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Piezoelectric model of rainfall energy harvester

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Abstract— **In this paper a model to predict the harvest of the energy contained in rainfall by means of piezoelectric transducers is presented. Different studies agree on the level of suitable generated voltage on the electrodes of a piezoelectric transducer subjected to rainfall, but a complete characterization on the supplied power is still missing. This work, in order to limit optimistic forecasts, compares the behavior of the transducers subjected to real and artificial rainfall, a condition that has shown promising behavior in laboratory**.

Keywords—energy harvester, piezoelectric effect

I. INTRODUCTION

In recent years an increasing attention to the possibility of generating energy without the use of conventional thermal power or nuclear plants, led the study on the employment of smart materials. The use of renewable energies such as solar and wind power seems to be the best way to ensure the requirements for the achievement of high levels of power and a reduced environmental impact, even leading to innovative research topics concerning power quality measurements under electromagnetic emissions [1-5]. On the other hand a study on an alternative energy harvest can be taken: the piezoelectric materials seem to be the most suitable solution for the low power supply. The basic idea is to convert the mechanical energy of vibration or pressure into electrical energy. Different scenarios have been considered: in [6] a study on the harvested energy from vibrating shoe-mounted piezoelectric cantilevers is presented; in [7] the energy harvesting from the vibrations of bridges is faced; in [8] the harvesting of energy induced from the deformation of pavements due to moving vehicles is analyzed; in [9] the harvesting from automotive tires is discussed; in [10] a harvesting from seismic mass is presented and also an optimization is discussed; in [11] an innovative piezoelectric grass energy harvester is proposed; in [12] the energy harvesting from low frequencies travelling sound is presented, in [13] the wind energy harvesting is studied. Also the rainfall energy harvest has been faced [14-17]. The idea is to convert, by means of piezoelectric plates, the kinetic energy possessed by the drops of rainwater into electrical energy. A pioneering comparison of different piezoelectric materials, in order to investigate the possibility of energy generation water droplets energy sources for low power electronic devices, has been studied in [16]. These studies agree that the single drop of water hitting the piezoelectric plates generates voltages less than a dozen of volts (peak to peak, and without load), but no evaluation on power has been proposed. The drops of rain strike the piezoelectric material in a cantilever configuration, which may be subject to study to improve the energy produced [18-20]. Although the voltage peak to peak, produced by droplets, seems high enough to interact with electronic devices or rectifiers a more accurate characterization is required, in order to dispel excessive optimistic predictions. The concept of energy flow, presented in [21,22], clarifies the dissipation of energy during the harvesting process, in order to separate the electromechanical coupling coefficient of the system, natural frequencies, damping ratio and electric load. A good analysis on the optimal AC–DC power generation for a rectified piezoelectric device is presented in [23, 24] and in [25] the problem of the storage energy has been considered. It is clear that the average harvested power particularly depends on the input vibration, larger surfaces allows greater impact areas, and a potentially higher collected power, but the cantilever configuration has its optimal geometrical structure [26-30], and so, in order to improve the harvested power, particular configuration of piezoelectric in parallel or series can be considered [31, 32]. For larger surfaces, hitted by random pulses, approaches based on the theory of random vibrations proposed in [33,34] can facilitate the raindrop energy harvesting. Matched inductive loads and schemes, which place a capacitor before the load in the conditioning circuit [35,36], increase the electrical energy transferred to the electrical system. A more definite analysis will concern the behavior of the device in the presence of strong stresses in terms of the electromagnetic field [37-39], by modeling the device as a receiving antenna [40].

II. PIEZOELECTRIC TRANSDUCERS AND RAINDROP

Piezoelectricity is a property present in many materials: the generation of an electric charge in certain non-conducting materials, such as quartz crystals and ceramics, when they are subjected to mechanical stress (such as pressure or vibration) is known as direct piezoelectric effect, whereas the generation of vibrations in such materials when they are subjected to an electric field is the inverse effect.

The ability of piezoelectric materials to convert electrical energy into mechanical and vice versa depends on their crystalline structure. The necessary condition occurs because the piezoelectric effect is the absence of a center of symmetry in the crystal, which is responsible for charge separation between positive and negative ions and the formation of the Weiss domains, ie groups of dipoles with parallel orientation.

