Pedestrian crossing system for the mechanical energy harvesting using piezoelectric materials

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Abstract: In recent years, researchers have been developing solutions to reduce our energy consumption by optimizing existing systems in different ways. Indeed, it is not enough just to create or use renewable energies but we must also not waste the available energy. This and systems are developed to recover unused energy of human body movement, which will be used to power either the equipment itself or another.

This paper proposes a pressure-type generator that collects human mechanical energy by stepping, a prototype is already designed and manufactured. The average output voltage can reach to 20.9 V by step for F =100N, and finally, we did a series of tests to prove that the device can have great power output performance in the low frequency environment of the human foot movement.

1-Introduction

The global increase of the word population, and the development of various electronic devices, human life becomes more and more inseparable from electrical energy [1-4]. The world’s energy demand is expected to reach 18 billion tonne oil equivalents (t.o.e.) by 2035 under current policies. (Energy harvesting from human motion: materials and techniques) which has forced the scientific research community to look for other sources of energy, especially renewable ones, namely, solar energy, wind energy, thermal energy, piezoelectric [5-8].

In this paper, we will be interested to the energy harvested by the piezoelectric materials, because of its high electrical conversion coefficient and no external power supply being required, beside, vibration energy can be harvested from many sources around us, such, roads, railways, buildings, and biological system movements, without any production of pollution. (Optimization design and experimental investigation of piezoelectric energy harvesting devices for pavement [3].

Recently, a new renewable energies has been under studies, kinetic energy from human body movements. This source of energy come from fact that human body offers a number of exploitable movements to generate energy : bending of legs,3 oscillation of the arms,4 breathing, … (Energy harvesting from human motion: materials and techniques), this idea of harvesting the energy of the human’s body motion had been encouraged by the amount of amount of generated energy when human hell falls to the ground, which is about 67 W for a 68kg person [9-15].
Encourage by several projects in this direction [16-19], our work comes to enrich the data by the comparison of use of many piezoelectric materials, also to try to have more performed system by the optimization in his parameters, in order to increase the harvested energy.

2- Pedestrian crossing system description

The movement of the human is considered periodic because, the left leg and the right leg alternate, and the action of “touching the ground-supporting-lifting the leg-swinging-touching the ground” is repeated regularly with a certain cycle. The resulting force of pressure on the earth is estimated between 2-3 times the weight of the human body [20, 21].

![Figure 1: Schema of the harvester system.](image)

The harvester system (figure 1) has as objective, use of the piezoelectric effect in order to convert the mechanical energy of the human being that it is to walk, run or jump in exploitable electric energy, this conversion will be through the following elements of the system:

- Six piezoelectric patches.
- Two centered springs of length 12cm x outside diameter of 9.1cm x inside diameter 8.8cm.
- Eight substrate springs, more rigid than the other two and must not vibrate with the same dimensions but with a length of 14 cm.
- Three plates: - A plate above 35 cm wide, 55 cm long and 4 mm thick on which the materials have been glued. - One below dimension 40 cm x 65 cm x 1.5 cm on which all the springs are fixed. - A plate in the middle of dimension 22.5 cm x 32.5 cm x 2 mm attached to the centered springs. The upper plate adheres to the top of the system and is connected to 8 springs. These springs remain in their original form when the system is not deformed.

In order to design the energy harvesting system using load zirconate titanate (PZT) patches. The patches are manufactured by APC International limited, USA [12]. The PZT-5H disc was shown in figure 2.
The material used in our work is PZT. This smart ceramic have a high piezoelectric coefficient [22-24]. In order to investigate the feasibility of PZT for energy harvesting application, the electromechanical proprieties as shown in Table 1.

Table 1. Electromechanical properties of the piezoelectric material.

| Material properties                  | Value        |
|--------------------------------------|--------------|
| Material type                        | PZT-5H       |
| Piezoelectric constant $d_{33}$ (pC/N) | 630          |
| Relative dielectric constant $\varepsilon$ (SI) | 3300         |
| Young’s modulus (N/m²)               | $51 \times 10^9$ |
| Density ($10^3$ Kg/m³)               | 7.6          |
| Thickness (µm)                       | 113          |

Figure 3 shows the system compositions relatively inexpensive and is easily scalable in size and have a capacity to generate from milli-watts to many watts depending on system size and human flow. The prototype of mass springs system has been manufactured to verify the prediction model, design, analysis, and resulting performance.
During deformation, the moment the foot passes over the system, the one above will strike the springs compress then the plate in the middle. After the passenger crosses the system, the plate and the outer springs return to their normal state thanks to their rigidity. Since the part of the mechanical energy generated by the passing passenger is stored in the two centered springs, the springs release this stored energy in order to bring about a back and forth movement of the plate in a repetitive manner until the springs return to their original shape, and these vibrations cause beats between the two plates. Therefore, by using the springs, the vibration time is extended which helps us to harvest more energy. The spring characteristics as shown in Table 2.

