Study of the behaviour of electrostrictive polymers for energy harvesting with FFT analysis

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Electrostrictive polymers energy harvesters are an emerging technology that promises high power density, low cost and scalability. Power can be produced simply by stretching and contracting a polymer film. At present, the investigation of using electrostrictive polymers for energy harvesting (a conversion of mechanical to electrical energy) is beginning to show potential for this application. The relative energy gain basically depends in the current induced by the mechanical strain and frequency. Previous work of some of the co-authors, has indicated that one can measure the dielectric constant, the Young modulus and the electrostrictive coefficient of a polymer film by the determination of the current flowing through the sample when simultaneously driven by electrical field and mechanical excitation. This paper investigates the effects of this method for different frequencies for both electrical field E and strain in order to develop a more in-depth understanding of the changes in system response for increased current and energy harvesting. Results relating amplitude strain and the frequency for electrical field provide a framework for developing energy harvesting techniques which improve the overall performance of the system. Experimental data indicate that the current induced with polymer is proportional with the change in frequency of the deformation. In the present paper the theory is detailed and the simulation results are compared with experimental ones. Good agreements are found between both approaches.

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1. Introduction

The global demand for renewable energy is growing and the last few years have witnessed an increasing focus in the research in this field. Wireless sensors with ability for self power generation can potentially be employed in devices for wireless data [1] or in a large number of areas such as artificial muscles or vibration control [2, 3]. Electroactive polymers offer unique properties as an electromechanical transducer technology compared with more conventional transducer technologies such those based on piezoelectric or electromagnetic [4-8]. The type of electroactive materials known as electrostrictive polymers has shown considerable promise for variety of actuator application [9] and may be well suited for harvesting energy from vibration sources such human motion [10-12]. In order to achieve this purpose many studies on the material itself have been devoted to increasing the permittivity of the material or including conductive nano-particles for decreasing the required bias electrical filed [13]. Others studies such as works performed by Lieu et al [14], Ren et al [15], Guyomar et al [16] proposed a simple but original method for measuring the dielectric constant, the Young modulus and electrostrictive coefficient of polymer film based on the FFT of current flowing through the sample when simultaneously driven by an electrical filed and a mechanical excitation so the purpose of this paper is to expose the application of such an approach for increasing the conversion abilities of electrostrictive materials with FFT analysis. It will be shown in this study a strong relationship between the amplitude of the lines which corresponds to the current frequency of strain, the frequency of polarization and the strain amplitude, thus this contribution describes the development of new setup for characterizing the harvesting capabilities.

2. Polymer materials and preparation

One type of commercially available polymer is used in this work PU 0.5 vt% C polyurethane. Polyurethane (PU) films as well as filled polymer films were prepared by solution casting [17-18], powder was first dissolved in N ,N-dimethylformamide (DMF) at 80^0 C for 30 min (10 wt %). Then carbon nanopowder (average particle size 30nm) was added to the stirred solution , the volume content of carbon in the composite was fixed to 1% in order to ensure a homogeneous distribution of the filler. The nanopowder was ultrasonically dispersed in the mixture cooled with ice, after which the viscous mixture was poured onto a glass plat and cured at 60^0 C for 12h and heated at 80^o C during 6h to remove most of the solvent. Permittivity measurements were carried out using

an HP 4284A LCR meter. The dielectric constant was calculated and evaluated using an SI1255 HF frequency response analyzer, the thickness of the sample was (80 $^{+}$-5) µm. It was pointed out in the introduction that the saturation of strain versus electrical field S(E) appears in the high electrical field regime especially for the thicker specimens (Fig.1); possible reason for this phenomenon was the presence of an electrical constraint, the saturated polarisation [19].

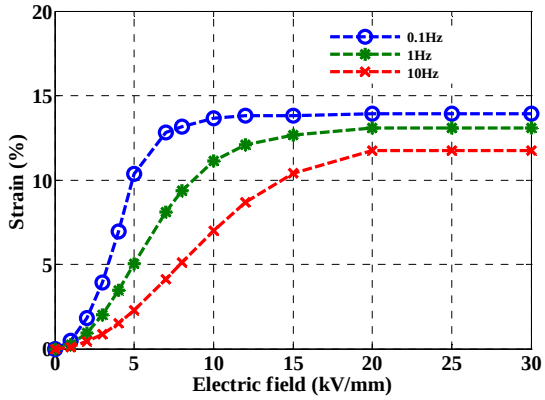

Fig.1. Strain versus the electrical field.

