ENERGY HARVESTING: AN INTERESTING TOPIC FOR EDUCATION PROGRAMS IN ENGINEERING SPECIALITIES

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Анотація

Наразі можливість заміни батарей, як джерела живлення, або для досягнення кращого обслуговування існуючих чи зменшення їх розмірів, є дуже актуалною і може бути реалізованою за допомогою альтернативних, так званих Енерго-Збиральних (ЕЗ) методів, які полягають в отриманні енергії з навколишнього середовища або відновлення і зберігання енергії, що виробляється людським організмом в повсякденній діяльності. Проте, це вимагає спеціальних технологій і матеріалів та, як правило, мультидисциплінарної команди. З цієї причини, включення теми про енерго-збиральні методи та технології в освітні програми інженерних спеціальностей в технічних вузах має велике значення.

У цій статті ми наведемо деякі результати міждисциплінарного співробітництва у цьому напрямі, реалізованого на факультеті науки і техніки в Нова Лісабонського університету. Приведені результати експериментів по ЕЗ, проведені, в основному, з використанням п'єзоелектричного ефекту, для того, щоб розрахунку потужності, яка може бути отримана з рухів грудної клітки при диханні та з ніг при ходьбі.

Abstract

Nowadays some possible alternative methods to replace the batteries as power source, or to achieve better maintenance of existing (or smaller) batteries, are the so called Energy Harvesting (EH) methods, i.e. to obtain energy from the environment or recover and store energy generated by the human body in its usual activities. However, this requires specific technology and materials and usually a multidisciplinary team. For this reason, inclusion a topic on energy harvesting in educational programs of several engineering specialties at technical universities is of great importance.

In this paper we present some results from interdisciplinary collaboration at Faculty of Science and Technology at Nova University of Lisbon on the energy harvesting. Experiments were performed in order to calculate the power that could be generated from the chest movements during breathing and from the feet during walking, etc. For the experiments, mostly piezoelectric effect was explored.

Introduction

Currently, the energy supply for the portable and autonomous equipment comes almost exclusively from the battery. Unfortunately the maintenance of those sources of energy brings disadvantages due to the need for frequent recharging or replacement. In many cases the battery brings extra weight and volume to the electronic equipment, limiting its autonomy. As an example, the medical equipment has high costs, both because of the sophisticated technology and because of the maintenance. The later factor is critical, mainly due to the frequent need for replacement (or recharging) of batteries. The electronic devices implanted in the human body are examples for this constant maintenance, requiring sophisticated medical operations too. Unfortunately for the patient, the replacement of the batteries is absolutely necessary, due to their short lifetime or their short recharging cycles. The chemistry research is pushing the lifetime of the batteries to higher values but it means also higher technology, higher costs and more pollution of the environment. There must be some other way to reduce the need for batteries and battery maintenance, or if possible, to make unnecessary at all, the use of batteries. Their role as energy storage elements is very well played by the supercapacitors, especially for short time intervals.

This article describes how the energy is harvested from the environment or from the human body. The harvested energy is either directly used to supply an electronic consumer, or is stored as said before. The modern electronic technology is so efficient that even lowest amounts of energy harvested from the environment are enough for the proper functioning of certain systems, e.g. MEMS systems

Environment Energy Sources

There are several techniques to obtain energy from the environment, either for storage or for direct supplying the electronic consumers. The energy harvesting device generates electrical energy from the environment applying different conversion methods. In an early work, S. W. Angrist calls this conversion a "Direct Energy Conversion" [1]. Presently the converters are carefully designed for each different source of environmental power. They are expected to have high conversion efficiency, mostly due to the lowest values of energy collected from the environment. Kinetic, thermal and electromagnetic energy are some of the possible examples, presented hereafter.

