Human Motion Energy Harvester for Biometric Data Monitoring

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Abstract. In this paper we present an energy autonomous sensor system fully integrated into the heel of a shoe for biometric data monitoring. For powering the wireless sensor system a pulse-driven energy harvester was developed, which uses the acceleration-impulses from heel-strike during walking. In preparation of the device development acceleration measurements were carried out. The pulse-driven energy harvester is based on the electromagnetic conversion principle and incorporates a 4x4 coil matrix. A beam fixed at both ends is used for suspending the magnetic circuit. The geometric parameters of coil and magnetic circuit were optimized for maximum power output. For an idealized acceleration pulse with a width of 5 ms and a height of 200 m/s² an average power output of 0.7 mW was generated using a step frequency of 1 Hz. The functionality of the self-sustained sensor system is demonstrated by measuring the temperature and step-frequency of a walking person and transmitting the data to a base station. We also found that the implementation of the suspension can have a significant impact on the harvester performance reducing the power output.

1. Introduction

The idea of energy harvesting from human motion, in particular from the human gait for powering mobile electronic devices goes back to 1996 [1]. Meanwhile, a lot of work has been done around the world in this area and several demonstrators showing the feasibility of power conversion from human walking were presented [2]. However, the demonstration of useful applications is still exceptional.

The energy available in the human gait comes in different forms: acceleration pulses from heel-strike, acceleration during the swing phase of the leg and weight on the ground and shoe during downward movement. In either case, the available acceleration is non-harmonic and occurs periodically at a very low frequency around 1 Hz. Thus, operating conventional vibration based energy converters in resonance will not be feasible. However, acceleration pulses can be used to deflect the seismic mass of a vibration based mechanism out of the equilibrium position resulting in an oscillation with the Eigen-frequency of the system. In this manner, a simple and flat design is achievable, necessary for integration into the sole of a shoe. Moro et al presented such a device, which was a shoe-

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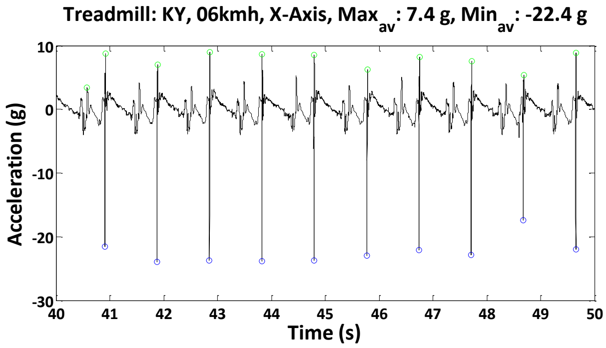
a)



b)

Figure 1. a) Fotograph of a running shoe with mounted acceleration sensor showing the axes-orientation. b) Example of an acceleration record (x-axis) from a treadmill run at a speed of 6 km/h.

mounted piezoelectric cantilever for converting kinetic shock energy from heel-strike during walking [4]. In this work a pulse-driven energy harvester was developed, which is based on the electro-magnetic conversion principle. For the first time a self-sustaining sensor system including the energy harvester device and a wireless sensor system was successfully integrated into the sole of a shoe. The device is excited by acceleration pulses which occur from heel-strike during human locomotion.

2. Design and Modelling

2.1. Excitation conditions

Previous to the device development acceleration measurements were carried out with two different persons on a treadmill at four different motion speeds. Figure 1a shows the used running shoe with the acceleration sensor attached at the outer side of the shoe sole. A triaxial accelerometer was used with the x-axis orthogonal to the ground (figure 1a) for recording the acceleration impulses from heel-strike during motion. An example of an acceleration record is shown in figure 1b. The motion speed was 6 km/h (fast walking). The weight of the person KY was 105 kg. The average of the positive and negative acceleration peaks was 7.4 g and -22.4 g, respectively. In table 1 the peak average is summarized for all measurements carried out.

