrane, with different pre-strain (λ_p equal to 3 or 4 noted L_p on fig.5), scavenged energy is plotted in function of poling voltage (constant or equivalent voltage) for a maximal deformation. This energy is calculated for the three different scavenging cycles: at constant voltage V, constant charge q and constant electric field E.

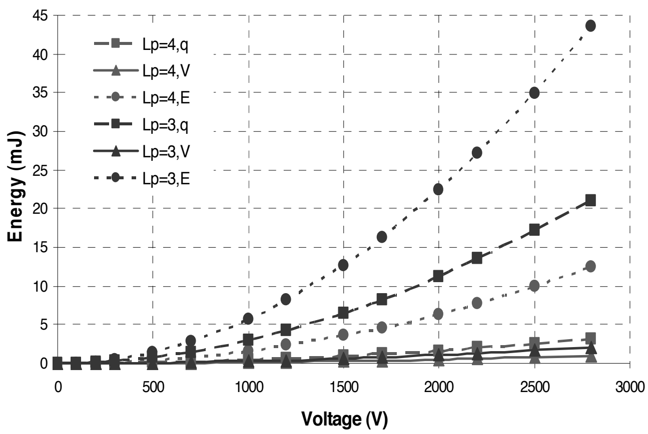

Fig.5: Scavenged energy in biaxial deformations

Cycle at constant electric field scavenges the most energy but is very difficult to realize. This cycle needs a loop control to ensure constant electric field. So, only cycle at constant charge or voltage will be realized.
For a maximal deformation, we can theoretically scavenge $1.21 J.g^{-1}$ for a constant charge cycle and a pre-strain λ_p equal to 3.

EXPERIMENTAL

2.1 Dielectric scavenger fabrication

A sequence is realized to stretch biaxially the polymer 3M VHB 4910 on a specific support. Thus the film is sandwiched between a pair of structural flexible frames and we pattern the grease electrodes by manual serigraphy (conductive silver grease Circuitwork CW7100 from Chemtronics). The electrodes thickness is about 100µm with the support used. We are developing new mask with a thickness of 20µm.

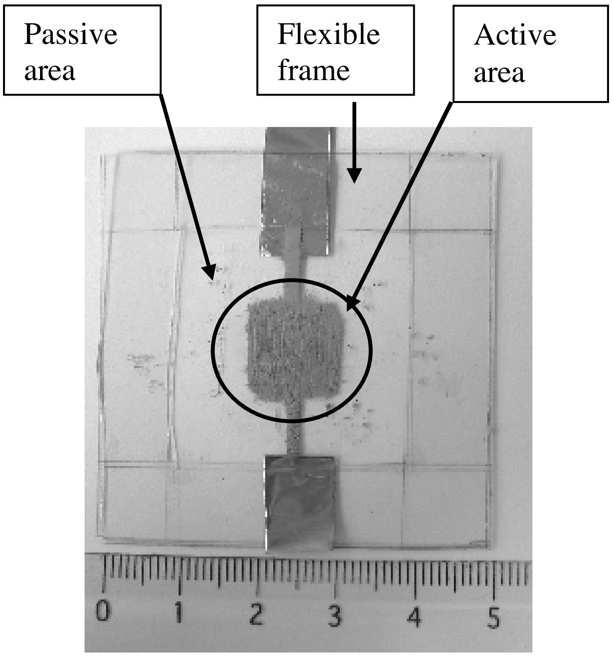

Fig. 6: Dielectric generator

The polymer can be represented by a resistance R_p in parallel with a variable capacity C_p. The electrodes are resistive and can be modeling by a serial access resistance R_e.

2.2 Experimental results

The polymer tested has a pre-stretch ratio λ_p equals to 4. On phase 1, it is a square membrane with 1cm side and 63μm thick.

The polymer resistance is superior to 1GΩ, and access resistance is less than 3Ω.
Moreover, dielectric breakdown voltage was measured to 3500V which is inferior to value classically measured. In fact, dielectric failure operates in air, just on the edge of active area. Encapsulate the device with a thin membrane will avoid this phenomenon. To ensure the same mechanical properties for the device, the 3M VHB 4910 polymer should be used.

We realize testing cycle to simulate the active phase of dielectric generator. During the phase A to B, we stretch electrically the polymer (A' to B), and not mechanically with a high voltage (3kV) provided by a DC/HDC converter from EMCO (see figure 7). This solution is easier to set up. Then, the applied voltage is reduced quickly (from 3kV to 1kV) and the active phase starts.

