Non-resonant electromagnetic energy harvester for car-key applications

X. Li[1, 2], T. Hehn[3], M. Thewes[4], I. Kuehne[5], A. Frey[6], G. Scholl[4], and Y. Manoli[2, 3]

[1]Research & Development, Daimler AG, Sindelfingen, Germany
[2]Fritz Huettinger Chair of Microelectronics, IMTEK, University of Freiburg, Germany
[3]HSG-IMIT, Villingen-Schwenningen, Germany
[4]Electrical Measurement Engineering, Helmut-Schmidt-University, Germany
[5]Faculty of Engineering and Business Administration, Heilbronn University, Germany
[6]Faculty of Electrical Engineering, Augsburg University, Germany

E-mail: xiaoming.li@daimler.com

Abstract. This paper presents a novel non-resonant electromagnetic energy harvester for application in a remote car-key, to extend the lifetime of the battery or even to realize a fully energy autonomous, maintenance-free car-key product. Characteristic for a car-key are low frequency and large amplitude motions during normal daily operation. The basic idea of this non-resonant generator is to use a round flat permanent magnet moving freely in a round flat cavity, which is packaged on both sides by printed circuit boards embedded with multi-layer copper coils. The primary goal of this structure is to easily integrate the energy harvester with the existing electrical circuit module into available commercial car-key designs. The whole size of the energy harvester is comparable to a CR2032 coin battery. To find out the best power-efficient and optimal design, several magnets with different dimensions and magnetizations, and various layouts of copper coils were analysed and built up for prototype testing. Experimental results show that with an axially magnetized NdFeB magnet and copper coils of design variant B a maximum open circuit voltage of 1.1V can be observed.

1. Introduction

In recent years our daily routine has fundamentally changed with the use of many consumer electronic products, like smart phones, wearable electronics, and wireless sensor networks. The frequency of battery replacement or the operation time on one battery charge of such mobile devices are important factors influencing the decision in the choice of consumer products. To match these market trends the power consumption of electronic circuits and systems can be decreased due to the achievements in microelectronics on one hand but on the other hand, the battery capacity and lifetime is not keeping up in pace with the increase in performance demand. Energy harvesting which can convert ambient energy into electrical energy to recharge the battery can lead to a prolonged lifetime, or can even be used to directly supply the electronic devices and replace the battery altogether [1].

In the automobile branch there are also many potential application possibilities of energy harvesting technologies [2] with a clear target to reduce component maintenance cycles and costs, and to serve increasing requirements of monitoring and diagnostic functionality. In this paper the research on an electromagnetic energy harvester for application in a remote car-key is presented. The motivation is to extend the lifetime of the battery of the car-key or even to replace it in order to realize a fully energy autonomous, maintenance-free car-key product.

Electromagnetic vibration energy harvesters have been investigated in many research facilities over the last few years. The prototypes have varying sizes, employ different electromagnetic coupling architectures, and work under a wide range of conditions thus resulting in very diverse output voltages and powers. To obtain the maximum harvesting performance, most of these energy harvesting mechanisms are based on the resonant vibration approach, using a mass-spring-damper system to convert kinetic mechanical energy into electrical via a magnet-coil coupling interface based on Faraday's principle [3]. However, a resonant energy generator can only achieve this best performance over a very small frequency range. Because of various manufacturing limitations in small device dimensions it is rather difficult to implement a relatively big inertial mass and a soft spring for a traditional mass-spring-damper system. Thus most of the reported prototypes work efficiently only at a resonance frequency of 50Hz and above while some MEMS based micro structures have resonance frequencies of a few hundred Hz or even in the kHz range. In contrast, the available ambient vibration sources in many scenarios are normally random and have a rich frequency spectral content with a typical bandwidth of 1Hz to 20Hz. Consequently, to be targeted at practical applications in wearable electronics, some previous research has concentrated on energy harvesters for human motion. Von Büren and Tröster in 2007 proposed a linear inertial electromagnetic generator for body-worn applications with a coupling architecture based on opposite polarized magnets which provide the oscillating mass, and a flexible parallel-spring bearing. During normal walking 2-25µW of generated power has been obtained depending on the mounting position [4]. Bowers and Arnold in 2008 reported a spherical magnetic generator intended for energy harvesting from human motion and observed a maximum RMS voltage of ca. 0.7V and a power of 1.44mW [5]. Another non-resonant energy harvester by Yang and Lee presented in 2010 uses a free-standing cylindrical magnet moving inside a sealed cavity of five pieces of printed circuit boards embedded with multi-layer copper coils. This structure generates the maximum output power 0.4µW under matched load conditions [6].

