PIEZOELECTRIC MATERIALS USED FOR PORTABLE DEVICE SUPPLY

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Abstract:

The focus of this paper is to study the feasibility of a piezoelectric generator harvesting the mechanical energy of human movements, in order to supply portable electronic devices which power is in the range of [10µW; 1mW], for example: hearing aid devices, microchip of identification badges, electronic textiles. The piezoelectric generator consists of three stages: a mechanical application device which transforms the voluntary movement of the user into a high dynamic constraint; the piezoelectric device which is the parallel association of 20 identical PZT ceramic bars polarized in 31-mode; and a static converter that converts the electrical energy in a suitable form to the targeted portable application. In this paper, the two first stages are described. On the one hand, the low frequency model of the piezoceramics is presented. On the other hand, the mechanical application device is described and experimental measurements are interpreted. With a 5Hz and 2N constraint, the power delivered by the 20 simultaneously constrained piezoceramics reaches 13,2µW with a 100kΩ load.

Keywords: Mechanical energy harvesting, Functional applications, PZT, Sensors, Structural applications

Introduction

For the last ten years, the market of portable electronic devices has developed considerably, making problematical the question of their electrical supply. But in the same time, their decreasing consumption has made them potential applications for portable generators based on mechanical energy harvesting in human environment [1]. The source of mechanical energy may be a vibrating structure [3] or directly the human body [2]. For exemple, foot or hand movements produce more than 5W. The electromechanical conversion requires a transducer, which may be piezoelectric [2], electromagnetic [3] or electrostatic [4]. Even if a small portion of this energy is converted into electrical form, it may be sufficient to electronic devices which power is in the range of [10μW; 1mW].

The objective of the present research is the design, modelling and testing of a piezoelectric portable generator. Three conversion stages are necessary (see Fig. 1). The first one, called mechanical application device, transforms the voluntary movement of the user into a high dynamic constraint. This constraint is applied to a piezoelectric device, which is the parallel association of 20 identical PZT ceramic bars (see Fig. 1 and 3), polarized in 31-mode. This is the electromechanical conversion stage. The last stage consists in a static converter that converts the electrical energy in a suitable form to the targeted portable application.

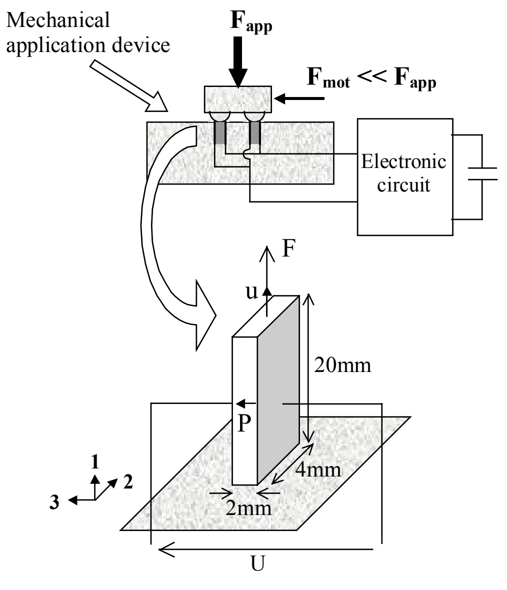


Fig. 1: Principle of the portable piezoelectric generator and schematics of the 31-mode piezoceramic

Piezoelectric device modelling

First of all, the central part of the generator has been studied: a PZT ceramic parallelepipedic bar is embedded at one end and a low frequency constraint is applied on the other end, perpendicularly to the polarisation axis (31-mode) (see Fig. 1), resulting in a voltage U between the metallized faces. All other deformation modes are supposed negligible. According to the reference axes, with axis 3 along dielectric polarization P, the dimensions of the piezoceramic bar are called L_1, L_2 and L_3. The following relations link constraint T_1, relative deformation S_1, electrical field E_3 and electrical induction D_3 respectively to force F, deformation u, voltage U and current I:

$$T_1 = \frac{F}{A_1}; \quad S_1 = \frac{u}{L_1}; \quad E_3 = -\frac{u}{L_3}; \quad I = A_3 \frac{dD_3}{dt} \qquad (1)$$

