ANALYSIS OF ELECTRICAL GENERATOR FOR POWER HARVESTING FROM HUMAN MOVEMENTS

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Keywords: Eletromechanical generator, Human energy harvesting, Biomedical devices.

Abstract: In this paper various architectures of electromagnetic harvesting devices, realized in the Department of Information Engineering of the University of Brescia, is reported, estimating their usability for biomedical applications. Furthermore, this paper shows a first attempt of a new electromagnetic generator architecture. The proposed system is modelled and simulated showing promising results.

1 INTRODUCTION

Power harvesting modules are a viable solution to the problem of supplying autonomous systems reducing the problem of battery disposal and replacement. They can also improve the performances of wireless devices. The reduction of power consumption of electronic devices has made possible to supply them through the harvesting and subsequent conversion of energy that is present in different forms in the environment.

An interesting field where the energy harvesting could raise the performances of the devices is the biomedical sector. In this paper, we will show various architectures of electromagnetic harvesting devices proposed in literature, estimating their usability for biomedical applications. Afterwards we will describe a first attempt of the research group with a nonlinear resonator which has been designed and tested . Lastly we will hint at two promising architectures that have been conceive in the research group and that will be objective of future works.

There are different sources of energy usable for the electrical conversion. *Mechanical energy from vibrations* is the most common and usable energy source available in the human environment. Numerous issues must be taken into consideration for a proper design of a device which harvests energy by vibrations, the most significant concerns the low frequencies of mechanical vibrations.

Using a linear approach, the geometric dimensions of the resonating elements are a problem in order to reduce the resonance frequency. In fact reducing a device on a millmetric scale, or smaller, limits the resonance frequency: using ordinary material, a small dimension entails a great resonance frequency and a small mass (the first natural frequency of a vibrating system can be express, qualitatively, by $\sqrt{K/m}$). A possible solution could be the introduction of non linearity in the system introducing behaviours not intuitively predictable and potentially exploitable for the proposed purpose. An example is to use a material with nonlinear elastic strain for the elastic suspension of the swinging mass. This solution has been analyzed by the research group and in the next section we will show the preliminary numerical and experimental results based on the existent prototype reported in Sardini and Serpelloni (2010).

An interesting solution in this direction is the device proposed by Bowers and Arnold (2009), in which a spherical unidirectional magnetized permanent magnet ball moves arbitrarily in a spherical cavity wrapped with copper coil winds.

Jia and Liu (2009) proposed a liquid metal magneto hydrodynamics generator; this innovative solution uses the induction of electric current due to movement of an electricity conductive liquid metal in a magnetic field. The advantage of this appealing idea is its flexibility of actuation and controllability, its high adaptability to harvesting from a unidirectional movement and its relative high efficiency (more than 45%) in relation to common harvesting devices.

Another possible solution that at the moment is under consideration is the double conversion of the kinetic energy of the movement, at first in pressure energy of a fluid and subsequently in the kinetic energy of a rotational electromechanical generator. Mitcheson, Green, Yeatman and Holmes (2004) analysed the different architecture of vibration-driven micropower generators and their research conclude that the devices Coulomb Force Parametric Generator (CFPG) are the preferable solution for the systems in which the vibration source frequency is variable and the allowable mass frame displacement is small compared to the external source of vibration. This architecture will be showed in the next section.

In the research group a new device for the generation of electricity applied to an electronic instrumented total knee prosthesis is under development. This device has been simulated and the results obtained are in the following reported.

2 ANALYSIS OF PROPOSED DEVICES

The research group is interested to insert within a knee prosthesis an autonomous system to measure the resultant forces existing in the joint.
These data are very important because a proper value of forces is fundamental to assure a correct functionality of the limb and the deambulation, in addition it permits to estimate the distribution of the contact forces on the medial and lateral polyethylene component surfaces and consequently its life (Blunn et al. (1991), Currier et al. (2005), D'Lima et al. (2006, 2007)).

The goal is to integrate in a single device both the sensors and electronic circuits with a power harvesting supply system and a wireless data transmission. An external reading unit close to the knee (about few meters) receives the data and allows their analysis also by remote control.
Crescini, Sardini and Serpelloni (2009) realized a first attempt of an autonomous sensor executes autonomously force measurements into a protected environment and wireless transmits data directly from the inside of the implant to an external readout unit. The forces transmitted across the knee joint during normal human activities such as walking, running or climbing can be directly measured. Batteries are completely eliminated by harvesting energy from an externally applied magnetic field collected by a miniature coil within the implant.