2. Design and fabrication of the energy harvester

It is well-known that the development of energy harvesters is very application specific which means that the following key points of the general requirements of a mass product must be taken into account from the very beginning of the design phase for an energy harvester in a car-key.

- Production and assembly compatibility to existing product – The packaging size of the generator should be compatible to a coin battery (CR2032) and its bracket (shown in figure 1)
- Target product use case – An energy generator in a car-key works daily mostly under car-body vibrations and human motion conditions with dominant spectral content between 1 to 10Hz almost in all three moving directions (figure 2 shows the results of vibration testing of a car-key in a trousers pocket while walking at 6km/h)
- Environmental requirements – fulfilling automobile product standards (temperature, vibration durability, EMC, and so on)
- Cost-effectiveness – standard printed circuit board (PCB) technology, reliable and low cost assembly process in mass production, less special and expensive materials

2.1. Non-resonant energy harvester design

The conventional mass-spring-damper coupling architecture has always a natural resonant frequency, which can be simply written as $\omega_n = \sqrt{k/m}$. In order to have the natural resonant frequency match the spectral content of human motion for a most efficient performance in such resonant systems, one may reduce the spring constant *k* and increase the mass *m* of the oscillator. The design of the low frequency micro-power generator in [4] is based on this principle. But, if the spring in the system is removed, the system changes to a non-resonant one, which is the idea behind the generator principles in [5] and [6].

Fig. 1 Commercial series car-key (Source: Daimler AG)

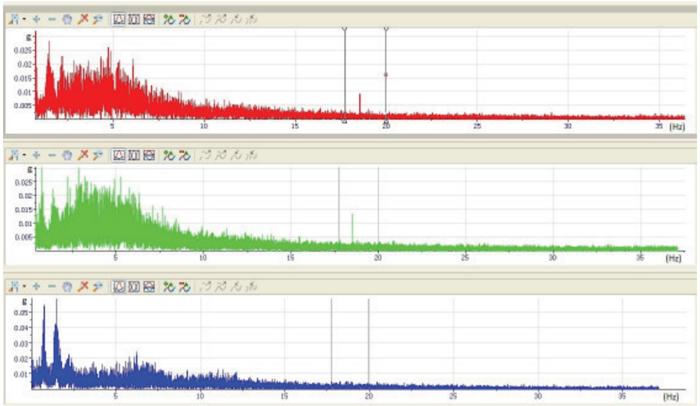

Fig. 2 Spectrum diagram of x/y/z direction in vibrational testing of car-key in trousers pocket by walking at 6km/h

A novel non-resonant electromagnetic vibration energy harvester structure intended for remote car-key application is proposed in this study. The basic idea of this non-resonant generator is to use a round flat permanent magnet which moves freely in a round flat cavity covered on the two flat sides by a PCB embedded with multi-layer copper coils and on the round side by displacement plates made by the same material of PCB substrates (figure 3). The relative motion between magnet and PCB-housing causes a time-varying magnetic flux through the copper coils and thus induces a voltage.

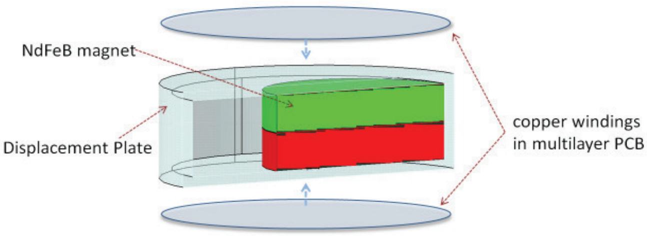

Fig. 3 Car-key power generator structure concept

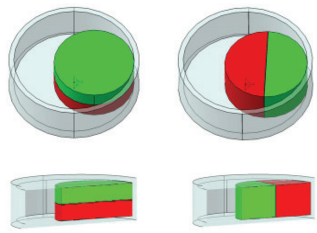

Fig. 4 Magnetic polarization in Z-Axis (left) and in X-Y plane (right)

The primary goal of this structure is to easily integrate the energy harvester within the existing electrical circuit module into the commercial car-key design feature. In other words the whole size of the energy harvester is comparable to a CR2032 coin battery plus its bracket. Consequently, this simple structure would cause no big cost impact for the series product integration and assembly.

