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Comparison between piezoelectric and magnetic strategies for wearable energy harvesting

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Abstract. This paper introduces the design and fabrication of energy harvesters for the power generation from human body motion. Two alternative strategies are compared: piezoelectric and magnetic inductive. The generated energy is used to supply body sensors including accelerometers and temperature sensors and RF module. Two prototypes of the magnetic based generator and of the piezoelectric generator are built and tested with shaker at resonance condition and by dedicated bench reproducing joints rotation during walking. The experimental results show that the magnetic prototype can generate 0.7mW from human body motion, while the piezo harvester generates 0.22 and 0.33µW respectively for flexion and extension at angular velocity lower than 1rad/s and 45° amplitude.

1. Introduction

Many industrial and academic researches have been recently addressed to low power techniques for energy harvesting from the environment [1-3]. The available energy sources are light, wind, temperature gradients, radiofrequency waves and kinetic energy of sea waves, but in the last years other sources started to be exploited as mechanical vibrations of machines and human body motion. The small power amount obtained by harvesters is suitable for supplying electronics and portable devices with low consumption specifications, however these strategies allow reducing the number and size of batteries and eliminating cables. The first aspect has positive impacts on environment and economy due to pollution and costs related to batteries disposal; the second aspect is highly appreciated in the field of sensor networks where complicated cablings are often needed. Furthermore, energy harvesters allow supplying sensing devices in critical positions where accessibility is limited, for example in telemedicine applications and biological parameters monitoring. In the field of human body monitoring, the continuous monitoring of patients is feasible through miniaturized and wearable harvesters combined with miniaturized sensors integrated in the body without heavy and uncomfortable batteries for the power supply.

The contribution of this paper is in the field of energy harvesting from human body, which is characterized by additional design complications compared to other fields of kinetic energy harvesting, already discussed in the literature. The authors, in previous works, analyzed the performances of different energy harvesters: piezoelectric [4], magnetic inductive [5], electrostatic capacitive, and magnetically levitated [6]. Also they patented some dedicated devices [7-9]. The critical aspects of harvesting power from the motion of human body are discussed and some design strategies are proposed, with particular focus on two transduction strategies: magnetic inductive and piezoelectric. The design, prototyping and testing of two wearable energy harvesters for human body are introduced. The magnetic generator consists of a movable magnet able to oscillate in a polymeric guide between two fixed magnets situated at the ends of this guide that work as magnetic springs. This harvester has 25mm diameter and 60mm length. The magnetic field generated is used to produce electricity into a wire coil with 400 turns. The conditioning circuit for the electrical power management includes diode bridge, capacitor and battery. The piezoelectric generator is based on a composite transducer including piezoelectric fibers in polymeric matrix. This solution allows higher bending ratios of the transducer compared to traditional piezoelectric sheets and improve the device reliability. The two harvesters are tested on dedicated benches reproducing the body motion.

Finally, a small wireless sensing unit is connected to the generators and supplied with the power produced by the harvesters during the walking activity; the duty cycle of the system is then estimated.

2. Wearable harvesters design approach

The harvester design activity should be preceded by the analysis of vibrating excitation source. In general applications, as machines, vehicles or mechanical systems with variable operating regimes and velocities, the input force has random shape. In case of human body during walking or running, the excitation, although strongly irregular, is periodic because it is related to the alternate motion of limbs. For specific activities (e.g. walking at normal velocity), the frequency of the periodic excitation is almost constant and can be measured and predicted with statistical analyses (Fig. 1).

The next step is the evaluation of the average energy associated to the input signal; this calculation can be performed, for instance, by measuring the acceleration (or the overall acceleration range) in the position where the energy harvester should be attached. The acceleration allows estimating, at least roughly, the size and the mass of the generator and of its oscillating parts. In this preliminary design activity the goal is to provide the order of magnitude of masses and suspensions stiffness with reference to the response/excitation amplitude ratio.

Then, the analysis of frequency spectrum of excitation signal is needed to properly tune the dynamic response of the generator and to maximize its mechanical response (and the output power). The power spectral density (PSD) curve describes the energy distribution in the frequency domain and should be used for the fine dimensioning of the harvester and for its tuning through the modification of the mass and stiffness parameters previously defined only roughly. The dynamic parameters are finalized in detail at this stage and remain the same for the overall life of the wearable harvester.

The last important specification of the energy harvester is the bandwidth. Working as a mechanical filter, kinetic harvesters are excited dynamically only within specific frequency ranges. It is important that the harvester is able to capture a wide range of frequencies from the randomly shaped excitation source to improve its conversion efficiency. For this reason, wide band generators are more performing than narrow band generators: the firsts can catch the energy associated to large frequency ranges, the seconds can only catch the outer energy closely to their resonances. Some strategies to widen the bandwidth of harvesters have been discussed in the literature, such as modal coupling of multiple transducers, series coupling of multiple generators, and the use of bi-stable structures.