3. Modelling and abilities analysis

This section aims to expose a theoretical derivation of the maximal output power that can be obtained using electrostrictive materials; in this configuration the current generated by the polymer was used to measure the harvested power. The approach for modelling the current is based on the full constitutive equation for an electrostrictive material (including the elastic equation) which can be written as:

$$\begin{cases} S_1 = M_{31}.E_3^2 + s_{11}^E.T_1 \\ D_3 = \varepsilon_{33}.E_3 + 2.M_{31}.E_3.T_1 \end{cases} \quad (1)$$

Where S_1, T_1, E_3 and D_3 are respectively the strain, the stress, the electrical field, and the electrical displacement. Moreover, s_{11}^E is the elastic compliance and, ε_{33} is the dielectric permittivity under constant strain and M_{31} electrostrictive coefficient. In our case, as the length (L) of the sample is much greater than its thickness (e) and its width (l), and since the electrical field is only applied in the 3 direction, it is possible to express the constraint T_1 according to the strain S_1:

$$T_1 = \frac{1}{s_{11}^E}(S_1 - M_{31}.E_3^2) \quad (2)$$

Or the elastic displacement D_3 flowing through the polymer film can be calculated from the expressions for S_1 and E_3 by replacing T_1 (equation 2):

$$D_3 = E_3[\varepsilon_{33} + \frac{2.M_{31}}{s_{11}^E}(S_1 - M_{31}.E_3^2)] \quad (3)$$

Assuming uniform strain and electrical field over the sample allows expressing the macroscopic equation of the current $I = A.\frac{\partial D}{\partial t}$ (with A referring to the sample surface area) flowing out of the polymer as a function of the strain and electrical field:

$$I = A.\frac{\partial D_3}{\partial t} = A.[\frac{\partial E_3}{\partial t}(\varepsilon_{33} + \frac{2.M_{31}}{s_{11}^E}.S_1 - \frac{6.M_{31}^2}{s_{11}^E}.E_3^2) + \frac{2.M_{31}.E_3}{s_{11}^E}.\frac{\partial S_1}{\partial t}] \quad (4)$$

For realistic values of the current (less than 100 µA), load resistance (less than $10\,\Omega M$) and electrical field (1-100 MV/m^{-1}), the component $\frac{6.M_{31}^2}{s_{11}^E}.E_3^2$ can be neglected compared to the $\varepsilon_{33} + \frac{2.M_{31}}{s_{11}^E}.S_1$. Expression (4) can then be simplified as follows :

$$I = A.\frac{\partial D_3}{\partial t} = A.[\frac{\partial E_3}{\partial t}(\varepsilon_{33} + \frac{2.M_{31}}{s_{11}^E}.S_1) + \frac{2.M_{31}.E_3}{s_{11}^E}.\frac{\partial S_1}{\partial t}] \quad (5)$$

For simplicity, we consider the strain profile to be sinusoidal: $S_{ac} = S_{dc} + S_0.\sin(\omega_m t + \varphi)$. Here, φ is the shift phase between the strain and electrical field, ω_m the pulsation of the mechanical excitation and S_0 its amplitude. Simultaneously, the film is driven by an electrical field applied in the 3 directions through the electrodes and it is assumed to be given by $E_3 = E_0.\sin(\omega_e t) + E_{dc}$, where E_{dc} corresponds to the DC bias, ω_e to the pulsation of the electrical excitation and E_0 to its amplitude. So Eq. (5) becomes:

$$I = B_1.\omega_e + B_2.(\omega_m + \omega_e) + B_3.(\omega_m - \omega_e) + B_4.\omega_m \quad (6)$$

With $B_1 = A.(\varepsilon_{33} + \frac{2.M_{31}}{s_{11}^E}).E_0.\cos(\omega_e t)$,

$B_2 = \frac{M_{31}.E_0.S_0.A}{s_{11}^E}.\sin((\omega_m + \omega_e)t + \varphi)$,

$$B_3 = -\frac{M_{31}.E_0.S_0.A}{s_{11}^E}.\sin((\omega_m - \omega_e)t + \varphi) \quad \text{and}$$

$$B_4 = \frac{2.M_{31}.E_{dc}.S_0.A}{s_{11}^E}.\cos(\omega_m t + \varphi)\,.$$

The model of the polymer was thus simplified by the circuit (*Rp*, *Cp*) in parallel, where *Cp* is the capacitance of the clamped polymer and *Rp* is a resistance representing the dielectric losses. The equivalent electric scheme of the setup is shown in the Fig.2.