A. Kinetic Energy

This source of energy is one of the most readily available to be converted from the environment, and from the human body. The mechanical deformation of a certain structure and the displacement of a mass are the basic principles of the kinetic energy conversion. Basically, three methods could be applied to convert the mechanical deformations and movements into electrical energy: piezoelectric, electrostatic and induction (electrodynamic or electromagnetic).

i. Piezoelectric Generator

The piezoelectric effect characterizes a class of certain crystalline structures that become electrically polarized when subjected to pressure. The reverse effect is also known, i.e. when electric field is applied to the crystal, its dimensions change according to the applied electric field (inverse piezoelectric effect). Initially, quartz was the most well known piezoelectric material, but now mostly ceramic materials based in metal-oxide are used due to the lower price.

The piezoelectric effect is often applied nowadays to convert the mechanical into electrical energy. In Fig. 1 a piezoelectric generator is shown that converts the force applied by user jumps, in electrical energy.

The generator presented in Fig. 1 contains four piezoelectric transducers (tapes), producing electric charge when subjected to compression. The generated voltage may be high, but the value of the produced current is (unfortunately) low. Some piezoelectric systems tend to achieve better performance through applying higher frequencies of mechanical vibrations. An early study based on a MEMS harvester system [2] presents a (high frequency) vibrating cantilever structure that is tuned electronically by capacitors in order to achieve higher mechanical frequency of resonance.

Fig. 1 Piezoelectric generator

ii. Electrostatic Generator

The electrostatic harvester (generator) is based on two charged conductors that are in relative motion (oscillation), varying their distance, i.e. forming a variable charged capacitor. The energy stored in the capacitor varies, thus providing a mechanism for mechanical to electrical energy conversion. One of the disadvantages of this converter is the requirement for an external voltage supply, used to charge the capacitor with an initial voltage, allowing the conversion process to start. The easier integration in MEMS is one of the significant advantages for this type of converters (harvesters). Figure 2 presents an electrostatic generator [3], able to produce 100μW/cm^3.

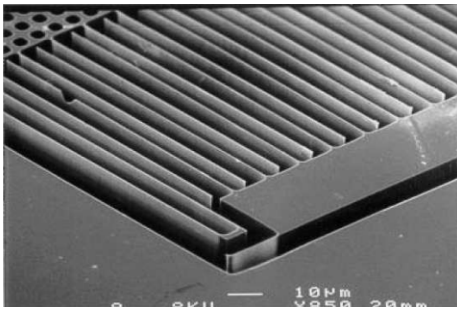

Fig. 2 Electrostatic generator

iii. Electromagnetic Generator

The electromagnetic generator is based on Faraday´s law, i.e. inducing an electric field by variation of the magnetic flux. Moving a magnet whose flux is linked with a fixed coil is a known technique to perform an electromagnetic generator. Moving a coil with in the vicinity of a fixed magnet is another way to achieve the same results. An early work which employs this principle is the Seiko Kinetic watch from SEIKO Watch Corporation (Fig. 3).

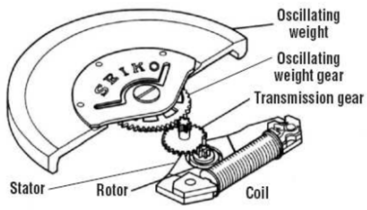

Fig. 3 Seiko Watch using an electromagnetic generator

B. Electromagnetic Field Energy

The electrodynamic principle of operation is rarely applied as it requires an electric current to be the source of magnetic flux.

The earliest known and used energy source in the technology history is the solar radiation. Different photovoltaic systems allow energy conversion in a widest range, from milliwatts to megawatts. The solar energy as a power source is used often in portable devices due to its simple implementation and integration. As an example, the micro PV cells, produced by the Sandia National Laboratory in Albuquerque, USA, are extremely small but can be used on clothing like military uniforms, allowing soldiers to recharge their electric equipment while walking. This is completely possible because of the high energy levels that the sunlight sends to the Earth. E.g., the yearly outdoor irradiance in Tanzania is 2026kWh/m^2, with the indoor irradiance presenting values around 3.5 to 20W/m^2 [4]. In Europe, at an average surface irradiation of 1000W/m^2 using solar cells with 100 cm^2 and 10% of efficiency generates 1W of power, which is completely sufficient for many electronic devices.

