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Procedia Chemistry 1 (2009) 1211–1214

Procedia Chemistry

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Proceedings of the Eurosensors XXIII conference

FR4-based electromagnetic energy harvester for wireless tyre sensor nodes

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Abstract

An electromagnetic (EM) power generator having 46 Hz resonance frequency is designed to scavenge mechanical vibrations occurring in tyres due to tyre-road contact. The major innovation is the use of FR4 as a structural spring material as well as utilizing a spacer and stopper mechanism increasing the shock resistance by limiting the maximum deflection. The novel magnet assembly and spacer design provide high power density. The tangential acceleration waveforms of typical tyre rotation is used as an input in the experiments and 0.4 mW power is obtained over a 100 Ω load resistance for 15g peak-to-peak amplitude at 22,83 Hz, corresponding to about 150 kph vehicle speed. Maximum acceleration is limited with the shaker, larger power values are expected in actual operation. The performance is obtained off-resonance and superior to resonant Silicon MEMS based scavengers.

Keywords: FR4; electromagnetic energy harvesting; environmental vibrations; tyre-road contact

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1. Introduction

Motivation for this work is to design a compact, low-frequency and broadband electromagnetic energy harvester to power wireless tyre sensor nodes with optimal performance using the tangential acceleration waveforms, which occur as a result of tyre-road contact. Silicon based energy harvesters typically have high-resonant frequency (>KHz) because of high Young's modulus and operate in a narrow bandwidth, hence result in poor scavenging performance for most environmental vibrations that are typically below 100 Hz and broadband [1]. On the other hand, FR4, which is a very commonly used PCB material has a Young's modulus of 15-20GPa and has high intrinsic damping. We thus propose here FR4 for energy scavenging applications while investigating wireless tyre sensor nodes as a case study. A novel actuator design having resonance frequency within the range of the environmental vibrations is developed and tested. In addition, the maximum deflection of the actuator is limited by utilizing mechanical stopper mechanism since a vehicle tyre experiences high-g accelerations during actual operation.

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doi:10.1016/j.proche.2009.07.302

2. Accelerations due to tyre-road contact

Wireless tyre sensor nodes are widely used in vehicle monitoring applications like in the cases of SmarTire [2] for active tyre pressure monitoring and Pirelli's Cyberwheel [3], where special sensors are used to send information to dynamic control system of the vechicle that maintains the stability. Since these sensors should at least operate till the end of a single tyre life and it is important avoiding the battery change during operation, powering these wireless sensors via harvesting environmental vibrations is attractive.

In a rotating vehicle tyre, accelerations in three different directions that are lateral, tangential and radial [4] occur as the tyre periodically contacts with the road as shown in figure 1.a. Among these time varying accelerations, tangential accelerations that is shown in figure 1.b are studied in this work as the main source of environmental vibration causing out of plane motion of the magnet.

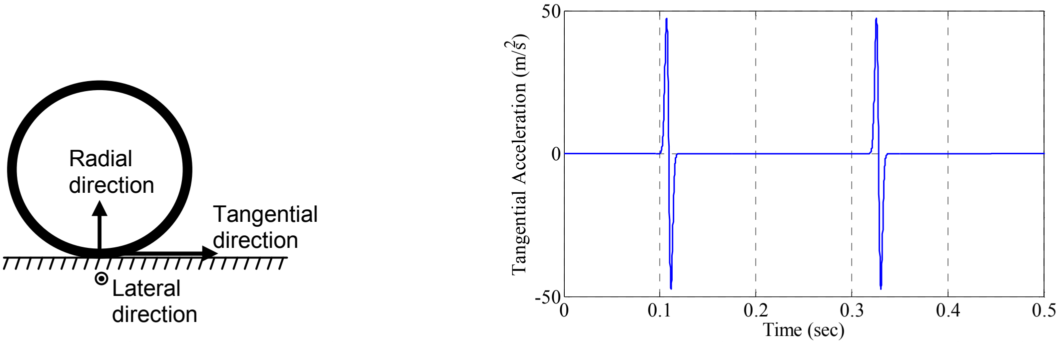

Fig. 1.(a) a schematic showing the contact acceleration directions. (b) a typical tangential acceleration waveform resulting from the tyre road contact [4]

The tangential acceleration waveforms can be fitted with the derivative of a Gaussian function enabling easier numerical analysis. The contact time duty-cycle is estimated at 10-15%. The signals are like impulse and have rich harmonic content. Therefore, energy harvesting at sub-harmonics is an efficient way to increase the range of harvesting frequency besides the resonance operation that is already the optimum for energy scavenging.