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Applying an electric field to a piezoelectric material, the Weiss domains are aligned in proportion to the field. Consequently, the size of the material change, by increasing or decreasing if the direction of the Weiss domains is the same as or opposite to the electric field. To describe in simplistic terms, a stress (tensile or compressive) applied to a piezo crystal will alter the separation between the positive and negative charge sites in each elementary cell leading to a net polarization at the crystal surface. The effect is practically linear, i.e. the polarization varies directly with the applied stress, and direction dependent, so that compressive and tensile stresses will generate electric fields and hence voltages of opposite polarity. It is beyond the scope of this study provide an exhaustive description of the phenomenon and of the changes that have been developed to optimize the electrical performance and mechanical specifications, interesting discussion can be found in [22].

In this study the energy harvester consists of a piezoelectric film on an epoxy cantilever sandwiched between electrodes that are used to collect the generated power. A water drop falls on the structure and it creates an impulsive force that brings the internal lattice structure of the piezoelectric element to deform, causing the loss of simmetry, and therefore to the generation of small dipoles, which global effect is an impulsive voltage on electrodes. Mechanical vibrations follow the impact, stress is induced within the material, thus giving rise to an electrical source. A sheet of piezoelectric material has some limitations in the mechanical-electrical transduction for low-frequency signals, since the effects of the induced electric field, generated in the hitted region, are mitigated by the surrounding areas, and for large sheets effects are tenuous.

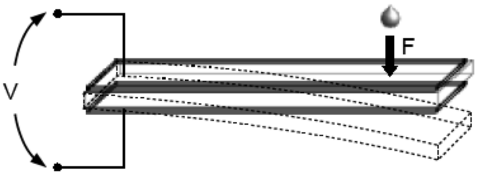

Fig. 1. Schematic of the cantilever under the piezoelectric effect.

The behavior of generated pulses depends on the state of locking of the piezoelectric film: if it is bound by both ends, or only one. In this study only the response of the model locked by one end is evaluated.

Different studies in the literature show encouraging results with regard to the generation of electricity from water droplets [14-16]. The piezoelectric transducers can reach tens of volts, but this result does not yet allow to attribute to them the character of power generators. The water drops continuity in the same place is very variable: there may be intervals of seconds (small rainfall) or fractions of seconds (downpour). Different performances due to variable drops dimensions (mass) and impact point make it hard to model the phenomenon. The voltage has a peak waveform, not a continuous voltage, so an equivalent average voltage has to be defined. For a power system the equivalent average current can be obtained by using a bridge rectifier and a smoothing capacity; for the theoretical model initially this approach has been not considered.

To evaluate the power output of a piezoelectric transducer it is necessary to define a range of possible stresses. The single drop of water can have a diameter that varies between 0.2 to 6 mm. Considering a cruise speed on impact of approximately 2 m/s for the small drop and 9 m/s for the largest, it is possible to estimate the energy input: $E_{min} = 3.1 \mu J$, $E_{max} = 0.063$ J. Also considering the interval of two seconds to have a successive drop, the power is: $P_{min} = 1.5 \mu W$, $P_{max} = 0.031 W$.

The energy input is little, so no comparison can be made with a traditional photovoltaic system.

The harvestable power, however, is affected by several factors. The drop, while centering fully the piezoelectric film, is not able to transfer maximum energy as it is subject to the phenomenon of splashing: the collision is not complete since the main drop is separated itself into small drops leaving the impact surface. It must therefore associate an efficiency of a collision. In the same way we should introduce a performance of the electrical-mechanical system. The drop stresses the piezoelectric according to the 31 mode and not all the energy is converted into charges on the plates of the transducer. Finally an electrical performance coefficient is to be introduced to take into account the losses of the rectifying bridge. The output power is given by:

$$P_{out} = \eta_{collision} \cdot \eta_{piezo} \cdot \eta_{rect} \cdot P_{max}. \qquad (1)$$

The output power is certainly reduced, then the objective is to maximize it.

The transducers on which the experiments were is the MEAS LDT1-028K [41]. The Meas PVDF is modificable, can be cutted in order to obtain particular shapes

Fig.2. Meas LDT1-028k polyvinylidene difluoride (PVDF) transducer.

