Flexible smart textile with excellent energy harvesting toward a novel class of self-powered sensors

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ABSTRACT. The field of power harvesting has experienced significant growth over the past few years due to the ever-increasing desire to produce portable and wireless electronics with extended lifespans. The present work aims to introduce an approach to harvesting electrical energy from a mechanically excited piezoelectric element and investigates a power analytical model generated by a smart structure of type polyvinylidene fluoride(PVDF) that can be stuck onto fabrics and flexible substrates, although we report the effects of various substrates and investigates the sticking of these substrates on the characterization of the piezoelectric material.

Keywords : Power harvesting, Wireless electronics, Piezoelectric energy, Technical textile, PVDF

1. INTRODUCTION

Over the past decade, the wireless sensors and portable electronics carried by the individual had a rapid increase [1,2]. Each of these devices is typically powered using a traditional electrochemical battery. However, the use of batteries involves drawbacks, such as limited energy storage capability, potential damage to environment, and and a limited life time, have limited further development and applications of wearable electronics. To overcome this issue,many efforts have been focused on wearable energy harvesters, allowing the conversion of ambient energy surrounding the system to usable electrical energy [3-4]. Such as the mechanical energy dissipated from human motion [5, 6], including electromagnetic [7-11], electrostatic [12-13], thermoelectric [14], and piezoelectric harvesters [15-19]. Compared with electromagnetic, electrostatic and thermoelectric methods, the piezoelectric approach to power harvesting provides several advantages including: higher energy density, and the ability to be fabricated in custom shapes and higher flexibility of being integrated into a system.

The focus here is on piezoelectric materials, which accumulate electrical charge in response to applied mechanical stress. Representative piezoelectric materials can be categorized into piezoceramics and piezopolymers. However, PZT (lead zirconate-titanate) is a commonly used piezoelectric ceramic. On the other hand, piezopolymer commonly used is (polyvinylidene fluoride, PVDF). Compared with rigid, brittle, and heavy PZT [20,21], PVDF is particularly interesting due to their low cost, considerable flexibility, durable, good stability, and easy integration into elements such as clothes and shoes [22- 30].

Recently, a great amount of researches have been conducted to develop simple and efficient energy harvesting devices from vibration by using piezoelectric materials based on smart textiles which harbor potential in various applications such as energy harvesting , sensing and actuation [31-37]. Smart Textiles are defined as textile products, they may be divided into two classes : passive and active smart textiles, such as fibers and filaments, yarns together with woven, knitted or non-woven structures , which able to sense and respond to changes in their environment [38,39].

furthermore Recent developments in the domain have led to the design of a number of mechanisms that can be used to harvesting electrical energy, from a variety of textiles substrats including textile plus interface layer, Kapton and alumina , and so on [40-42].

In addition, Almusallam. A, et al [43] presented an experimental study on clamping Effect on the Piezoelectric Responses of Screen-printed Low Temperature PZT/Polymer Films on Flexible Substrates. Later, Almusallam. A, et al [44] made a series of studies about the use of a flexible piezoelectric nano-composite films for kinetic energy harvesting from textiles.

In this context, the study has shown a piezoelectric patch that could recharge a small device within few hours when excited by a kneepad located on the knee due to walking [45].
This paper has investigated the development of a novel energy harvesting systems, which are a clean and durable solution, based on the thin film PVDF sticking on flexible substrates such as fabrics. The smart structure shows greater piezoelectric and dielectric properties compared to our previou work [45]. These properties are explored and discussed in this paper.

2. GENERAL THEORY OF KINETIC ENERGY HARVESTING

2.1 Standard approach to energy harvesting

The simplest method to recover energy is to directly connect the electrical circuit supplying the piezoelectric elements. This device is shown in Fig. 1(a) wherein the resistance *R* represents the input impedance of the supplied electric circuit. In this case, the load voltage is alternative. The waveforms associated with this technique are shown in Fig. 1(b), and in this case, a permanent sinusoidal stress has been performed.