The remote powering harvesting system provides also for the signals transmission by the same electromagnetic coupling, at 125 kHz, through the coil antenna of the transponder interface.

This solution obliges the patient to put this external coil and to have that on the knee during the measure of the forces. In order to remove this complication in the normal activity of the patient, the research group, after having tested the correct operational requirements of the system, has been addressing itself to the evaluation of a new solution completely integrated in the prosthesis for the generation of the power supply.

The energy harvesting by inertial electromagnetic generator, that scavenges the kinetic energy of the human movement, has been the new objective.
An electromagnetic inertial generator is a device that converts the mechanical energy of a mass swinging in a magnetic field in electrical energy, through *Faraday-Newmann-Lenz law*.

The mechanical energy in the human body is almost totally in kinetic form and generated by the movement of the limbs, consequently it is characterized by low frequencies and it is generally discontinuous. This situation doesn't allow an efficient exploitation of energy and the generator's design is fundamental to obtain a sufficient power for the electricity supply of the devices.
The most common architectures of electromagnetic inertial generator can be described by a linear second order differential model:

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = f(t) \qquad (1)$$

where m is the mass that swings, $x(t)$ is its generalized displacement (the motion can be rotational or translational), $c\dot{x}(t)$ and $kx(t)$ are respectively the viscous damping force and the linear restoring force acting on the mass, and $f(t)$ is the active force due to an external imposed actuation. Generally the driving force $f(t)$ has transmitted by device's casing upon a mass m conveniently designed, a restoring force allows a cyclic movement, a braking force cross the motion while the magnetic field has produced by a permanent magnet that, generally, is the swinging mass. Mitcheson et al. (2004) showed that substantially these devices can be reduced in three categories. Depending on kind of resistant and restoring force the analytical model is named: Viscous Damping Resonant Generators (VDRGs), Coulomb Damping Resonant Generators (CDRGs), and Coulomb Force Parametric Generators (CFPGs). Next we show different possible solutions in order to reduce the resonance frequency and in particular we examine the characteristics of the VDRGs and CFPGs architectures.

As for the VDRGs, the first solution proposed by Sardini and Serpelloni (2010) has been studied for the electrical energy supply of an autonomous sensor implanted in a human knee, consisting of completely embedded structures with no physical links to the outside world. The primary aim has been reducing the resonance frequency. The operating principle is based on the relative movement of a planar inductor with respect to permanent magnets. A mathematical model has been formulated assuming the electromechanical generator as a spring-mass-damper system with a base excitation.

A specific configuration of magnets is proposed and analyzed by FEM simulations (Figure 1) with the aim to improve the conversion efficiency, increasing the spatial variation of magnetic flux.

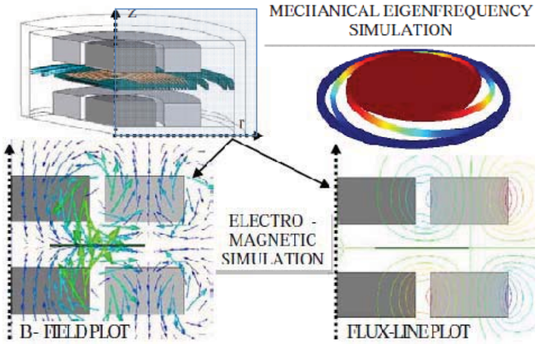

Figure 1: Simulation plots in mechanical eigenfrequency and electromagnetic domains. Reported in Sardini and Serpelloni (2010).

The system has been tested and experimental measurements showed a typical maximum power of about 16 mW at 30 Hz with a “LATEX” material for the membrane. In order to improve the characteristic of the device, over all in the direction of a reduction of natural frequency, the material has been chosen with non linear elastic characteristic. In this case the mathematical model is different from the one used in equation (1). The restoring force is non linear by adding a cubic term, and damping is proportional to the speed with an electrical and mechanical component.