III. CANTILEVER MODEL

In order to achieve early information on the generable power, an equivalent model has been studied. In figure 3 is reported the electro-mechanical scheme presented in [28]. The mechanical and electrical part are connected via a particular transformer, which as shown in [42] is far from usual electric transformer since current transformer ratio is not the reciprocal of voltage ratio. In the mechanical scheme the stress σ has the role of voltage; first derivative of strain, $\dot{S}$, the one of current. On the equivalent inductance L_m the applied voltage is related to the second derivative of strain, on the equivalent resistance R_m voltage is related to the first derivative and on the capacitance C_m directly to the strain. The derivative is related to the longitudinal axis of the harvester, referred as axis1, not to time. Impact and following vibration are related to axis 3.

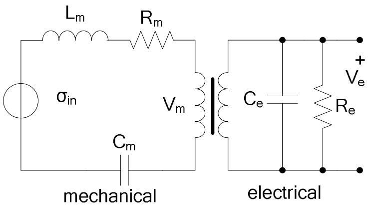

Fig.3. Equivalent electro-mechanical scheme.

For a mode 31 the principal mechanical and electric relations are:

$$\begin{aligned} S_1 &= s_{11}\sigma + d_{31}E_3; \\ D_3 &= d_{31}\sigma + \varepsilon E_3, \end{aligned} \tag{2}$$

with S strain, s compliance coefficient, σ stress, d piezoelectric strain coefficient, E electric field, D displacement field, ε permittivity. In the mechanical part the inductor L_m represents the equivalent mass and the inertia of the vibrating mass, R_m represents the mechanical losses, C_m represents the mechanical stiffness, stress generator σ_{in} is due to external mechanical vibration, the equivalent transformer relates the physical quantities with those electrical [28]. In the electrical part C_e represents the capacitance of the piezoelectric element, R_e an external load and V_e is the voltage across the piezoelectric transducer. Electric and mechanical parameters depend on the shape and the vibration mode of the piezoelectric transducer. By applying the equivalent Kirchhoff's rule on first loop:

$$\sigma_{in} - L_m\ddot{S} - R_m\dot{S} - S/C_m = V_m, \tag{3}$$

the equivalent transformer constitutive equation are:

$$\begin{aligned} V_m &= n_v V_e, \\ I_m &= \frac{1}{n_i} I_e. \end{aligned} \tag{4}$$

The equivalent inductance L_m is due to the geometrical configuration of the system, one edge of the cantilever is fixed, the free other is hitted by the mass of the drop of water, the inertia moment of the mass is evaluated [28]:

$$J = 2\left[\frac{wt_{mylar}^3}{12} + wt_{mylar}b^2\right] + \frac{wt_{piezo}^3}{12}, \tag{5}$$

with b distance between middle points of layers as shown in figure 4.

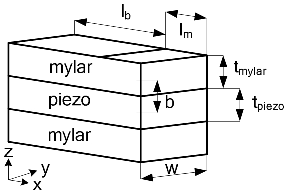

Fig. 4. Layer of the PVDF cantilever.

The average stress in the beam is:

$$\sigma_{in} = \frac{1}{l_b}\int_0^{l_b} \frac{M(x)b}{J}dx, \tag{6}$$

where

$$M(x) = F_{in}(l_b + l_m/2 - x), \tag{7}$$

with l_b length of cantilever, F force exerted by the drop.

K_1 is the geometrical coefficient which relates stress and external force:

$$\sigma_{in} = K_1 F_{in}. \tag{8}$$

During the vibrations K_1 relates also the stress due to the mass of water attached to the cantilever:

$$\sigma_L = K_1 F_m, \tag{9}$$

and in similar way it is related to the second derivative of the strain by:

$$\sigma_L = K_1 K_2 m\ddot{S}, \tag{10}$$

with m mass of water and K_2 geometrical coefficient.

The equivalent inductance and resistance are :

$$L_m = K_1K_2\, m,\quad R_m = K_1K_2\, b_m \tag{11}$$

with damping factor $b_m = \sqrt{\frac{K}{m}}\bigg/\frac{m}{Q}$, $K = 1/s_{11}$ Young's module and Q =10.