C. Thermal Energy

Thermal energy is a ubiquitous source that can be easily or not easily harvested from the environment and also from the human bodies. Thermal harvesters are usually based on thermal gradients and this is not so easy to apply to the human activities. Nevertheless there are devices applied on persons, animals, etc. For example, the same SEIKO Corporation has a thermal wrist watch.

Human Energy Sources

The human body can be considered as a storehouse of energy. All the movements dissipate energy, which may be harvested and stored. The actively and passively dissipated energy during the simple human activities is given in the classical work of T. Starner and J. Paradiso [5].

A. Body Temperature

Thermal energy can be converted into electricity due to the difference between the ambient and body temperatures It is estimated that 14% of the human heat is lost through breathing by warming and humidification of the exhaled air. The great part of of the rest of the heat is lost through the skin [6]. The heat produced by the evaporation of sweat is estimated as 7%.

The Carnot efficiency limits the power to be recovered. Assuming a normal human body temperature (310K, 37°C), with an ambient temperature of 20°C, the Carnot efficiency gives:

$$\frac{T_{body}-T_{ambient}}{T_{body}} = \frac{(310K-293K)}{310K} = 5.5\% \quad (1)$$

This value decreases when ambient temperature increases. Considering the sleep task from table 1, a power of 81W is available, so using the Carnot method to calculate the recoverable energy leads to a value of 4.5W at 20°C. A typical model of a thermoelectric generator consists in a thermocouple containing n and p semiconductor types, electrically connected in series with a load and thermally in parallel. This generator (harvester) produces difference of potential and hence, an electric current proportional to the temperature gradient between hot and cold junctions. The principle of operation is the Peltier / Seebeck effect and requires a temperature gradient between the semiconductor junctions and the environment (the principle is similar to the metallic thermocouple sensor) [7].

B. Breath and Blood Pressure

Breathing and blood pressure are two other possible sources of energy. In exhalation, the aid of a mask with a turbine is used to convert the mechanic energy of the exhaled air into electricity. The mechanical power generated is approximately 1W [8]. Chest expansion during inspiration can be used as another method to harvest energy. This process may use the piezoelectric effect to convert the mechanical strain into electricity. The breathing is estimated to develop a mechanical power of 0.83W in each of the 10 breaths per minute. Blood pressure is presented as another method, developing mechanical power of 0.93W in each of the 60 beats per minute (of the flowing blood through the aorta). Movements of the upper and lower limbs (excluding walking) can also be used as energy sources.

Table 1. Generated power

Activity	Mechanical Power developed	Electrical Power generated	Energy available per movement
Blood Flow	0.93W	$0.37^{\leftarrow} W$	0.37J
Exhalation	1.00W	$0.40^{\rightarrow} W$	2.4J
Breath	0.83W	$0.091^{\uparrow} - 0.42^{\leftarrow} W$	0.5-2.5J
Upper limbs	3.00W	$0.33^{\uparrow} - 1.5^{\leftarrow}$W	1.5-6.7J
Fingers	6.9-19.00mW	$0.76^{\uparrow} - 2.1^{\uparrow} mW$	143-266uJ
Walk	67.00W	$5^{\uparrow} - 8.4^{\downarrow} W$	8.3-14.0J

The mechanical energy cannot be converted completely in electricity due to losses in harvesters and the other mechanisms. As a rule, the electronic devices must have extremely high efficiency both in energy conversion (harvesters) and energy consumption (the control circuits). Larger losses in the various components are translated into lower conversion efficiencies, as shown in Table 1. The data are presented considering the mechanical generator having 50% efficiency; the turbine + generator reaching 40% efficiency; the piezoelectric generator having 11% efficiency and the double (including mechanical to mechanical and other) conversion reaching 12.5% efficiency [8].