Moreover, the constraint frequency is small compared to the resonance frequency of the piezoceramics (70kHz), so the unidimensional model is established using the static equations of piezoelectricity:

$$\begin{cases} S_1 = s_{11}^E T_1 + d_{31} E_3 \\ D_3 = d_{31} T_1 + \varepsilon_{33}^T E_3 \end{cases} \qquad (2)$$

ε_{33}^T, s_{11}^E and d_{31} are respectively the dielectric permittivity at constant T, the mechanical elasticity at constant E and one of the piezoelectric constants.

The resolution of (1) and (2) leads to the system:

$$\begin{cases} \dfrac{1}{N^2 C_m} \cdot NV = \dfrac{d}{dt}\left(\dfrac{F}{N} - U\right) \\ NV - I = C_0 \dfrac{dU}{dt} \end{cases} \qquad (3)$$

where N, C_0 and C_m design respectively the ratio of a transformer, the dielectric capacitance and the equivalent mechanical capacitance:

$$C_0 = \frac{A_3 \varepsilon_{33}^S}{L_3}; \quad C_m = \frac{L_1 s_{11}^E}{A_1}; \quad N = \frac{d_{31} L_2}{s_{11}^E} \qquad (4)$$

The equivalent circuit deduced from (3) is presented in figure 2. The N ratio transformer represents the electromechanical coupling, between the electrical branch and the mechanical branch, where forces are represented by voltages and velocities, by currents.

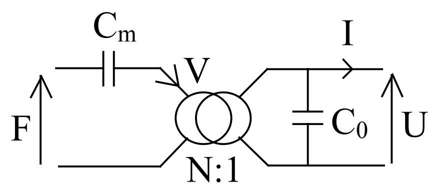


Fig. 2: Quasi-static model of a piezoceramic bar polarized in 31-mode

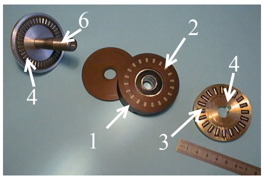
For one 20mm×4mm×2mm piezoceramic (PZT material PIC151 from PI Ceramic), the parameters values are: C_0 = 920pF, Cm = 38nF and N = -0,056. At frequencies below 100Hz, mechanical and dielectric losses are negligible.

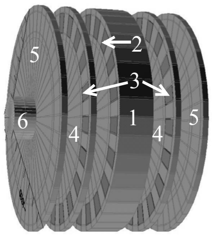
This model is useful to interprete the experimental measurements of voltage and power. Moreover, it can be included in a complete simulation circuit including the static converter that is connected at the output of the transducer.

Mechanical application device

This stage of the generator has been conceived according to a precise objective: to transform the low level and low frequency force of the human user in a high level and higher frequency force applied to the piezoceramics, with a minimum effort from the user. So the principle of the application device is as follows (see Fig. 1).

The piezoelectric bar is embedded in a supporting structure, made of a mechanically hard and electrically insulator material. A constant and standard constraint is applied on its surface via the bearings of a manually actuated mobile structure. The 31-mode has been chosen in order to facilitate the electrical connections: the access to the metallized sides is easy, and they cannot be damaged by the bearings. With this method, a high level force (F_{app}) is applied to the piezoceramics, with only a small motion force (F_{mot}) from the user. But the frequency of the mechanical excitation is still that of the human movement. In order to multiply this frequency, a rotational application device has been designed (see Fig. 3).





0 : Mechanical application device
1 : Supporting structure
2 : Piezoceramics
3 : Needles
4 : Cages
5 : Spring washers
6 : Axis
7 : DC Motor
8 : Electrical connections

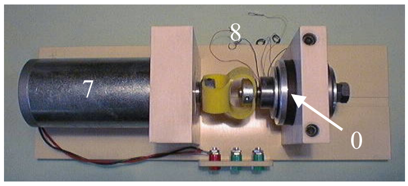


Fig. 3: Schematics and pictures of the mechanical application device

The twenty piezoceramics are circularly distributed in a supporting structure. They are alternatively compressed by needles that are maintained in a cage driven in rotation by a motor (see Fig. 3). In the future portable generator, the axis will be coupled to a crank, driven manually. A second cage of needles is necessary to allow the rotational movement of the whole mobile structure. The static constraint F_{app} is applied by a spring washer and a nut. F_{app} is evaluated via the tightening torque measured with a dynamometer.

