# A VIBRATION-BASED ENERGY HARVESTING SYSTEM FOR IMPLANTABLE BIOMEDICAL TELEMETRY SYSTEMS

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Abstract: Using the new trend of energy harvesting, an envisioned electromagnetic power transducer that uses human gait to produce electrical energy is presented as a solution to energize biomedical devices. Regardless of the walking speed, starting at 0.7 Hz, it is possible to store a total energy of 2.2 mJ, using two 1000 µF capacitors as energy storage elements. Afterwards, this energy becomes available to the telemetric system through an efficient power management module. Since the end application, an implantable biomedical telemetric system, needs a total of 360 µJ to operate, the here presented power transducer is well suited for implant power needs.

## 1 INTRODUCTION

In order to extend the lifetime of an implant, a completely autonomous power source should be used. Nowadays, batteries and electromagnetic induction are the best alternatives, yet they come with some issues to address. Batteries do not last long and in the case of rechargeable batteries a solution to recharge them must be found. Electromagnetic induction solves those drawbacks, but the unaesthetic external apparatus can be uncomfortable and easily broken if its extended use is required.

Taking a step forward it is presented an electromagnetic transducer capable of sufficing power needs of a smart hip telemetry system. With virtually infinite available energy it is possible to extend the lifetime of the implant and solve many, if not all, the aforementioned issues.

This paper presents a telemetric system as the end application for an electromagnetic vibration-based energy harvesting power transducer. Afterwards, a power budget for the intended telemetric system is defined in order to give an overview of its power needs. Later, a theoretical study on this type of transducers is conducted as a background to the development of a fully functional

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generator prototype. Finally an energy storage subsystem and respective power supply circuit are presented as solutions for efficient power storage and usage, respectively.

## 2 TELEMETRY SYSTEM

Hip prosthesis loosening is one of the main issues affecting patients who undergo a hip arthroplasty (Puers et al., 2000). In order to early detect this loosening, an instrumented and telemeterized prosthesis is being developed (Morais et al., 2009). The system comprises a group of piezoelectric (PZT) transducers, signal conditioning circuitry, data processing block and a RF transmitter, (Fig. 1).

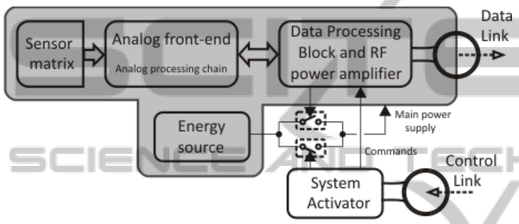


Figure 1: Telemetry system block diagram (Morais et al., 2009).

At the beginning, the entire system is in a shutdown mode in order to preserve energy. After activation, upon an external command, the system becomes energized by connecting the main power supply. After system start-up, sensor data is acquired by using precision peak detectors. The resulting low-frequency signals are then converted using 2nd-order Delta-Sigma analog-to-digital converters, processed by a low-power microcontroller and transmitted to a base station, located at the patient belt, through a very low-power RF transmitter. When this process is finished the entire system is deactivated returning to the shutdown mode.

### 2.1 Energy Harvesting and System Remote Activation

In order to reach an optimized energy management, the telemetric system is kept in a completely shutdown mode, being activated when needed or when energy becomes available through the power transducer.

As soon as vibrations are present, the transducer converts those vibrations into electrical energy. This energy is then stored in a primary energy reservoir for later use. Even though a Li-ion medical grade rechargeable battery is currently the primary energy source, the ultimate goal is to use the transducer as the main and possibly sole power supply. Meanwhile transducer stored energy may be used as a complementary energy source or, for long periods of telemetric system shutdown mode, it may be used to recharge the battery, (Fig. 2).

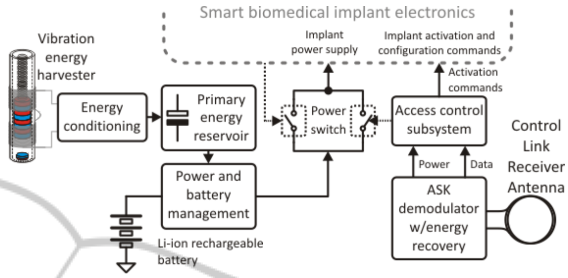


Figure 2: System overview with special focus on the energy harvester and system activation modules.