C. Walking

Walking is one of the daily activities that consumes more energy. Figure 4 presents a model that describes a human gait as an inverted pendulum [9]. In [6], an expression that relates the energy dissipated between each gait is presented:

$$E = E_{cini}(sin^2 2\alpha) \tag{2}$$

E_{cini} is the accumulated energy in the previous gait. It can be calculated as a gain due to exchanges between potential and kinetic energy of the previous gait:

$$E_{cini} = mgl(1 - cos\alpha) + \frac{1}{2}mv^2{}_{top} \tag{3}$$

In the previous expression, *l* defines the length of the leg, *m* the mass of the user and *g* the gravitational acceleration force. A dissipated energy of 47.24J is achieved if a person with 80kg and 1.2m of leg length walks at 1.3m/s and an angle of 20° between each gait. If each gait takes 0.6s, a power of 79W is dissipated over the shoes, bones and muscles.

D. Limbs Motion

Generators driven by application of forces [10] and driven by vibrations [11] are other typical generators. A shoe can be described as an example for the first ones. The force applied by the foot produces the mechanical stress, which a sole made of piezoelectric material is often used as harvesting mechanism that generates electric power, e.g. as in Fig. 5 (left view). The same figure shows also a purely mechanical harvesting by rotation of electric generator.

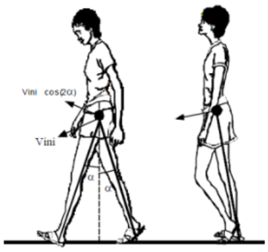

Fig. 4 Inverted pendulum model for human gait

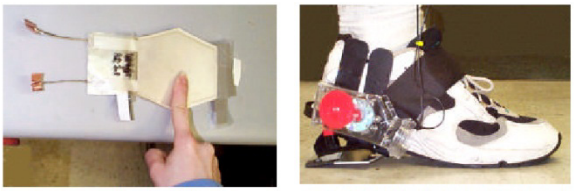

Fig. 5 PVDF Insole Stave and simple shoe-mounted rotary magnetic generator

Experimental Results: Power Extracted From Human Breath

Tests were performed in order to analyze the power generated by a piezoelectric tape attached to a band fixed around the chest of a person.

For measuring and recording, a factory made respiratory effort transducer SS5LB was connected to MP35 unit from Biopac, which has an internal microprocessor to control the data acquisition. The SS5LB transducer measures the respiratory effort and transmits the signal from the chest expansion and contraction to be recorded (Fig. 6). The transducer was applied to determine the depth of the breathing and to calculate the breathing rate. By this measurement it was possible to compare the normal breathing to the deeper one, and to observe the power generated by the harvesting piezoelectric tape (Fig.7).

Fig. 6 Respiratory effort transducer SS5LB and its location

The piezoelectric tape is a sensor composed by Macro Fibers (MFC) that offers high performance, durability and flexibility. It consists of rectangular piezoceramic rods (wires) sandwiched between layers of epoxy polymer, electrodes and polyimide film. The piezoelectric tape used in this work is the M-1700-P2 (170mm x 7mm), developed for NASA and commercialized by SmartMaterial Co. The piezoelectric tape presents a capacitance of 91nF, free strain of -670ppm and a blocking force of -42N.

Fig. **7**Piezoelectric tape,

The first step was to find the interrelation between the power consumed by the load resistor, attached to the piezoelectric harvester, and the chest expansion while breathing normally and deeply. The relation between the SS5LB sensor signal and the SS5LB extension is shown in Fig. 8.

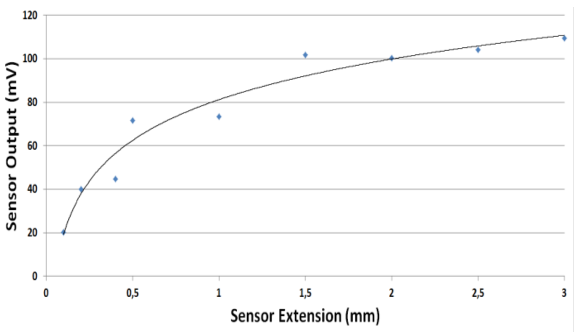

Fig. 8. Relation between SS5LB output and SS5LB extension

Considering that the maximum output of the SS5LB sensor is proportional to the maximum depth of breathing, a relation between the chest expansion (in mm) and the output signal is possible to be achieved for each individual person. This kind of calibration allows to find the relation between the chest expansion and sensor extension (in mm), useful for the proper construction of the harvesting piezoelectric tape.