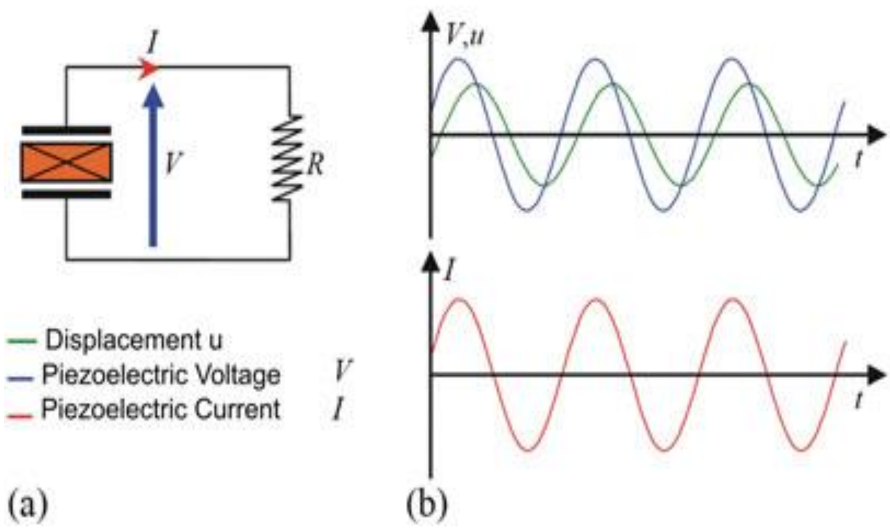

Figure 1. Standard approach Alternating Current (AC) to energy harvesting : (a) standard network and (b)

standard waveforms.

2.2 Analytical and modelling of power harvesting system

As one of the important vibration-based energy harvesting methods, piezoelectric conversion has received much attention because of the simple structure of piezoelectric converter and ease of application characteristic of piezoelectric materials There are two types of piezoelectric effects that can be used for technological applications : the direct piezoelectric effect that describes the ability of a given material to convert mechanical strain into electricity. On the other hand, the converse effect, which is the ability to convert an applied electrical solicitation into mechanical energy.

Two equations are used to depict the piezoelectric nature of a material and they have been considered from Jaffe and Cook [5]. Equations (1) and (2) are defined as the piezoelectric constitutive equations :

$$\mathbf{S_\alpha = s_{\alpha\beta}.T_\beta + d_{i\alpha}.E_i} \quad (1)$$

$$\mathbf{D_i = d_{i\alpha}.T_\alpha + \varepsilon_{ij}.E_j} \quad (2)$$

$$\boldsymbol{\alpha = \beta = 1, 2, \ldots, 6 \qquad i, j = 1, 2}$$

The first equation defines the mechanical response of the material, while the second equation defines the electrical response. Where S is the strain, T is the stress, E is the electric field, D is the electric displacement, d is the piezoelectric electromechanical coupling coefficient, s is the compliance, which relates stress and strain at constant electric field, ε is the dielectric permittivity, which indicates the charge stored in the capacitive element of the piezoelectric material at constant stress, and the subscripts represent the direction of each property.

$$\mathbf{S_1 = s_{11}.T_1 + s_{12}.T_2 + s_{13}.T_3 + d_{31}.E_3} \quad (3)$$

$$\mathbf{S_3 = s_{13}.(T_1 + T_2) + s_{33}.T_3 + d_{33}.E_3} \quad (4)$$

$$\mathbf{D_3 = d_{31}.(T_1 + T_2) + d_{33}.T_3 + \varepsilon_{33}.E_3} \quad (5)$$

When placed on an isotropic substrate (the fabric plus interface layer), the lateral strain is the same in each direction $S_1 = S_2$ and the stress $T_1 = T_2 = T$, equation (1) can be re-written as

$$\mathbf{S_1 = (s_{11} + s_{12}).T_2 + s_{13}.T_3 + d_{31}.E_3} \quad (6)$$

Thus, the value of S_1 and S_2 must be determined as a function of T_3 using Hooke's law

$$\mathbf{S_1 = \boldsymbol{S_3} = (-\frac{\boldsymbol{\upsilon_{sub}}}{\boldsymbol{\gamma_{sub}}}).T_3} \quad (7)$$

Also, the mechanical compliance matrix parameters were calculated using the following equations

$$\boldsymbol{s_{11}} = \frac{\mathbf{1}}{\boldsymbol{\gamma_{piez}}}; \qquad \mathbf{s_{12}} = -\frac{\boldsymbol{\upsilon_{piez}}}{\boldsymbol{\gamma_{piez}}}; \qquad \mathbf{s_{13}} = -\frac{\boldsymbol{\upsilon_{piez}}}{\boldsymbol{\gamma_{piez}}} \quad (8)$$