3. Tyre energy harvester design

3.1. Overall harvesting system

Figure 2.a and Figure 2.b show the novel actuator geometry and the compact tyre scavenger system respectively. The FR4 spring is sandwiched between two thicker FR4 platforms, which are attached to each other tightly. The magnets are placed on top of the aperture having a size of 6 x 6 x 0.32 mm. The volume of the device is primarily determined by the coil and the main magnet that is oversized relative to the FR4 springs, which are underneath the magnet. The smaller magnets beneath the oversized magnet are used as spacers and they stay hidden inside the pickup coil. By this way, the system becomes compact, which increases the power density in turn.

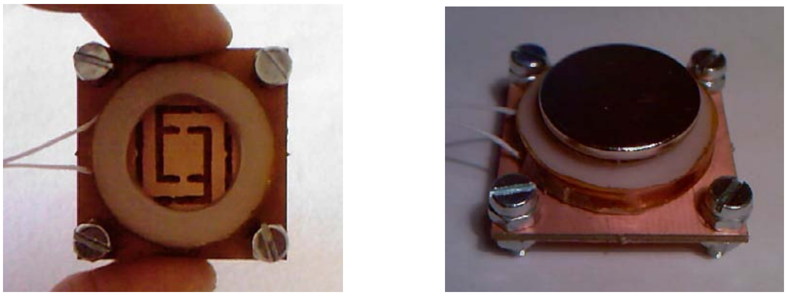

Fig. 2. (a) FR4 spring geometry. Two modes of vibration are 14.4 Hz (torsion) and 24.4 (OOP) (b) assembled structure with an oversized magnet placed on top having a radius of 10 mm and a height of 2 mm.

3.2 Magnet configuration and stopper mechanism

Besides acting as spacers enabling to place a bigger magnet on top, the stacked magnet configuration that is illustrated schematically in Figure 3 provides a higher magnetic flux gradient compared to a single magnet, which in turn induces a larger emf.

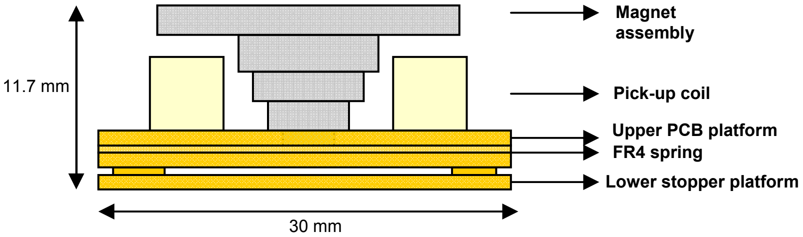

Fig.3. a schematic illustration of stacked magnet configuration which is used as i) mechanical stopper ii) creating a higher flux gradient.

Furthermore, the lower stopper platform and the pick-up coil itself act as mechanical stoppers to prevent failure of springs due to high-g accelerations under road conditions. When the spring experience large deformation, it makes hard contact with the platform or the bobbin. The maximum deflection of the spring is tuned in the limits of the elastic recovery, so any kind of plastic deformation and failure are prevented. FR4 performed very well in reliability tests up to 250 million cycles and can be operated at fatigue stress level up to 100MPa [5]

4. Shaker experiments & results

In order to test the power generation performance and the robustness of FR4 harvester, different shaker experiments are carried out. First, the device is tested at its resonance frequency with a sinusoidal input to determine its Normalized Power Density (NPD) [6]. The device is tested for 10.8 m/s^2 acceleration input amplitude at its resonance operation, it exhibits an RMS power of 0.876 mW across a load resistance that is 100 Ω. This performance is quite well for a low frequency harvester.