2.2. *Experimental prototype fabrication*

For the experimental prototypes, the diameter of the inner cavity is fixed to 20mm, while the height (distance between the two multilayer PCBs) is fixed at 3.1mm. The flat and round shaped magnets, which have different diameters in each prototype, have a common height of 3mm, so that they can freely and smoothly move within the cavity. The displacement plates (shown in figure 5, type S) and the screws make the prototype assembly quite easy and the distance precisely adjustable.

In this particular non-resonant generator design approach, under random ambient excitation, the magnet will be moving in a random direction and rotating at the same time. In fact, the relative motion between magnetic field and the coils can occur only after the magnet overcomes the friction with the housing and gets an initial velocity. Based on Faraday's electromagnetic theory, two main factors play an important role for the optimization of the induction:

- The magnetic flux density and the gradient through the coils
- The form of the coils on the multilayer PCB

Permanent magnets manufactured by the company HKCM (http://www.hkcm.de) with different diameters and polarization direction in Z-Axis or in X-Y plane (shown in figure 4) are applied for performance testing. For finding the most efficient coupling architecture four different layouts of the copper coils were analyzed and built up for testing (shown in figure 5). On the outer circle surrounding of the 4-layer PCB there are bonding points (green points in figure 5), which are used for connecting the copper winding on each layer of the circuit board. Each PCB has 8 through-holes (brown points in figure 5) for screw fixing points. The 4-layer PCB in the prototypes were made by the standard FR4 PCB substrates, and all the PCB copper windings are 100µm wide and 35 µm thick. An energy harvester prototype assembly is shown in figure 6.

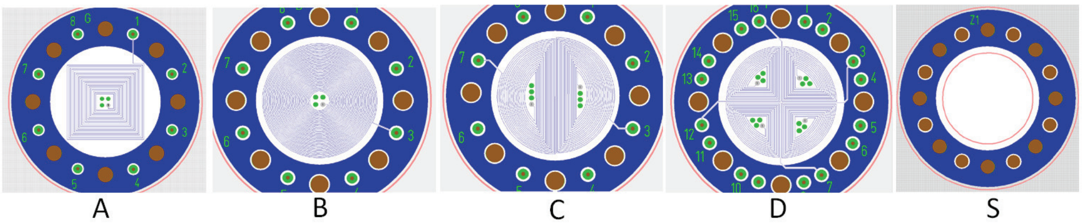

Fig. 5 type A, B, C and D: four layouts of copper coils; type S: layout of displacement plate

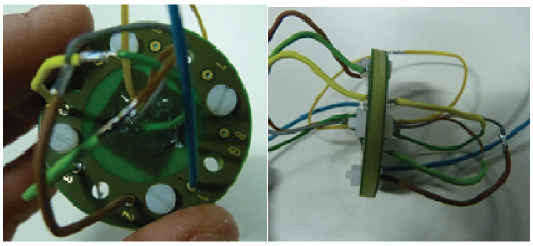

Fig. 6 Car-key energy harvester prototype assembly (layout type A as example)