An acceleration profile of a single heel-strike is shown in figure 2a. The average width of the acceleration pulse is approximately 5 ms. Based on the measurement data idealized pulse profiles with different acceleration peaks were synthesized. An example is shown in figure 2b. Each pulse profile is designed from a half-sine with a pulse width of 5 ms. The pulse height was varied between 100 m/s² and 300 m/s². The pulse profiles were then used in subsequent numerical system simulations and for characterization of the device on a lab-shaker. For optimizing the design parameters of the energy harvester an idealized profile was used as well with a pulse height of 200 m/s² (figure 2b). The reason

Table 1. Average acceleration peaks in x-direction during 120 s treadmill runs. Weight of the two persons: KY: 105 kg, SB: 78 kg

Motion speed		Peak average positive (g)		Peak average negative (g)	
		Person KY	Person SB	Person KY	Person SB
4 km/h	(slow walking)	6.5	4.2	-9.9	-11.5
6 km/h	(fast walking)	9.2	5.6	-21.8	-17.6
8 km/h	(jogging)	8.7	4.5	-27.4	-20.2
10 km/h	(running)	10	7.3	-39.5	-24.2

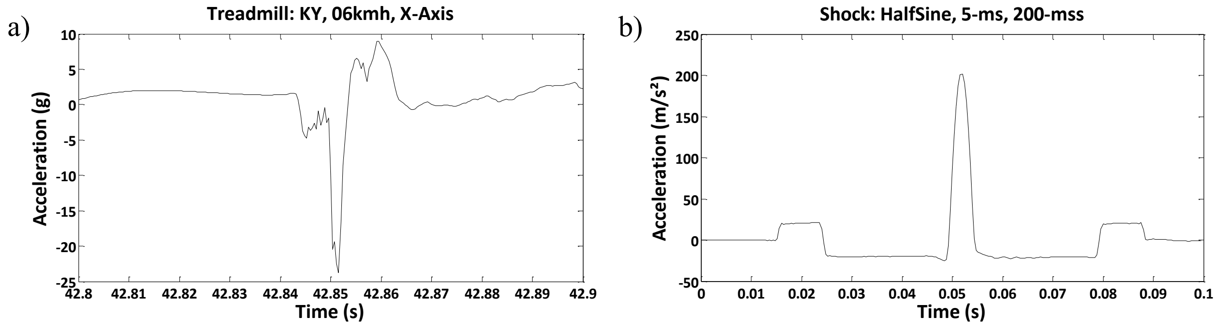


Figure 2. a) Acceleration profile of a single heel-strike. b) Idealized acceleration profile of a single heel-strike: a half-sine pulse with 5 ms pulse-width and 200 m/s² pulse-height.

for using a synthesized pulse profile for the parameter optimization process is the fact that our lab-shaker was not able to replicate the measurement data.

2.2. Design and parametric model

The energy harvester incorporates a 2x2 coil array and two identical magnetic circuits. Each magnetic circuit contains two smaller air gaps (instead of a single, larger one) for placement of the induction coils. In this manner a larger coil volume is achievable while a reduction of magnetic flux density is avoided. A schematic diagram of the energy harvester structure (cross-section of one of the two magnetic circuits) including relevant design parameters is shown in figure 3a. The total width W_{total} is limited by the size of the shoe and must not exceed 38 mm since the total device width is restricted to 40 mm. The gap between coil and magnet was chosen to be 0.5 mm. The width of the coil W_{coil} follows from W_{sheet}, W_{mag} and the gap as shown in table 2. The width of the magnet and the back iron sheet was optimized in order to achieve maximum power output for this particular design. The height of the back iron sheet is limited by the maximum height of the device, which is designed to be 20 mm. The wall thickness of the housing and the inner displacement amplitude are designed to be 2 mm and 3 mm, respectively. As a result, the maximum possible value for H_{sheet} is 10 mm. Consequently, H_{mag} must be 5 mm. The value for L_{mag} and L_{sheet} is equal to H_{sheet}. The outer and inner diameter of the coil is 6 mm and 2 mm, respectively. All relevant parameters are summarized in table 2.

In figure 3b a 2D-simulation of the magnetic field distribution is shown. The homogeneous field in the two gaps is clearly visible and the mean value of the magnetic flux density is about 0.4 T.