### 2.2 Energy Consumption Profile

In order to determine if the power transducer is capable of solely powering the telemetric system, the first step to take is to define its power budget.

Table 1 resumes the power budget of the microelectronics version of the telemetric system taking into account its aforementioned sequence of events and macro device evaluation.

Table 1: Estimated telemetric system energy needs.

| Event | Power | Time | Energy |
|---|---|---|---|
| Start-up | 660 µW | 10 ms | 6.60 µJ |
| Sig. cond. | 2.6 µW | 5 s | 13.20 µJ |
| Conversion | 64.3 µW | 267 ms | 17.18 µJ |
| Ctrl & P. | 680 µW | 277,4 ms | 188.6 µJ |
| RF TX | 13.2 mW | 10.41 ms | 137.4 µJ |
| Total | 0 | 5564.8 ms | 363 µJ |
| Shutdown | 0 | 294.4 s | 0 |

The sequence of events takes place in approximately 5.6 seconds and it may completely drain the stored energy. As explained later, a shutdown period of 294 seconds was considered a good compromise in order to provide enough time to recharge the storage elements. If subsequent data cycles are needed they will happen each 300 seconds. For a period of 300 seconds it is expected a total energy consumption of about 363 µJ with an average power of 1.21 µW (363 µJ/300).

## 3 PROTOTYPE DEVELOPMENT

In this section a prototype of an electromagnetic generator is presented.

### 3.1 Theory Background

Regarding power generation using human movements, Velocity-Damped Resonant Generators (VDRGs) are the best approach as suggested by von Buren et al. (2006) and Yun et al. (2008).

These generators, also known as inertial generators, can be represented using a basic mechanical structure, as presented in Fig. 3.

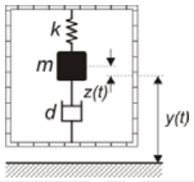


Figure 3: Basic mechanical representation of an inertial generator.

Independently of the transducer mechanism, used to build such generators, electrostatic, piezoelectric or electromagnetic, average generated power can be determined using (1).

$$P = m\xi_e Y_0^2(\omega / \omega_n)^3 \omega^3 / ( [ 1 - (\omega / \omega_n)^2 ]^2 + [2 \xi (\omega / \omega_n) ]^2) \quad (1)$$

This expression was the end result of a frequency domain analysis presented by Li et al. (2000). Here, $Y_0$ is the external excitation amplitude, $\omega$ is the system's excitation frequency, $\omega_n$ is the system's natural frequency, m is the inertial mass and $\xi = \xi_e + \xi_m$ is the overall damping factor, where $\xi_e$ and $\xi_m$ are the electrical and mechanical damping factors.

Since damping factors depend on the transducer mechanism, and the proposed transducer is of the electromagnetic type, $\xi_e = (B\ l)^2 / (2\ R_L\ m\ \omega_n)$ and $\xi_m = d / (2\ m\ \omega_n)$, where B is the magnetic flux density, l is the coil's length, d is the mechanical damping ratio and $R_L$ the electrical load presented at the generator output.

As discussed by Li et al. (2000), there is a power and voltage maximization at resonance ($\omega = \omega_n$), resulting in $P = m\xi_e Y_0^2\omega_n^3/ 4\xi^2$ and $V = BlY_0\omega_n/2\xi$.

### 3.2 The Generator

Taking into account the available volume inside a hip prosthesis model (Simões et al., 2000), serving as a base model for this project, a specific generator prototype was manufactured, (Fig. 4).

Figure 4: Electromagnetic power generator inserted inside a hip prosthesis model.

Fig. 5 clearly presents generator composition revealing the details of its operation. Considering Lenz's law, coils are expected to produce signals that are equivalent in amplitude and phase.

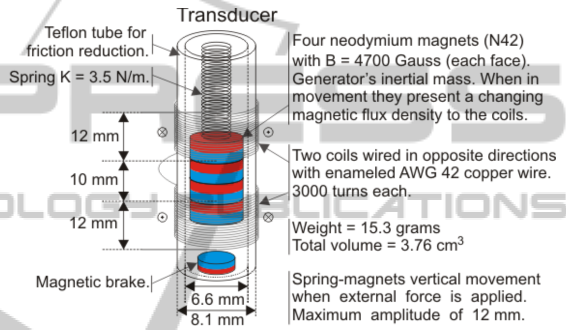


Figure 5: 3D representation of the generator.