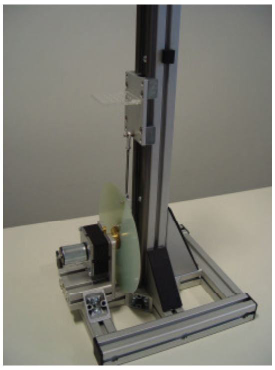

Fig. 7 Big Amplitude Shaker

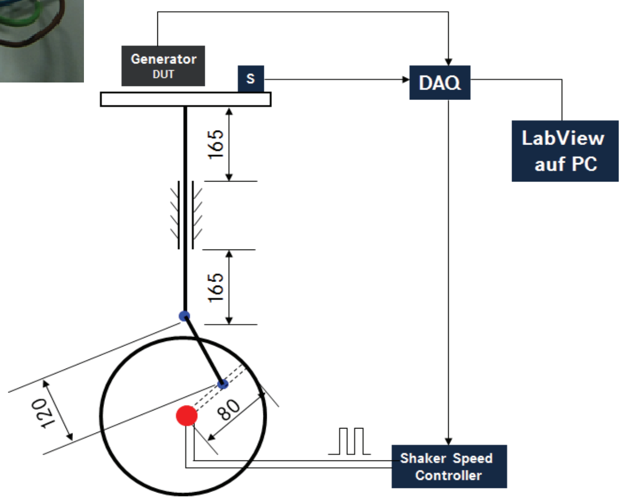

Fig. 8 Measurement setup diagram

3. Measurements and results

In the application the ambient excitation to a car-key is always a random vibration at low frequency and big amplitude. In order to simulate practical application scenarios, a "Big Amplitude Shaker" was developed (shown in Figure 7). The frequency and the amplitude of the reciprocating motion are controlled by the speed of the driving motor and adjusted by the length of the con-rod. Figure 8 shows the measurement setup diagram: the packaged prototype (DUT) is mounted vertically on the holder of the shaker, while the acceleration of the holder is detected by an accelerometer (Kistler® Type 8315A).

A LabVIEW® program running on the PC is able to control the speed of the driving motor of the shaker and to acquire the real-time data of the open circuit induced voltage of the generator as well as the accelerometer values.

Consequently, a total of 28 experimental prototypes of 7 types of magnets (various diameters and polarizations) and 4 types of winding layouts were assembled and measured. Table 1 shows the summary of the prototype matrix and the testing results of the maximum induced voltages, under the same input conditions with the experimental shaker calibrated at 3Hz vibration motion and 100mm amplitude.

The experimental results show that a maximum open circuit voltage of 1.1V was observed with a Z-Axis polarized magnet and copper coils of type B. The inductive voltage increases with the diameter of the flat magnet: comparing the results of the magnet with a diameter of 15mm to that of 3mm, the voltage is around 2~8 times higher, the reason being the larger magnetic flux. Comparing the coil layouts, the type D shows the best performance with the small size magnet, but this advantage is less with bigger size magnets. The polarization direction of the magnetic flux plays a less dominant role in the experiments.

						Coil Layout Type			
						A	B	C	D
					Coil resistance (Ohm)	55	115	92	80
Magnet Variant	Diameter (mm)	Material	B(T)	weight (g)	magnetic polarization	Inductive Voltage [V]			
	3	NI-N35	1,17	0,16	Z-Axis	0,06	0,22	0,22	0,4
	5	NI-N38SH	1,22	0,44	Z-Axis	0,15	0,4	0,25	0,8
		ND-N50	1,4	0,44	X-Y Plane	0,08	0,4	0,25	0,7
	7	ZN-N35	1,17	0,86	Z-Axis	0,35	0,7	0,4	0,64
	10	EP-N52	1,43	1,76	Z-Axis	0,53	1	0,6	0,8
		AD-N35	1,17	1,76	X-Y Plane	0,1	0,8	0,48	0,8
	15	NI-N45	1,32	3,96	Z-Axis	0,5	1,1	0,8	0,97

Tab. 1 Car-key energy harvester prototypes testing result

4. Conclusion and outlook

In summary, a novel electromagnetic energy harvester concept based on a non-resonant mechanism designed for a car-key application is demonstrated. Various magnet and coil forms were taken into account with a total of 28 experimental prototypes built up for testing. A maximum open circuit inductive voltage of 1.1V was obtained by a coil layout type B and a magnet of 15mm diameter.

Based on these results, further investigation into the theoretical method of parameter optimization is needed, e.g. the simulations model of the coupling between the electromagnetic flux and the copper coils in the random relative motion. Further investigations should include the influence of the magnet size and the configuration of the connection of copper-windings on each PCB layer.

References

[1] Manoli Y 2010 Proc. IEEE Eur. Solid-State Circuits Conf. (Seville) pp 27–36

[2] I. Kuehne et al.*: Energy autonomous sensors in the automobile,* 6. GMM-Workshop - Energieautarke Sensorik, pp.91-95, 2010

[3] D. Spreemann and Y. Manoli, *Electromagnetic vibration energy harvesting devices*, Springer Verlag 2012.

[4] T. von Büren and G. Tröster, *Design and optimiyation of a linear vibration-driven electromagnetic micro-power generator*, Sens. Acturators A135, 765-775 (2007)

[5] B. J. Bowers and D.P. Arnold, *Spherical magnetic generators for bio-motional energy harvsting*, Proc. PowerMEMS 2008, pp. 281-284.

[6] B. Yang and C. Lee, Non-resonant electromagentic wideband energy harvesting mechanism for low frequency vibrations, J. Microsyst Technol., Springer Verlag 2010.