The harvester design and dimensioning must be supported by detailed information of the overall autonomous system, including the supplied devices, performances, sensors sampling rate, data transmission frequency, etc. For this reason, the definition of ‘self-powered system design’ is definitely better than ‘energy harvester design’. Although the typology of components included in the autonomous system may vary among the applications, usually the following functional blocks can be identified (Fig. 2): current rectifier, charge reservoir (storage battery), one or more sensing devices (sensors), and transceiver device. Very frequently the energy generated by the harvester is stored in the battery before to be used; this operation requires the preliminary conversion of the alternate current produced by the harvester in continuous current. The battery is necessary to provide continuous supply even in case of irregular power generation and to reach the prescribed energy threshold needed to supply the utilizer. The energy generated and stored in the battery is suitable for the supplying only over the minimum charge threshold; this lower level of the battery charge is imposed by the energetic demand of the utilizers. Similarly, the time of energy transfer from the battery to the utilizer is function of the energy consumed in the unit time. All the mentioned constraints are to be considered when the self-power system duty cycle is designed. Power management strategies for the reduction of energy consumption are welcome for the improved working of the system: activating the system only above given battery charge thresholds (triggering), designated components switch-off during given operations (e.g. the antenna during data measurement and processing) are some examples.

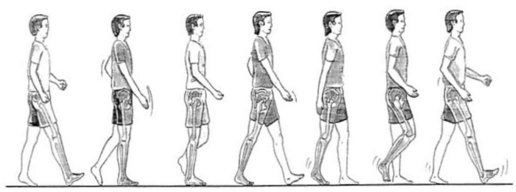

Figure 1. Kinematics of elbow and knee joints in walking activity [10].

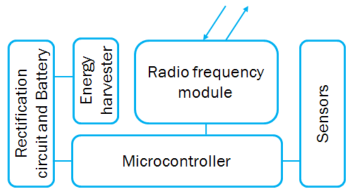

Figure 2. Typical architecture of self-powered sensing system.

3. Prototypes

3.1. Magnetic inductive generator

The magnetic inductive generator is based on the scheme of Fig. 3a, already described by the authors in [5]. The magnetic suspensions provide the mechanical stiffness, which is determined by the magnetic field associated to the magnets with opposite polarity; similarly, the electric current induced in the coil is proportional to the size of the oscillating magnets and to their relative velocity. The dimensioning of this harvester is significantly complicated by the strong electro-mechanical coupling among the components. It includes two fixed magnets (M1), the oscillating mass (M2) composed by three permanent magnets spaced with two teflon rings that moves in the polymeric guide, and the 400 turns coils (C1). The harvester in its final configuration is represented in Fig. 3b.

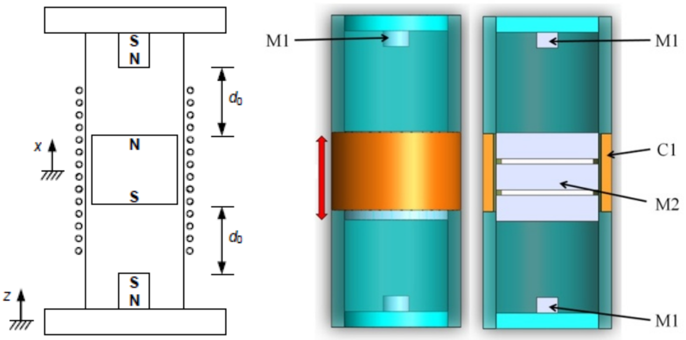

Figure 3a. Magnetic-inductive harvester scheme.

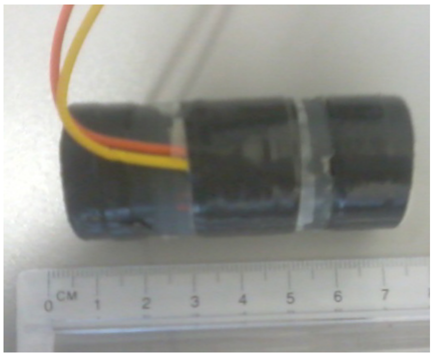

Figure 3b. Magnetic-inductive harvester prototype.

3.2. Piezoelectric generator

Differently from the first one, wearable piezoelectric harvesters are designed to be excited by the motion of joints and not necessary by vibrations [11]. The piezo transducer is embedded in clothes or other wearable fabrics and bended or extended by the motion of limbs. For the design, the detailed modeling of the joints is not needed because the transducer can be considered as adherent to the skin, similarly to clothes, and is not influenced by the motion of internal parts of the joints. Then, the only interesting parameters are the bending angles and velocity of joints. Traditional electro-mechanical transducers based on piezoelectric materials are usually rigid, heavy and brittle. These characteristics do not fit with the requirements of energy harvesting from human body motion where angular travels of joints are very large. Alternative materials with high conversion efficiency, good reliability and high flexibility are needed. This suggests moving to composite materials with polymeric matrix and piezoelectric fibers embedded. The technology called 'viscose suspension spinning process' (VSSP) allows producing fibers with diameters ranging from 10 to 250μm that possess all desirable properties of ceramic piezo materials (electrical, thermal, chemical), but that are not affected by their typical detrimental characteristics (brittleness, weight, low reliability). The samples used in this work (Advanced Cerametrics Inc.) have substrate in kapton and PZT-5A type fibers. Figure 4 reports the sample and one phase of testing on the dedicated test bench already described in [12].