Experimental measurements

At first, measurements have been conducted with various resistive loads, directly connected to the piezoelectric device.

The measured voltage is alternative (see Fig. 4a, 4b). The positive alternance corresponds to the progressive establishment of mechanical compression over the whole surface of the piezoceramic, the negative alternance corresponds to the piezoceramic relaxation, when compression progressively disappears from the surface.

With this experimental device, the real form of the dynamic constraint cannot be known with precision because of the difficulty to insert a stress gauge. But the hypothesis of a force rising exponentially leads to a voltage form that agrees well with measurements, even if the constraint fluctuations due to uncontrolled vibrations of the mechanical device are not taken into account (see Fig. 4c).

The voltage amplitude depends on the speed of the mobile structure, which influences the frequency, rise and fall time of the constraint. The voltage peaks are all the more high as the speed is high. Moreover, the voltage decrease depends on the load value (see Fig. 4a, 4b).

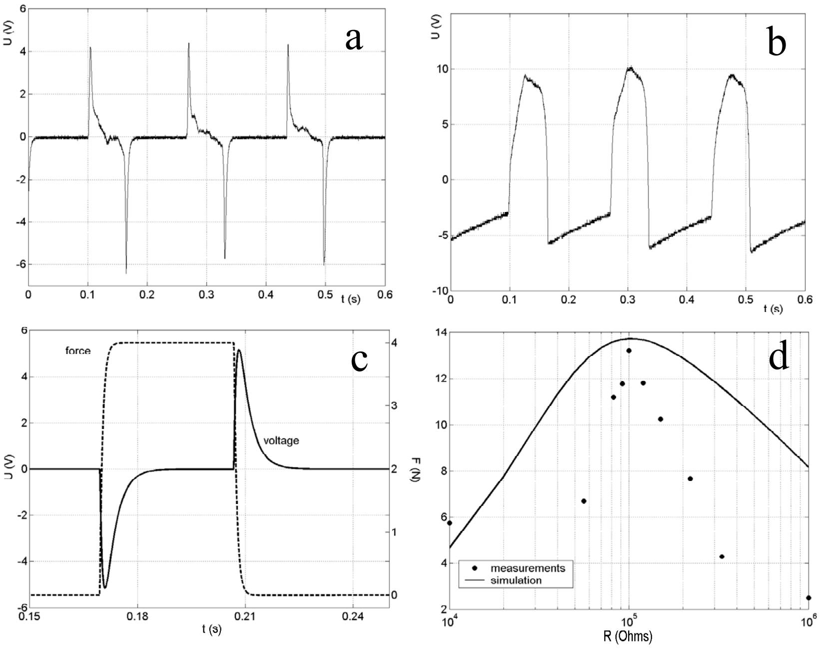


Fig. 4: Measured voltages (a: 150kΩ, b: 10MΩ), calculated voltage (c: 150kΩ) and electrical power function of load with a 55Hz and 2N force (d)

The delivered power has been measured as a function of the load resistance, with a 55Hz frequency constraint, which amplitude is estimated at 2N per piezoceramic (see Fig. 4d). The curve presents a maximum: 13,2µW at 100kΩ. The power curve obtained by simulation has a similar shape, with also a maximal value at 100kΩ. The difference between the two curves is probably due to the lack of information on the real form of the constraint during the compression phase.

Because of technical limits of the present mechanical device, it is not possible to apply the expected value of F_{app} = 10N per ceramic. But the tests conducted on this first prototype suggest many improvements that will be carried out in the next version of mechanical device. With 10N per ceramic, the expected power is 330µW for a 100kΩ load.

Further work will consist in a precise characterization of the generator, by measuring the electrical power curves for various frequencies and amplitudes of constraint.