At the second step, the harvester is tested with tangential acceleration waveforms similar to the one shown in figure 1.b. Again, the shaker, on which the harvesting system and the load resistance are placed is driven with tangential accelerations that are achieved via arbitrary signal generator. Figure 4 demonstrates the FR4 harvester's performance on induced voltage for selected vehicle speeds that are typical to occur for a vehicle having an outer diameter of 57 cm.

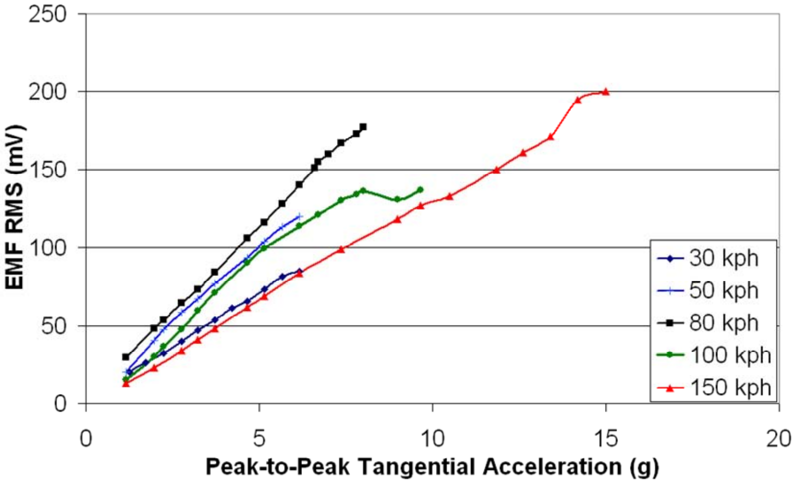

Fig. 4. emf obtained across 100 Ω load at selected vehicle speeds using 1Hz=6.57 kph as the conversion factor.

The maximum power scavenged corresponding to 200mV maximum emf is 0.4 mW and this is achieved at off-resonance operation. Due to shaker's frequency-amplitude limitation, the acceleration amplitude is set to the maximum of the shaker for each frequency. For example, only 15g p-p acceleration could be given for 150 kph, at which largest emf is observed, but p-p accelerations about 70g is expected in actual operation, so a higher level of voltage can be induced. Another important result is that the power extraction is more efficient at the subharmonics for off-resonance operation when a frequency sweep is performed. This could be observed from figure 4. The slope for 80 kph (one fifth subharmonic) is larger than other tested speeds. The same effective power generation is observed at odd subharmonics like one third, one seventh, one ninth and etc.

5. Conclusion

In this work, a low-frequency and a compact EM energy harvester is designed and tested. The manipulation of FR4 as a vibrating platform is the major innovation. FR4 lets design low-frequency and broadband harvesters due to its high intrinsic damping and is highly integrable with electronics. Since the environmental vibrations are also at low frequencies (typically below 100 Hz) and broadband, FR4 acts as a good alternative to silicon-based energy harvesters, whose resonance frequencies are typically on the order of kHz and narrowband. As a case study, powering wireless sensor nodes are investigated since they are widely used in many applications and the power consumption of the sensors are about 1mW. Considering the tangential acceleration waveforms resulting from the tyre-road contact as the main source of vibration, experiments are carried out emulating these waveforms. 0.4 mW power is achieved for 150 kph vehicle speed for a load resistance of 100 Ω. These values are expected to be larger at real operation. Moreover, many of these harvesters can be connected serially inside the inner liner of the tyre, which will increase the obtained power.

Acknowledgements

The authors are grateful to Dr. Erdem Alaca for his support during the research. We would like to thank Dr. Ipek Basdogan for providing access to shaker and Utku Baran and Adil Tolga Gorgulu for helping to carry out shaker experiments. Also, we thank Selim Olcer for his effort on manufacturing the FR4 actuators in our facilities. This work is accomplished by TUBA-GEBIP grant to HU.

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