| Table 2. Characteristics of the springs. |
|----------------------------------------|
| Spring properties | Value  |
| Spring stiffness K (N/m) | 72     |
| Spring high L (m) | 0.3    |
| Average diameter D (m) | 0.143  |
| Number of useful turns n (SI) | 7      |

3- Theoretical model of power harvested by piezoelectric materials

For simplicity, in all calculations only a single piezoelectric film energy harvester is considered. Based on the potential thermodynamics and energy exchange principles, the piezoelectric phenomenon can be formulated with the following equations (1) [25]:

\[ S = s^E \cdot T + d \cdot E \] (1)

\[ D = d_e \cdot T + e^T \cdot E \]

S, T, D, E, \( s^E \), \( d_e \), and \( d \) are respectively strain, stress, electric displacement and electric field, the dielectric permittivity, the piezoelectric coefficient, and the compliance.

By developing these equations, thus taking into consideration the one below [26, 27]:

\[ I = A \cdot \frac{\partial \rho}{\partial t} \] (2)
We can deduce the theoretical expression of the current I generated by a piezoelectric material which feeds a load R is:

\[ I = \frac{j d_{33} \omega^2 A S_{33}}{1 + j \left( \epsilon_{33} \frac{d_{33}^2}{\epsilon_{33}} \right) R \omega A} \]  

(3)

With \( d_{33}, \omega, A \) and \( \epsilon_{33} \) are respectively piezoelectric coefficient (C/N), pulsation (rad/s), active surface \((m^2)\) and permittivity (F/m).

By using this expression and bringing it into: \( P = R I^2 \), and as the ratio \( \frac{d^2}{s_{33}} \) is negligible compared to the permittivity \( \epsilon_{33} \), the expression of the harvested power becomes :

\[ P = \frac{R}{2} \left[ \frac{d_{33} \omega^2 A S_{33}}{1 + \left( \epsilon_{33} \frac{d_{33}^2}{\epsilon_{33}} \right) R \omega A} \right]^2 \]  

(4)

The simulation of the equation (4), will allow us to optimize at the level of several parameters, choice of springs, frequency, ... but the most important is the choice of materials to be used, this is why we present you below the curves of the simulation of this harvested power as a function of the resistance for several materials.

4-Experimental results of energy harvesting system:

The energy harvesting system contained the piezoelectric material, mechanism and electric circuits. The external circuit was integrated into the system to optimize the harvested voltage output. To obtain the optimum harvesting energy from the harvester energy system, the value of external load resistance was chosen as equal to the internal resistors of the material. In this section, the prototype was tested as shown in Figure 4. The output voltage of the energy harvester system was recorded by the oscilloscope, Gw INSTEK GDS-2074A.

![Figure 4: Pedestrian crossing system for the harvester during applied force.](image)

To perform the energy harvesting parameters, figure 5 show the evolution of the harvested electrical voltage at the output as a function of the applied force during the experience.
Figure 5: The harvested electrical voltage at the output as a function of the force.

Figure 5 shows the variation of the harvested voltage as a function of time for a compression force between 0 and 100 N. During excitation the maximum output voltage reaches a value of the order of 20.9 V. The experimental results show that the harvested voltage increases while increasing the force during human passing. Figure 6a and 6b show the power harvested by using PZT as a function of resistance and frequency at 100N.

Figure 6: The power harvested by using PZT as a function of resistance and frequency at 100N.

The theoretical model is presented for the sake of comparison with the experimental results obtained with the spring’s mass prototype. The power harvested by the system increased significantly until a maximal power density that matches with an optimal load resistance, after that the power decreased. On the other hand, the harvested power increases linearly with frequency but becomes constant at higher frequencies.
The maximum power harvested is 3.08 mW achieved with \( F = 100 \) N of force at 9 Hz with the optimal resistance 0.85 G\( \Omega \). Relating to the theoretical model and the experience, an increase in force and frequency, the rest of electromechanical proprieties remains constant should yield an increase in the materials voltage and therefore an increase in the power harvested.

The results obtained in this work contribute to demonstrate the ability of the Pedestrian Crossing System to improve the conversion efficiency of the energy produced during the human passage on pedestrian crossing into electrical energy for the development of micro generators.

5-Conclusion:

The aim of this paper is established a complete study of an energy harvesting system based on the use of piezoelectric materials and the Pedestrian Crossing System. The authors conclude that the combination of the two parameters (the force amplitude and the operating frequency) has a strong influence on the electrical conversion of piezoelectric ceramics for mechanical energy harvesting. The PZT material was used to harvest the mechanical energy by the piezoelectric effect. This element needed mechanical vibrations to produce energy, so we proposed a new system to harvest energy by using the Pedestrian Crossing System. According to our experimental results, we have found that the maximum of the harvested voltage could reach 20.9 V with applied force value is 100N. This article gives the experimental results that agree quite well with the theoretical predictions. This value demonstrated the excellent potential of this system for mechanical energy harvesting. It must be mentioned that this power value can be improved, for example, by using more ceramic buzzers or using another type of springs having lower spring stiffness in order to improve and generate more vibration fluctuations.
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