The equivalent capacitance relates strain with stress by using the compliance constant s_{11}:

$$\sigma_C = \frac{S}{s_{11}} = \frac{1}{C_m}\int \dot{S}dx. \tag{12}$$

In order to evaluate the voltage ratio n_v a strein zero configuration has been taken into account:

$$0 = s_{11}\sigma_T + d_{31}E_3, \tag{13}$$

electric field is related to voltage:

$$\sigma_T = -\frac{d_{31}}{s_{11}}\int E_3 dz = -\frac{d_{31}}{s_{11}}\frac{V_e}{t_{piezo}}, \tag{14}$$

$$n_v = -\frac{d_{31}}{s_{11} t_{piezo}}. \tag{15}$$

The electri current is:

$$i = \frac{V_e}{R} + C_e \dot{V}\,, \tag{16}$$

with $C_e = \varepsilon \frac{w l_b}{t_{piezo}}$. (17)

Without considering an external electric field:

$$D = \frac{d_{31}}{s_{11}} S\,, \tag{18}$$

the charge on the electrodes is:

$$q = w l_b D = w l_b \frac{d_{31}}{s_{11}} S\,, \tag{19}$$

current and current ratio are:

$$i = w l_b \frac{d_{31}}{s_{11}} \dot{S} = \frac{1}{n_i} \dot{S}\,. \tag{20}$$

The characterization has been made for an one-edge fixed cantilever but in a similar way the two-edge can be studied.

TRANSFER FUNCTION

Mechanical and electrical equations are:

$$L_m \ddot{S} + R_m \dot{S} + S/C_m = \sigma_{in} + V_m\,, \tag{21}$$

$$w l_b \frac{d_{31}}{s_{11}} \dot{S} = \frac{V_e}{R} + C_e \dot{V}\,, \tag{22}$$

by operating the Laplace transform:

$$S\left(s^2 + \frac{b_m}{m} s + \frac{1}{m K_1 K_2 K}\right) = \frac{\sigma_{in}}{K_1 K_2 m} + \frac{d_{31} K}{t_{piezo} m K_1 K_2} \tag{23}$$

$$S = \frac{\varepsilon}{t_{piezo} d_{31} K s}\left(s + \frac{1}{R_e C_e}\right) V\,. \tag{24}$$

Voltage transfer function is:

$$V = \frac{A_1 s}{s^3 + B_2 s^2 + B_1 s + B_0} \tag{25}$$

with

$$A_1 = \frac{t_{piezo} d_{31} K \sigma_{in}}{\varepsilon m K_1 K_2} \tag{26}$$

$$B_2 = \frac{b_m}{m} + \frac{1}{R_e C_e}\,, \tag{27}$$

$$B_1 = \frac{1}{m K_1 K_2 K} + \frac{b_m}{m} - \frac{d_{31}^2 K^2}{\varepsilon m K_1 K_2}\,, \tag{28}$$

$$B_0 = \frac{1}{R_e C_e m K_1 K_2 K}. \tag{29}$$

In figure 5 the magnitude of Bode diagram is traced; the maximum is located for the ωn = 260 rad/s. Such behavior is principally due to mechanical properties of the cantilever, it is an average profile since it is been made taking into account the resitance only of the obsilloscope (1 MΩ).

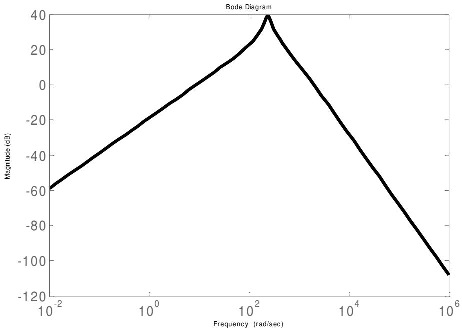

Fig. 5. Bode's diagram of the voltage transfer function.

IV. EXPERIMENTAL STUDY

In order to perform the verification of the transfer function, an indoor experiment to simulate the fall of rain on the piezoelectric material has been conducted. The experiment reconstructs the falling of drops of water on the cantilever, then the output voltage is recorded and finally it is compared with the performance obtained through the model. To simulate the fall of rain, however, was used a pipette, which allows to create artificially a drop of calibrated water, with a default speed due to the height of fall, figure 6. In the first place, it was necessary to fix the piezoelectric plate to a plane through a vise, in order to make stable the structure on one side and leave it completely free at the other, and this in order to keep intact the oscillatory properties of the material and therefore to reproduce the behavior of a cantilever beam. Furthermore, to make appropriate measures, the connectors of the lamina have been linked to the probe of an oscilloscope Lecroy model LT342L.

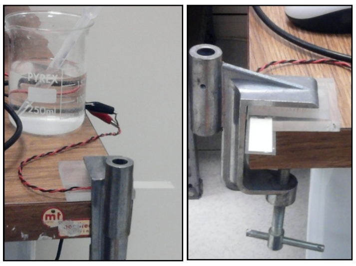

Fig. 6. Pipette, cantilever and vise.