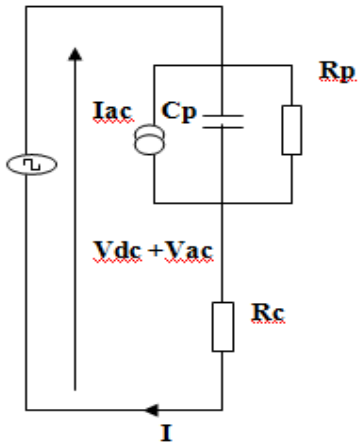

Fig .2. The equivalent electric schema of the setup [20].

The harvested energy density for one period of the sinusoidal excitation by using the same method [14] is given by the following expression:

$$W = \int_0^T E_3.I.dt = \int_0^T (E_0.\sin(\omega_e t) + E_{dc}).I.dt \qquad (7)$$

To show the usefulness of the phase shift angle between the electric field and the mechanical excitation and not to burden the calculation, we consider that the pulse of the electric field and that of the mechanical excitation are equal. Introduction of Eq.6 into Eq.7 leads to the following formula:

$$W = \frac{2\pi.M_{31}.E_0.E_{dc}.S_0}{s_{11}.T}\sin\varphi \qquad (8)$$

It can be seen that the harvested density energy reach maximum when $\sin(\varphi) = 1$ ($\varphi = \frac{\pi}{2}$). The experimental results from Fig.3a and Fig.3b show that the maximum current is reached with a phase shift of $\varphi = \frac{\pi}{2}$

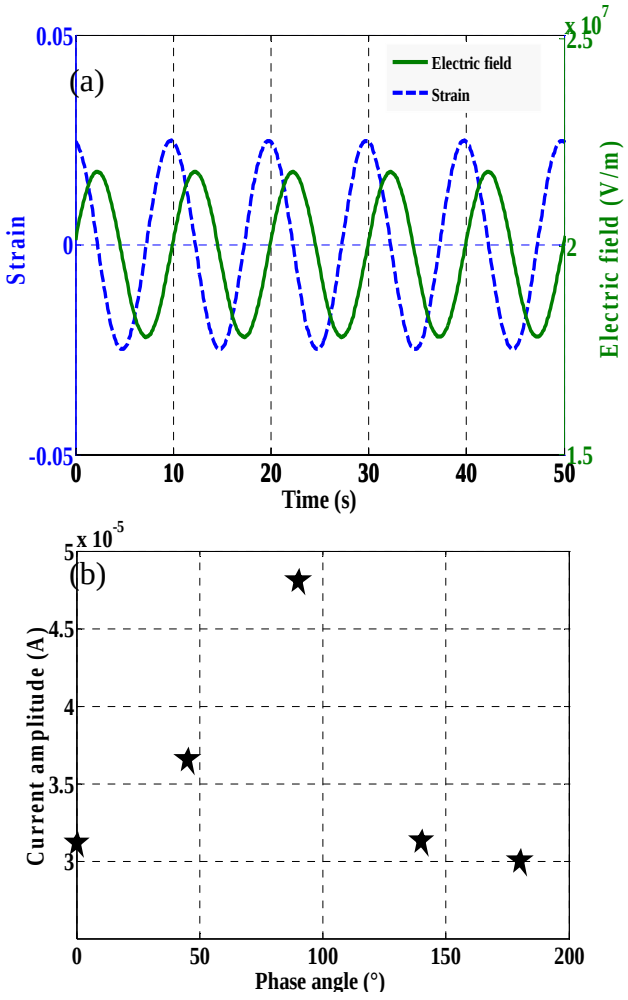

Fig. 3. (a)- Experimental Waveforms for Strain and proposed Electric field, (b)- Experimental waveforms for Current amplitude and Phase.