For testing purposes the generator is attached to the hip location of a group of human subjects, for actual human walking generator external excitation. Fig. 6 presents the synchronism test, where can be seen the expected doubled voltage amplitude at generator's output plugs, when coils are series connected.

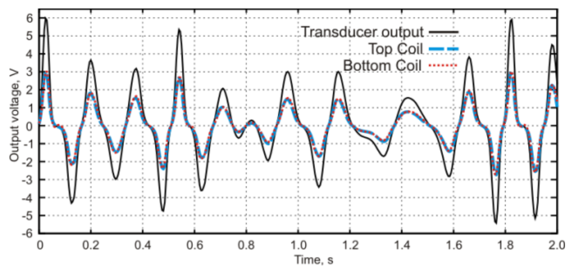


Figure 6: Transducer coils working in synchronism.

### 3.3 Energy Storage

In order to optimize harvested energy storage and to accelerate capacitors charging, a series rectifier configuration was used, (Fig. 7).

In order to prevent early capacitors' energy usage, a low power start-up sub-module is used.

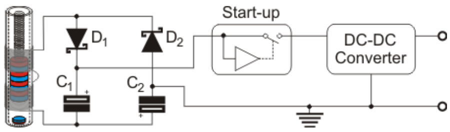


Figure 7: Energy storage and power supply circuit.

Only when capacitors' combined voltage reaches a usable level ($V_H$ = 3.2 V) this voltage is connected to the DC-DC converter and subsequently to the telemetric system. Once capacitors' combined voltage drops to a considered minimum value ($V_L$ = 1.2 V), the start-up sub-module disconnects generator's load.

Considering that each capacitor will be charged at half this values, using $E = C/2\ [(V_H)^2 - (V_L)^2]$ with $C = C_1 = C_2 = 1000\ \mu F$ an energy of 1.1 mJ is stored in each capacitor, leaving us with a total 2.2 mJ of usable energy.

Fig. 8 clearly shows that, for a worst case scenario, more than 40 seconds are needed to recharge the capacitors.

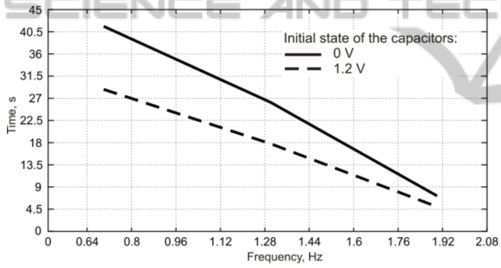


Figure 8: Average time taken to recharge storage capacitors, for a range of gait speeds.

Fig. 9 presents actual capacitors' voltage evolution, over time, for a set of pace frequencies, covering the full range of tested walking speeds.

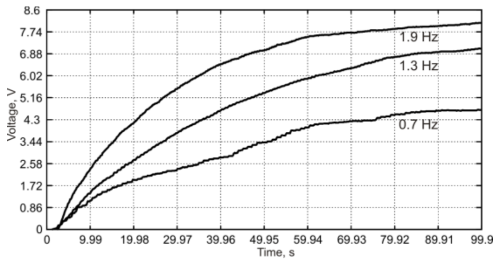


Figure 9: Capacitors' voltage evolution over time.

Considering that patients will probably not walk at a steady pace and may even stop to rest, if repeated data acquisition cycles are needed, 300 seconds between cycles is a secure compromise.

Taking all this preliminary results into account, it is considered that the proposed electromagnetic transducer is more than capable of solely powering the envisioned microelectronic telemetric system.

# 4 CONCLUSIONS

Since the end application is located inside a hip prosthesis, where vibrations are expected with abundance, the proposed electromagnetic generator follows the vibration to electrical energy conversion.

As demonstrated, using mechanical vibrations produced by the human gait it is possible to harvest enough energy, with this generator, to suffice power needs of the aforementioned telemetric system.

As future work it is intended to further maximize useful energy storage. This will allow extended telemetric system's working cycle and upgrade system functionalities.

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