Electromechanical coupling coefficient

Piezoelectricity means the coupling between mechanical and electrical effects, so it is natural to introduce the electromechanical coupling coefficient k_e, in order to quantify the efficiency of the electromechanical conversion. Calling W_C the electrical energy delivered to the resistive load and W_M the supplied mechanical energy, the square coupling coefficient k_e^2 is defined as the ratio W_C / W_M.

Figure 5 presents the various instantaneous powers during a complete cycle of compression/relaxation of the piezoceramics. The area under each curve corresponds to the energy generated or received on the considered interval. Generator convention is used for W_M, receiver convention for the other energies.

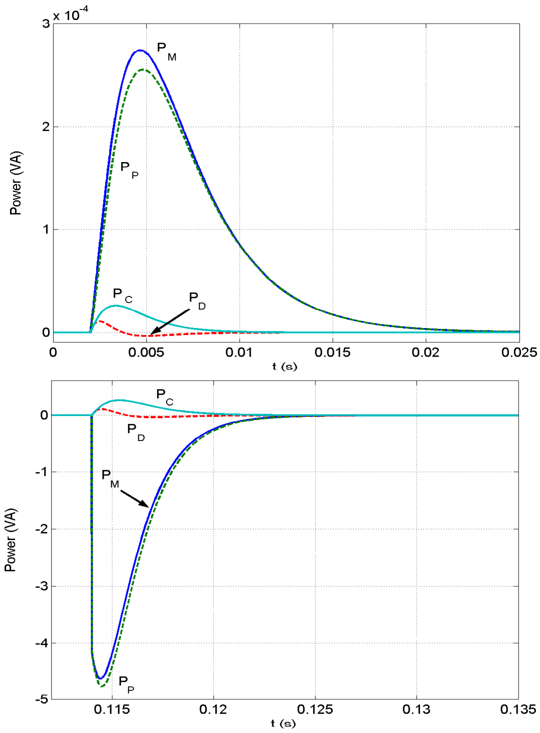


Fig. 5: Instantaneous powers during compression (top) and relaxation (bottom) of the piezoceramics

During compression, a large amount of provided mechanical energy (W_M = 1.6µJ) is stored under elastic form by the compressed bar (W_P = 1.5µJ). The rest is delivered to the resistive load (W_C = 86nJ). The energy stored in C_0 is null at the end of each phase. In the exemple given here, k_e^2 = 5.4%. During relaxation, the elastic energy (W_P = -1.5µJ) is released. A large part is restituted to the mechanical source (W_M = -1.4µJ). A small part is converted in electrical energy and delivered to the load (W_C = 86nJ), leading to k_e^2 = 5.7%. Square coefficient k_e^2 must not be confused with the efficiency, which value is 1 at the end of each phase. Moreover, k_e is much inferior to the intrinsic electromechanical coupling k_{31}, which corresponds to a particular electromechanical working cycle. The value given by manufacturers (PI Ceramic) for PIC151 material is k_{31}^2 = 12%.

Conclusion

The two first stages of an original piezoelectric generator have been presented.

At first, we established a model of the piezoelectric device, submitted to a low frequency constraint. This model is useful to interprete the measurements obtained with the experimental device. This device has been conceived in order to transform the low level and low frequency force of the human user in a high level and higher frequency force, applied simultaneously to twenty piezoceramics. Associated in parallel, they deliver an alternative voltage, which amplitude is all the more high as the constraint variation is rapid.

A significant electrical power is delivered by the piezoelectric device. With a 5Hz and 2N constraint, the delivered power presents a maximum: 13,2µW at 100kΩ. With an improved prototype of the mechanical device, it will be possible to apply a constraint of 10N per ceramic. The expected power is then 330µW for a 100kΩ load. In the range of [10µW; 1mW], many portable electronic devices are potential applications: hearing aid devices, GPS emitters, microchip of identification badges, electronic textiles.

Further work will concern the complete characterization of the piezoelectric device. In particular, the delivered electrical power will be measured at various constraint frequencies, and for various resistive loads.

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