4 .Experimental setup

4.1 Principle

Electrostrictive polymers were subjected to a dc-biased electric field in order to induce polarization, because the polymer is not piezoelectric. In this study, the configuration of electrical schema was investigated, by putting an electrical charged in series with the electrostrictive polymers. The setup developed for characterizing the electrostrictive coefficient in polymer film is shown schematically in Fig.4. The polymer film is mounted in sample holder composed of two parts: one fixed and another that can be moved in 1 direction with the help of an XM550 Ironless linear motor. The film is stretched with different value amplitude of strain for a given frequency. It is assumed that the sample strained along the 1 direction, by applying a phase shift with slot electric filed using a generator function (Agilent 33220A) connected to the high voltage amplifier (Trek 609D-6).

The sample is linked to an electrical load RMS current is monitored by a current amplifier (Stanford SR570).

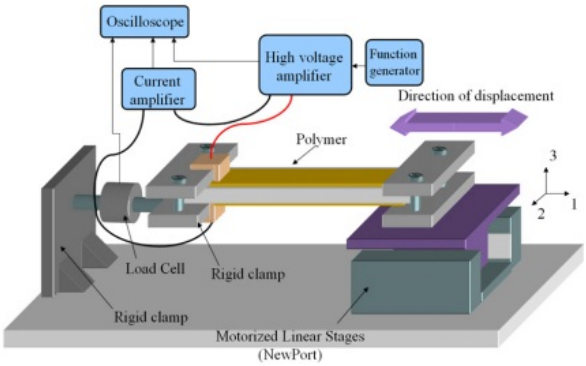

Fig. 4. Schema view of the experimental setup

4.2 Results and discussion

Permittivity measurements were carried out using an HP 4284A LCR meter. The dielectric constant was calculated from the capacitance at room temperature, results are depicted in Table 1. We quote the parameters of our film for a given frequency of 1 Hz. The parameters for polymers used in this experiment are given in Table 1.

The following section judges the accuracy of the measured output current and displacement, the validity of the modeling of the current, change in mechanical frequency and strain effect. Consequently, when the polymer was excited both electrically and mechanically, the power P harvested on the load was derived using the formula $P = R.I^2$, where R is the electric load and I is the RMS current resulting from the mechanical to electrical conversion with FFT analysis for this current. It is also important to increase the current ray corresponding to the mechanical frequency to have a vision on the performance of the system.

Table1. Parameters of polymers (PU 0.5 % C) at 1 Hz.

Electric field (KV/mm)	Young's Modulus *Y* (MPa)	electrostriction coefficient M_{31} (m^2/V^2)	Surface A (cm^2)	Thickness *e* (µm)
10	36	$84x10^{-15}$	4x1.6	80

The permittivity of the obtained sample has been measured using a LCR meter (HP 4284A). Results are depicted in Fig. 5.

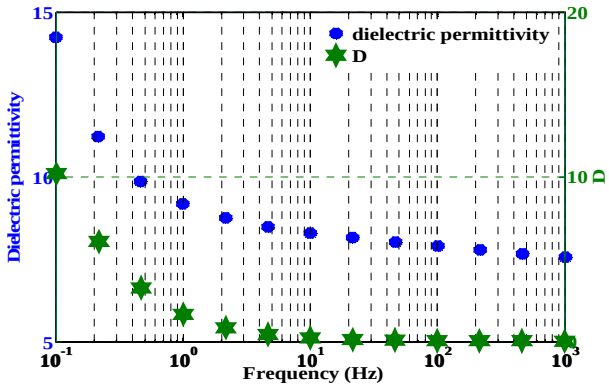

Fig. 5. Dielectric permittivity and loss (D) versus the frequency.

Figs. 6 (a, b, c) depict the strain amplitude dependence of the ray current. According to experimental results, we see clearly at a frequency of the electric field (f_e = 1 Hz) and mechanical excitation (f_m = 6 Hz) that the ray which is believed fm is increased with strain amplitude, for against the corresponding ray f_e decreases but remains higher compared to the corresponding f_m (Fig 6 a, b). Beyond a certain value of strain amplitude (10%), the ray of the mechanical excitation becomes similar to that of the electric field (Fig. 6c).