Relating the strain and the ratio of the generated charge to the applied force and combining with equations (4), (5) and (6) gives

$$\left(-\frac{\boldsymbol{\upsilon_{sub}}}{\boldsymbol{\gamma_{sub}}}\right).\mathbf{T_3} = \frac{\mathbf{1} - \boldsymbol{\upsilon_{piez}}}{\boldsymbol{\gamma_{piez}}}.\mathbf{T} - \frac{\boldsymbol{\upsilon_{piez}}}{\boldsymbol{\gamma_{piez}}}.\mathbf{T_3 + d_{31}.E_3}$$

It is possible to express the T stress as a function T_3 and E_3 , given by

$$\mathbf{T} = \frac{\gamma_{piez}}{1-\upsilon_{piez}} . \frac{\upsilon_{piez}.\gamma_{sub} - \upsilon_{sub}.\gamma_{piez}}{\gamma_{piez}.\gamma_{sub}} . T_3 - \frac{\gamma_{piez}}{1-\upsilon_{piez}} \mathbf{d_{31}} . \mathbf{E_3} \quad (9)$$

Whence the expression of the electric displacement D ; Substituting equation 7 into 3 and rearranging it results in

$$D_3 = d_{33} . \left(\frac{-2.\gamma_{piez}}{1-\upsilon_{piez}} . \frac{\upsilon_{piez}.\gamma_{sub} - \upsilon_{sub}.\gamma_{piez}}{\gamma_{piez}.\gamma_{sub}} + 1 \right) . T_3 + \left(\varepsilon_{33} - \frac{2.\gamma_{piez}.\upsilon_{piez}^2.d_{33}^2}{1-\upsilon_{piez}}\right) . \mathbf{E_3} \quad (10)$$

The current supplied in the polymer in the case of transverse mechanical stress is expressed in the form

$$I = A.\frac{\partial D}{\partial t} = A.\left\{ d_{33} . \left(\frac{-2.\gamma_{piez}}{1-\upsilon_{piez}} . \frac{\upsilon_{piez}.\gamma_{sub} - \upsilon_{sub}.\gamma_{piez}}{\gamma_{piez}.\gamma_{sub}} + 1 \right) . \frac{\partial T_3}{\partial t} + \left(\varepsilon_{33} - \frac{2.\gamma_{piez}.\upsilon_{piez}^2.d_{33}^2}{1-\upsilon_{piez}}\right) . \frac{\partial E_3}{\partial t} \right\} \quad (11)$$

A is the active surface of the polymer.
$\frac{\partial T_3}{\partial t}$ and $\frac{\partial E_3}{\partial t}$ are the time derivatives of the electrical field and strain, respectively.

$$\alpha = d_{33} . \left(\frac{-2.\gamma_{piez}}{1-\upsilon_{piez}} . \frac{\upsilon_{piez}.\gamma_{sub} - \upsilon_{sub}.\gamma_{piez}}{\gamma_{piez}.\gamma_{sub}} + 1 \right)$$

$$\beta = \varepsilon_{33} - \frac{2.\gamma_{piez}.\upsilon_{piez}^2.d_{33}^2}{1-\upsilon_{piez}}$$

The electric field E is equal to the alternating electric field E_R across the resistor: $E = E_R$.
The voltage output of the system across the load resistance is defined by the term Fig. 1

$$\mathbf{E_R} = -\frac{\mathbf{R.I}}{\mathbf{t_p}}$$

Where I is the current which crosses the load R, e is the thickness of the polymer film.
So :

$$\mathbf{E} = \mathbf{E_R} = -\frac{\mathbf{R.I}}{\mathbf{t_p}} \quad (12)$$

The general expression the current I is

$$I = A.\alpha.\frac{\partial T_3}{\partial t} - \frac{A.\beta.R}{t_p}.\frac{\partial I}{\partial t} \quad (13)$$