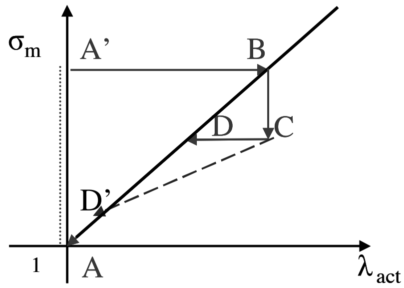

Fig. 7: Testing cycle for the dielectric generator

The evolution of the polymer is filmed and treated to calculate the deformation submitted by the film (Fig. 8).

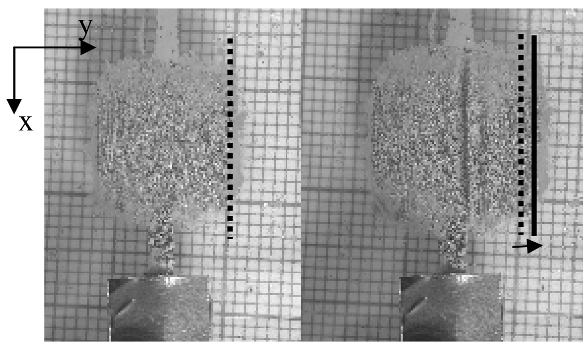

Fig.8: Extension ratio variation during phase A to B: λ_{act} on x axe is about 1.23

Any load is connected and we measure the evolution of voltage and current on the active phase during all the sequence (Fig.9).

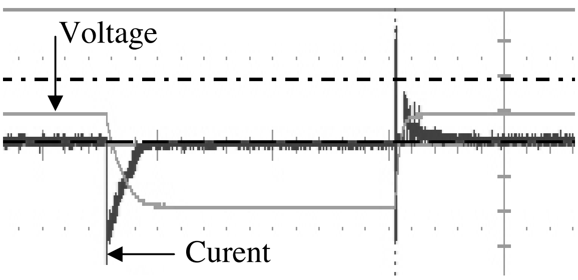

Fig 9: Waveform of electrical signal during testing cycle

We realize various series of prototype, and we measured the hypothetic scavenged energy with this structure (Fig.10).

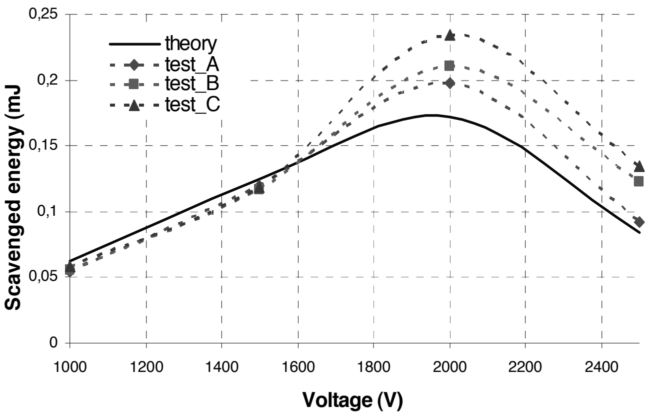

Fig.10: Comparison between experiment and model for a membrane pre-streched with a λp equal to 4.

Relative error is weak with low tension (10%), and grows up to 30% with high tension. In fact, as high the voltage is, as weak the variation of capacity is.
This scavenged energy is for one quasi-static cycle. Dynamic mode can be considered as a succession of quasi-static cycles with dielectric losses proportional to frequency.
With the example treated on figure 10, under a constant poling voltage of 2000V, we can scavenge 170µJ for one cycle. To scavenge 100µW, the power necessary to supply a low consumption system, we need to work at 0.6Hz. We note that 0.6Hz could be the frequency of human motion, bridge vibration…

3. DISCUSSION

Various experiments have been performed: with different pre-stretch for the film, with different size for the dielectric generator. We obtain the same kind of curves with relative error between 10% and 30%.
The improvement of the model is necessary. Dielectric experiments have been performed to test the influence of temperature, frequency and pre-strain on dielectric constant, conductivity. First results show us a dielectric constant higher than expected at room temperature in very low frequency.
Moreover, mechanical experiments have been performed to improve the model used by adding plastic dependency and temperature dependency.

4. CONCLUSION

The model developed in this study is complete and validate by various experiments, at room temperature. The model takes into account a lot of parameters and can be used to design power generators based on dielectric polymers. The maximum expected scavenged energy is about $1.21J.g^{-1}$ in a cycle at constant charge q, four times better than with piezoelectric.
We are now developing an innovating application: scavenge energy from human motion on knee level. This system is a patch placed in a knuckle and able to scavenge 100µW to supply autonomous device for medical or sport applications.

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