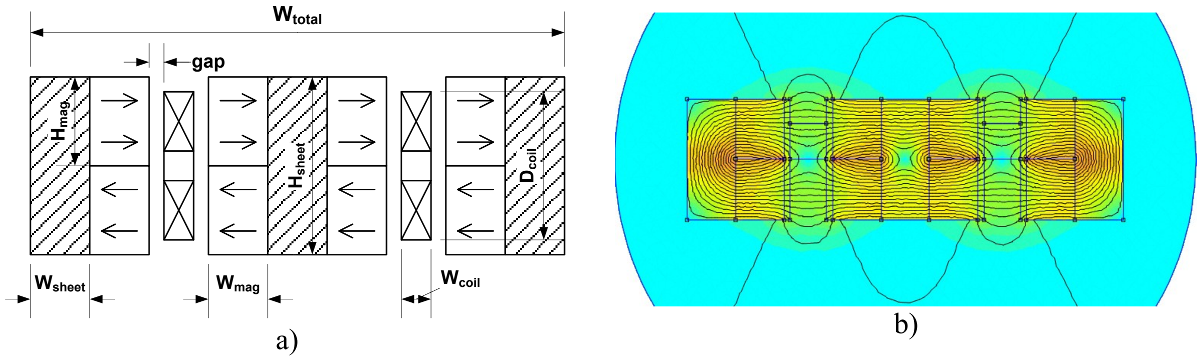


Figure 3. a) Parametric model of energy harvester structure. b) simulation of the magnetic field.

Table 2. Parameters of the energy harvester structure

Parameter	Value (mm)	Remark
W_{total}	38	limited by the available space of the shoe
W_{sheet}	4	optimized for maximum power output
W_{mag}	4	optimized for maximum power output
gap	0.5	fixed value
W_{coil}	3	$= (W_{total} - 3W_{sheet} - 4W_{mag} - 4_{gap}) / 2$
H_{sheet}	10	limited by the available space in the shoe
H_{mag}	5	$= H_{sheet} / 2$
z_{max}	3	internal displacement amplitude

3. Experimental

3.1. Prototype Development
A first prototype implementation of the heel-strike energy harvester is shown in figure 4a. Both magnetic circuits are firmly connected resulting in a single seismic mass, which is suspended using a fixed-end beam structure. The power-management circuit and the wireless transmission electronics are accommodated within the harvester housing. A temperature sensor connected by flexible wires is placed in the shoe close to the foot. The integration of the self-sustaining wireless sensor system is shown in figure 4b.

3.2. Measurements
Measurements of the transient electromechanical response of the pulse-driven energy harvester are shown in figure 5. Voltage and power output were measured using the optimum load resistance of 500 Ohm (see figure 6a). For each heel-strike the output voltage shows the response of a damped system. The instantaneous power output shows peaks up to 50 mW. For an idealized pulse profile with a width of 5 ms and a height of 200 m/s² an average power output of 0.7 mW was generated using a step frequency of 1 Hz.

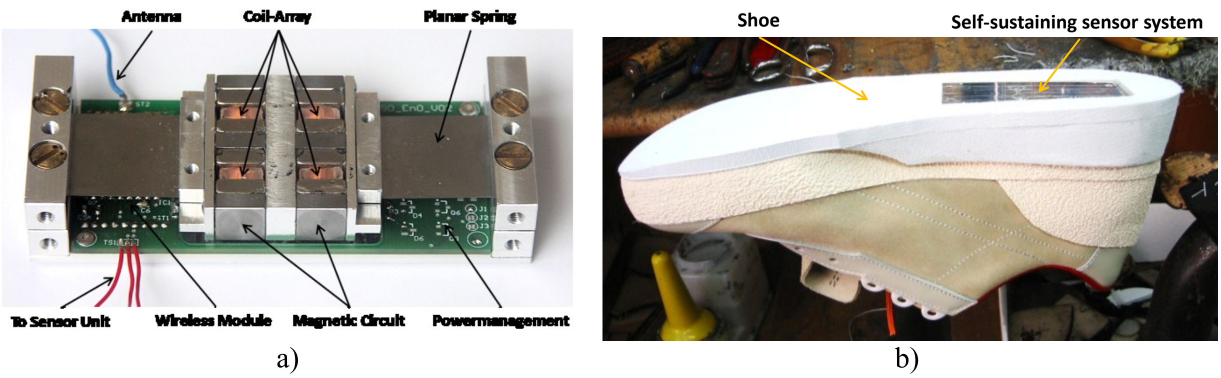


Figure 4. a) Prototype of the energy autonomous sensor system including the heel-strike energy harvester, power-management circuit and wireless data communication. b) Energy autonomous shoe incorporating the self-sustaining sensor system.