In the frequency domain, the current is expressed in the form

$$I = j.w.A.\left(\alpha.T_3 - \frac{\beta.R}{t_p}.I\right) \quad (14)$$

$$I = \frac{j.w.A.\alpha.T_3}{1+j.w.A.\frac{\beta.R}{t_p}} \quad (15)$$

In the case of a resistive load connected in series with the piezoelectric polymer working in piezoelectric mode, the objective is to take the expression of the power dissipated in the

resistive load, on the basis of the equation that links the power, current, and load $P = R \cdot I^2$
The power dissipated in the resistor R is expressed by the equation

$$P = \frac{R.(w.A.\alpha.T_3)^2}{1+\left(w.A.\frac{\beta.R}{t_p}\right)^2} \quad (16)$$

3. SIMULATION RESULTS AND DISCUSSION

3.1 Flexible textile substrates

A Smart structure of type PVDF was stucked on three different substrates, Kermel and thick woven fabric (Polyester 65%–Cotton 35%) and Cotton 100%. The Kapton substrate was used commonly as reference substrate material for investigating the dielectric and piezoelectric properties of the composite. However this material is used as a substrate for flexible electronic devices. The PVDF polymer layer was sandwiched between two silver electrodes that were used to enable film poling and perform study of the differents parameters. The investigated textile substrates are polyester-cotton, cotton, and polyamide-imide (Kermel) were plain weave, 65% polyester with a warp and weft.

3.2 Design mode study

This section focuses on the effect of substrats parameters textiles in order to increase the power recovered by the PVDF polymer film. Optimization of these substrats is implemented in order to ensure good performance of this electroactive polymer for energy harvesting.
The theoretical results are presented with an analysis of the 33-mode for the piezoelectric generator to verify the validity of the model developed for application in textile.

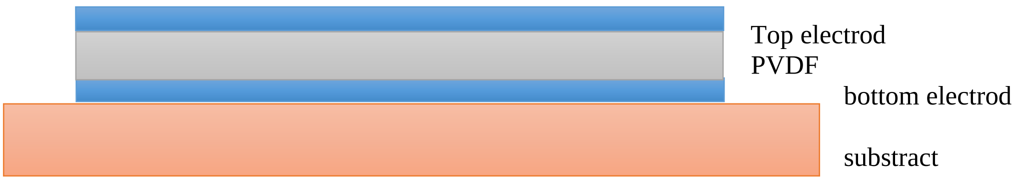

Fig.2. The smart structure stuck on woven fabric.

3.3 Effet of substrats on energy harvesting under compressive force

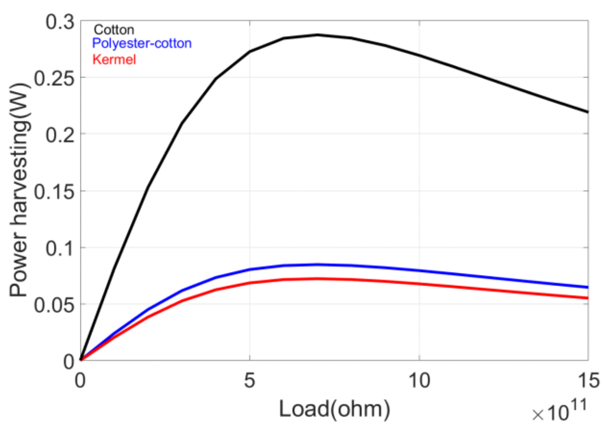

Fig.3. The power harvested as a function of resistive load for cotton, polyester-cotton and Kermel substrates when applying force F=80N at 6Hz.

Figure 3 shows the theoretical results obtained with piezoelectric polymer PVDF film stucked on substrats (cotton; polyster-cotton;kermel) having a thickness of 500 µm, the frequency 6 Hz, and the applied force 80 N.
The theoretical results show that the harvested power increases while increasing the resistance load, up to a optimal value in which the power decreases.

4. CONCLUSION

Textile substrate bears one of the most promising form factors for future electronic applications due to its wide degree of freedom in shapes with flexible and stretchable characteristics. This work investigates the energy harvesting performance of PVDF polymer material stucked on woven-fabric substrates. Clearly the energy harvesting performance is fundamentally linked to the piezoelectric properties of the stucked film.
The theoretical investigations confirmed a increase on the power harvesting values by 258mW, 96mW and 95mW for the cotton, Polyester-cotton and kermel substrates, respectively.

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