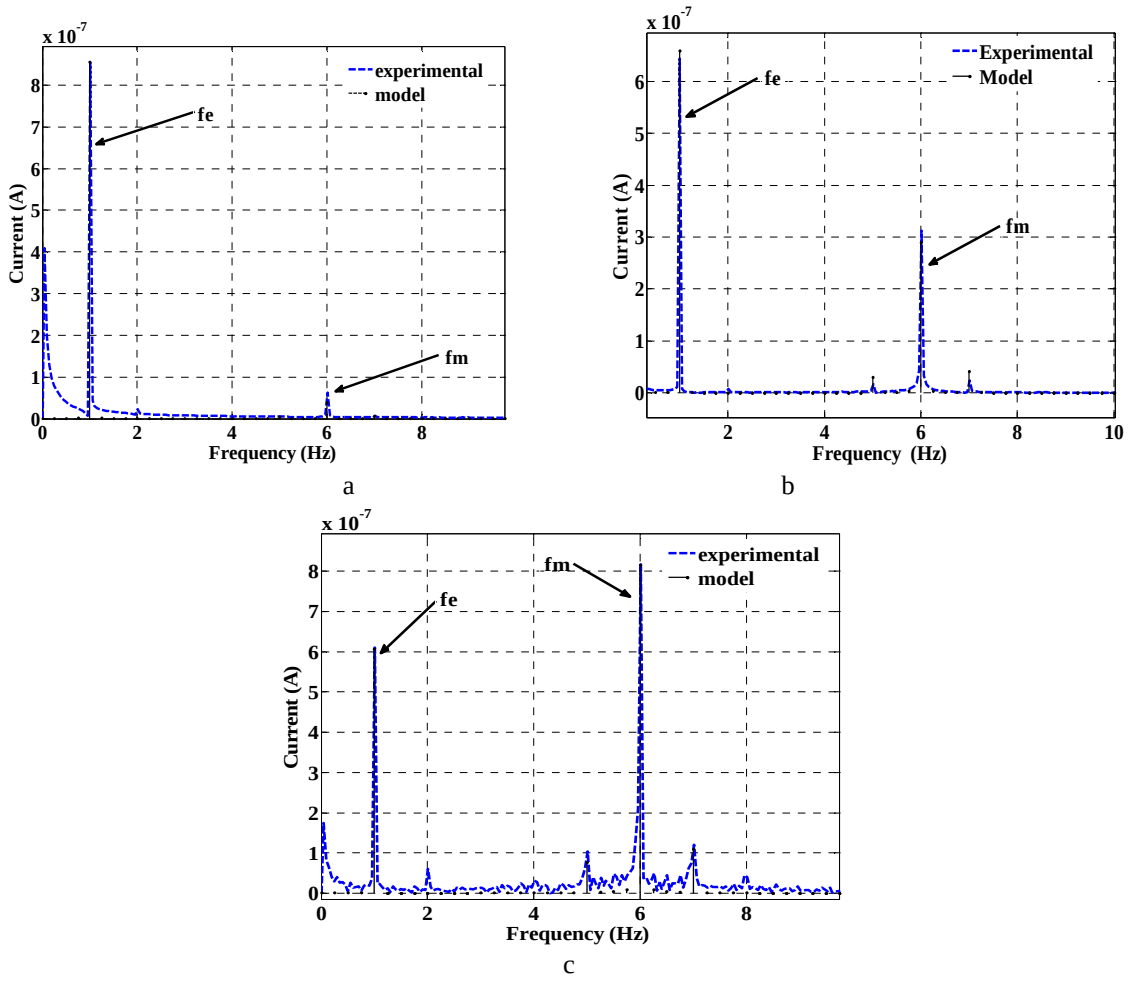

Fig. 6: FFT of the current measured with different strain level (a)- 0.6%, (b) - 3%, (c) - 10%

The second part of this experience describes the influence of the variation in frequency due to mechanical excitation (fm) on the spectral analysis of the current measured. It is clear from the figures (Fig.7: a, b, c) that the current ray for the mechanical excitation increases with fm, but the current ray for the electric field remains constant. This indicates that the variation of the frequency f_m has no effect on the ray current corresponding f_e.

5. Conclusion

In this paper we focused on new method to investigate the effect of varying frequency and amplitude of mechanical strain on the spectral analysis to retrieve an electrostrictive polymer. In each case, a good agreement between the model and experimental data was found. This model allows us to show the influence of mechanical parameters (frequency and amplitude) on the overall performance of the electromechanical conversion for electrostrictive polymer. These results demonstrated the excellent potential of this analysis for energy harvesting; electrostrictive polymers are thus promising candidate for replacing piezoelectric (PZT) materials. Moreover the analysis developed in this paper could be a good tool for estimating energy harvesting capabilities in the future.

Acknowledgements

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