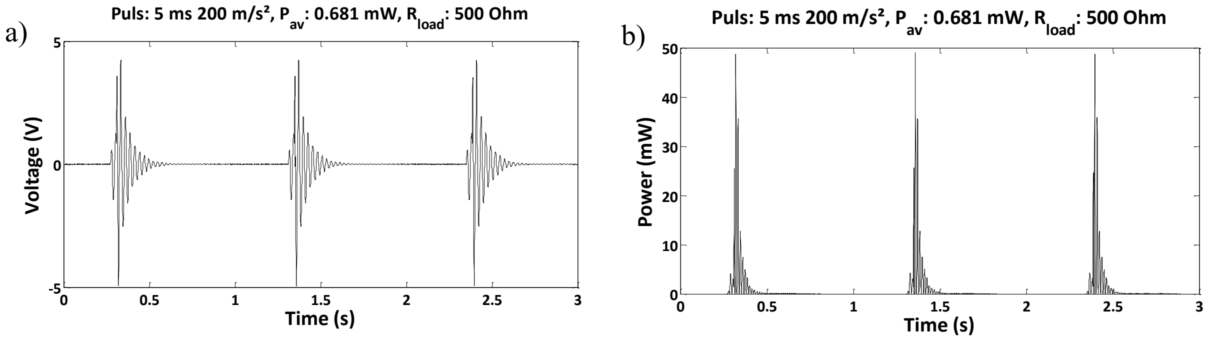


Figure 5. Time-response of the harvester using an idealized pulse profile with an acceleration peak of 200 m/s². a) Output voltage. b) Output power

According to figure 6a the optimum load resistance of the pulse-driven energy harvester is equal to the internal resistance of the induction coil (this measurement was performed using a pulse profile with a peak acceleration of 100 m/s²). Figure 6b shows the power output for pulse profiles with different peak accelerations. The power increases with increasing acceleration. However, due to the fact that the internal harvester structure reaches the limit stops at some point, the power levels off and does not increase further. We also demonstrated that the sensor system was able to transmit one data packet (sensor data) per heel-strike for motion speeds as low as 4 km/h.

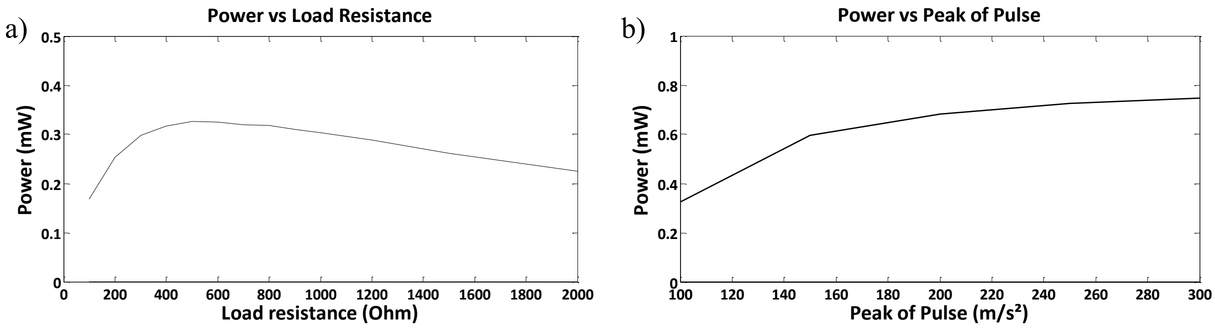


Figure 6. a) Average power versus load resistance. b) Average power versus pulse-height

4. Conclusions

We have demonstrated an energy-autonomous sensor system fully integrated into the sole of a shoe including a pulse-driven electromagnetic energy harvesting device, power-management circuit, sensor unit and wireless data transmission. The energy harvester was able to provide electrical power up to 0.7 mW on average using a step frequency of 1 Hz and a pulse profile with 200 m/s² peak acceleration. We found that the implementation of the suspension had a significant impact on the oscillation characteristic of the harvester structure reducing the power output. A fixed-end beam structure is not a practical solution for suspending the magnetic circuit. Therefore a re-design of the mechanical structure is necessary for improving the power output. Based on first simulation results we expect the power output to increase by a factor of 5 when employing a magnetic levitation principle as a suspension for the magnetic circuit.

References

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