The working frequencies of the generators has been simulated and their values are congruent with the experimental results in a range of possible frequencies included between 25Hz and 40Hz, how the Figure 2 shows.

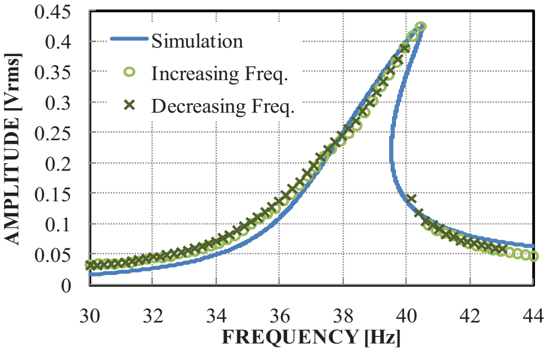

Figure 2: Comparison between simulation results and experimental data. Reported in Sardini and Serpelloni (2010).

The polymeric materials allowed the lowering of the resonant frequency compared to linear generators, but the presence of a resonant behaviour entails the maximum efficiency for a given frequency of excitation which depends on design of generator (geometry, material, reaction forces). This aspect reduces the scope of employment of a device to upper frequencies, because not simple practical problems emerge for the obtaining of a resonant frequency in the band of frequencies of the source. In fact, in this case, it needs to obtain a small resonant frequency without to increase the dimensions of the device.

It is evident that a similar resonant generator will not be adequately able to satisfy the requirements of biomedical employments.

The first comment is a theoretical consideration relating to different electromechanical generators that don’t work in a resonant manner.

A CFP generator is one of these ones; its model is showed in Figure 3: a swinging magnetic mass m is free to move in a propped case with an external coil in which the prevalent dissipative forces are of a Coulomb kind (e.g. taking a vacuum sealed case and using lapped contact surfaces).

Mitcheson et al. (2004), concluded that CFPGs have better performance when the ratio $Z_l/Y_0 < 0{,}1$, where Z_l is the maximum amplitude of the mass in the frame and Y_0 is the maximum amplitude of absolute movement of the frame how Figure 3 shows: it is typical of the case of human body motion in which $Z_l \approx 5mm \ll Y_0$.

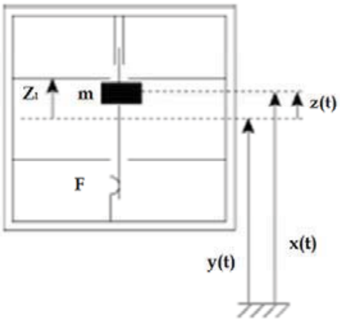

Figure 3: Model of Coulomb Force Parametric Generators.

It is interesting to notice that the elastic suspension doesn't exist and the friction force F makes impossible the relative motion $z(t)$ until an adequate acceleration produce on the mass m a force greater than the friction force F itself, so the CFPG device is not related to the frequency of exciting source: the magnet moves only when the acceleration exceeds a predetermined value, with the only constraint that the movement will be limited by the maximum amplitude Z_l allowed by the size of the device.

In this direction the solution proposed by Bowers and Arnold (2009) allows an optimal harnessing of the kinetic energy because the absolute movement of the case is completely converted in the relative movement of the swinging magnet. Indeed this harvester allows to have a power density up to 0,5 mW/cm^3, further it is characterised by a simple conception that allows a possible industrialization. The limits are connected with the noisiness, a great parameter of merit for a biomedical application, and with the effects produced by the reduction of the dimensions because of the increase of frictional forces.

The interesting solution designed by Jia, Liu and Zhou (2009) allows to obtain an efficient and non-resonant device capable of harvesting the kinetic energy with an efficiency up to 45% depending on the velocity of the flow in the duct.

The problem compared to solution proposed by Bowers and Arnold (2009) is represented by the difficulties with the volume necessary both for the hydraulic and magnetic circuit, further the architecture is complicated by the necessity of a hydraulic check-valve in order to obtain an unidirectional flow. On the other hand a good characteristic of this solution is the generation of a constant external voltage in a wide range of load resistance. The last two illustrated devices are been considered based on interesting and promising solutions in order to reduce the problem of resonant devices, and the purpose of the research group will be to plane two new device with a CFPG architecture or new possible hydraulic solutions.