The second step was aimed at finding the ideal load for the piezoelectric tape harvester. Figure 9 shows the continuous power absorbed in loads ranging from 1kΩ to 2MΩ.

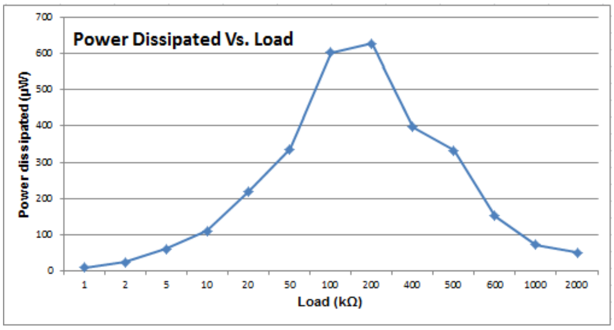

Fig. 9. Power produced by the piezoelectric tape generator

As it is seen, a load with a resistive value around 200kΩ will dissipate continuously 620µW. This load is used in the experiments to achieve a relation between the chest expansions vs. extracted power values.

The third step consists in finding the relation between the chest expansion, and the power delivered to the load (200kΩ). A person of 1.64m height and 60kg weight performed six normal breathings and six deep breathings, resulting in an SS5LB output signal given in figure 10:

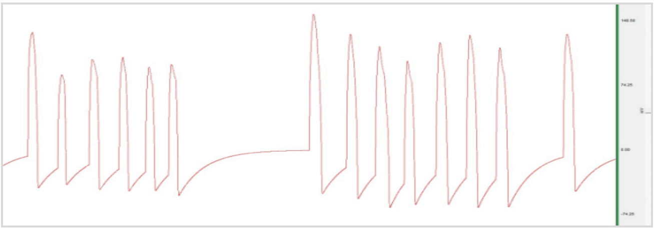

Fig. 10. SS5LB output signal

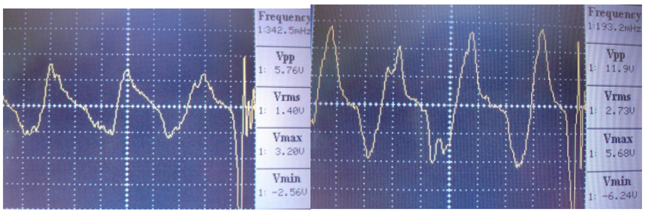

Fig. 11. Oscilloscope output signal

The first six signals in Fig. 10 are related to normal breathings, as the next six signals are related to deep breathings. As it is expected, the normal breathings give lower SS5LB output signals (peak to peak) than deep breathings. An oscilloscope was used to measure the AC voltage delivered to the load, resulting in signals presented in figure 11. The oscilloscope also calculates the rms voltage, allowing the calculation of the active power available at the (resistive) consumer. This power is given by equation 4, resulting in 9.8µW and 37µW for normal and deep breathing, respectively.

$$P = \frac{V_{RMS}^2}{R} \tag{4}$$

Previously, it was found a relation between the chest expansion in normal and deep breathings, resulting in an expansion between 2cm and 3.18cm while breathing normal, and an expansion between 3.54cm and 4.05cm while breathing deeply.

Conclusion

From the obtained experimental results and taking into consideration equation 4, it is possible to affirm that for a specific person, an expansion of the chest with 4cm can provide an average power of 37μW to any electronic sensor that presents ideal input impedance, around 200kΩ. Of course, a lot of work is necessary to achieve the adapting of the load to the piezoelectric harvester. By better adapted electronic circuits, the output power value can be improved. Another improvement must be obtained by the mechanical construction, enabling maximum compression in the piezoelectric tape, at minimum breathing effort, to get closer to the maximum possible values, as in Fig. 9.

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