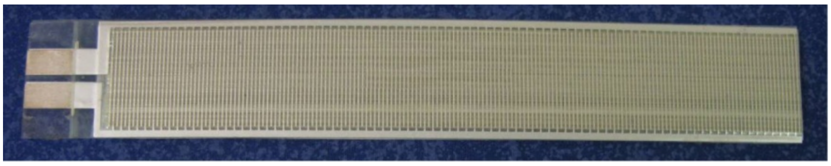

Figure 4a. Piezoelectric fiber-based transducer.

Figure 4b. Phase of testing.

4. Experimental results

The magnetic harvester is tested on an electromechanical shaker reproducing the dynamic excitation of the human body in walking activity (0.2g at 4Hz). The electric output power and current measured on the prototype are reported in Fig. 5. The piezoelectric harvester is tested on a dedicated test bench, designed to reproduce the motion of the human joints [12]; different bending angles and velocities are considered and some of the experimental results are reported in Fig. 6.

After the characterization, the harvesters performances are compared with the energetic requirements of simple MEMS sensors platform for human motion detection applied to garments (Atmel ATmega328 on Lilypad 328 Arduino) with three-axis accelerometer, temperature sensor and a RF module. For the magnetic generator, the output power is enough to supply a 1s sensing every 4.3 walking cycles and a 0.1s transmission every 20.0 cycles. This corresponds to 3.4 and 16.0m of walking distance respectively. For the piezoelectric harvester applied to four limbs of the body, the output power is enough to supply a 1s sensing every 234.4 walking cycles and a 0.1s transmission every 1092.5 cycles. This corresponds to 187.5 and 874.0m of walking distance respectively.

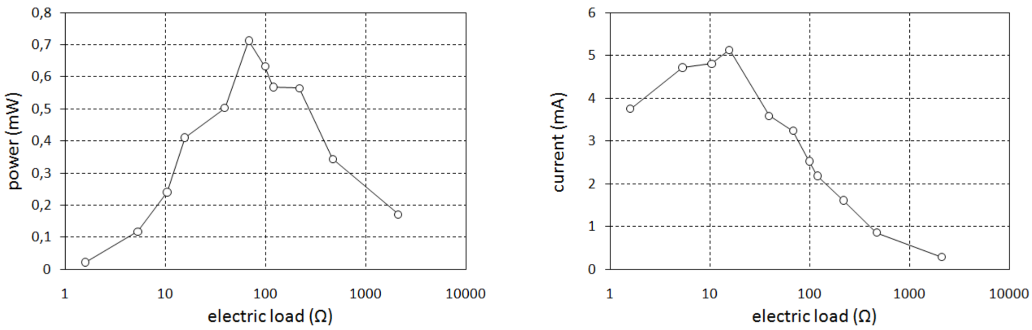

Figure 5. Experimental output power and current under 0.2g acceleration at resonance (4.1Hz) at variable electric loads for the magnetic-inductive generator.

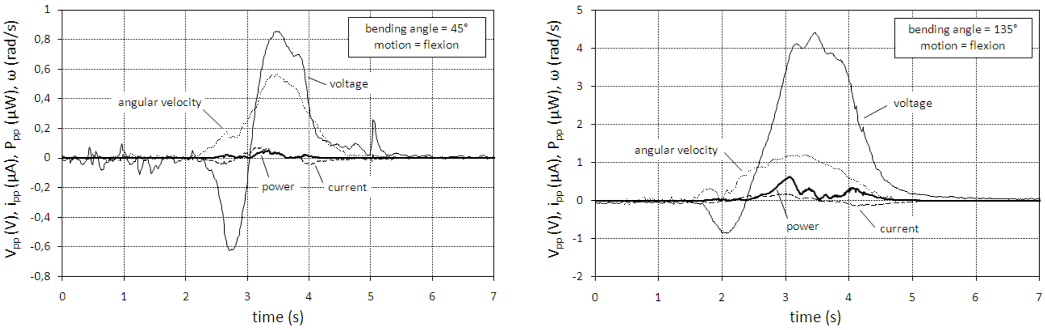

Figure 6. Experimental electric output of piezo harvester at 45° and 135° flexion angles.

5. Conclusions

The study revealed that magnetic inductive and piezoelectric transducers are suitable for harvesting energy from human body motion and supplying wearable sensors with reasonable duty cycles. The higher efficiency of magnetic generators is accompanied by higher masses and a movable part that may be felt as uncomfortable in some applications. Piezoelectric generators are completely embedded in clothes and do not impede motion of limbs, but their efficiency is quite lower as well as their power density compared to magnetic harvesters.

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