At the moment the new proposed solution consists in an electromagnetic generator in which the coils have been inserted in a prominent element of tibial prosthetic plate that is placed between the two condyle, while the magnets are placed into the condyles on the opposite surfaces. The electronic circuits and the force sensors are placed internally the tibial plate. A model of the device is in Figure 4.

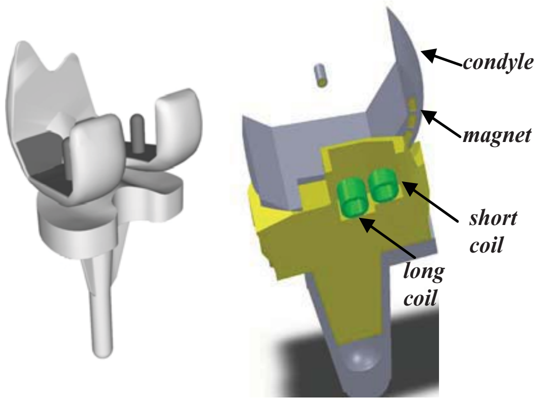

Figure 4: Total knee prosthesis and its cross section with electromagnetic generator.

In Figure 5 the results of Powers, Rao and Perry (1998) show that the sagittal knee motion in normal persons is much the same as in person with trans-tibial amputations (TTA). In the Figure 5 by the magnitude of the sagittal knee angle (about 60 degrees) and considering the normal time of swing, we obtain a mean angular velocity of 2,91 rad/s.

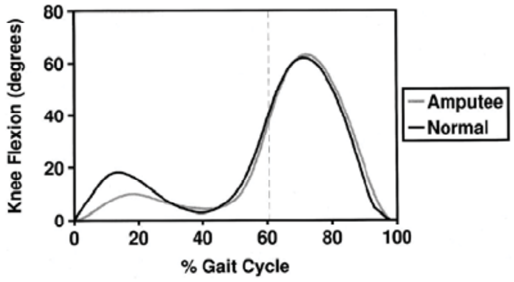

Figure 5: Mean knee motion curve for the trans-tibial amputee and normal persons; the vertical dotted line separate *stance* and *swing phases* of the gait cycle. Reported in Powers, Rao and Perry (1998).

In order to check qualitatively the validity of these solution a first numerical simulation has been realized, considering the geometry reported in Figure 4.

The simulation has been realized hypothesizing that running of the device is in the *swing phase* of the walking cycle of persons with trans-tibial amputations (TTA). The results in Figure 7 and 8 show the induced voltage in the short and long coils showed in Figure 4.

Inside each coil a magnetic core has been inserted, and the coils have not been connected in order to evaluate individually on each of them the effects of the magnets.

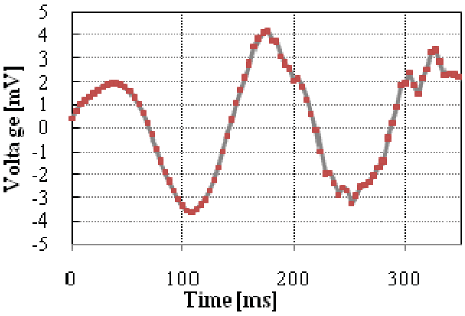

Figure 7: Induced voltage in short coil.

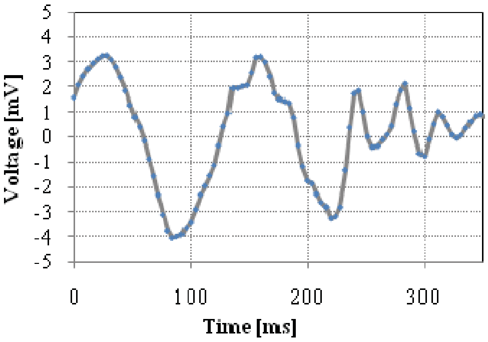

Figure 8: Induced voltage in long coil.

4 CONCLUSIONS

Two devices have been shown.

The first works in a resonant manner and it is in an advanced stage of the project. The second is still object of a series of judgments, in particular the future works will seek to improve the coupling effects between the elements of the magnetical circuits in order to increase the induced voltage.

The goal is to obtain an optimal disposal of the relative position of the magnets and the coils in order to increase the magnetic flux through the coils.

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