The pipette consists of a cylindrical capillary with thick walls, the end of which is cut along a section, figure 7, where the drops are formed. In particular, there is a linking relationship between the radius of the droplet and that of the capillary:

$$R_{drop} = \left(\frac{3R_{capillary}\gamma}{2g\rho} \right)^{\frac{1}{3}} \tag{30}$$

where ρ is the surface tension of water, γ is the density of water and g is the gravity acceleration.

Fig. 7. Schematization of the release stages of the drop from the pipette

The use of the capillary for the creation of the droplet has a limit which concerns the movement of the liquid through the capillary. The process of ejection of the droplet must be relatively slow, in order to maintain a certain condition of static equilibrium, and to create drops similar to the ones of rain.

The first experiment was conducted at a height of 80 cm. The oscilloscope is set to 2V/division in order to obtain a more accurate measurement, the waveform of the generated voltage is shown in figure 8. As a pulse stress the system, the system itself responds to the frequency that maximizes the output. A maximum of 6 V has been reached, this is due to the precision of fall in the edge area of the cantilever, to the use of a very large drop, to the absence of the phenomenon of splashing.

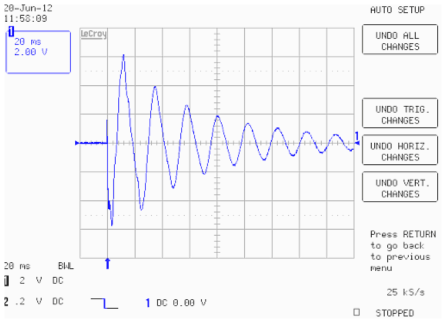

Fig. 8. Time profile of the recorded voltage.

V. VALIDATION OF THE MODEL

The response of the model can be performed by the SIMULINK program, in which a simple block diagram has been developed, figure 9.

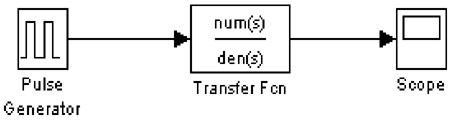

Fig. 9. Simulink model of the piezoelectric system.

The stress due to the water drop can be simulated by an impulsive force. A function similar to the delta of Dirac has been considered in the study. The pulse is defined as the limit for Δ that tends to zero of the rectangular function with height 1/ Δ and amplitude Δ, such function can have an infinite value for $t=t_0$ and outside the interval $[t_0, t_0+\Delta]$ the value is zero. Figure 10 shows the time profile of the pulse.

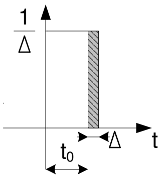

Fig. 10. Time-profile of the stress.

By considering an observation time equal to 10 s, the pulse generator has been considered as not ideal, and the impact of the drop on the piezoelectric has been set equal to 0.08% of the time interval. The mass is 0.12 g, final velocity is 1.24 m/s, force is 0.77 N. Figure 11. shows the comparison between the recorded voltage and the simulated one.

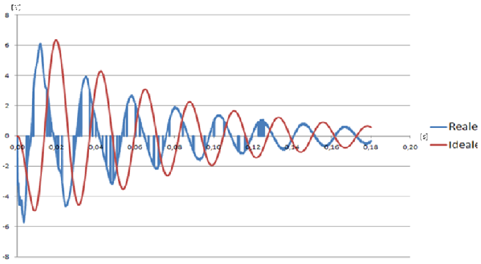

Fig.11. Comparison between the time profiles of recorded and simulated voltage.

It can be seen that oscillations in the simulated system are very similar to those recorded. Furthermore, the voltage values obtained are similar. In laboratory different experiments with varying height of fall of the drop, were performed. These experiments have shown that with increasing height there is an increase in the maximum value of the voltage produced by the drop, keeping constant its geometrical dimensions. However, it has been found that as the speed of fall increases, the splash phenomenon occurs, and a loss of mechanical energy causes a divergence of the theoretical results compared to experimental ones.

VI. CONCLUSIONS

This paper reports a detailed model of a piezoelectric harvester of rainfall energy. The model has been validated with data obtained from laboratory experiments. The time profiles of the simulated model and the experimental system have shown similar oscillations and similar peak values.

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