MICROSCALE ENERGY HARVESTER DRIVEN BY A BUILT-IN PERMANENT MAGNET FOR SELF-POWERED NODES IN APPLIANCE POWER CABLES

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Abstract: This work introduces a micro-scale vibrational energy scavenging approach that uses a permanent magnet as both inertial mass and magnetically induced actuation. This idea comes from our previous work, where the concepts of using a whole energy scavenging chip as inertial mass and maximizing the transduction area were introduced. In this case, the role of inertial mass is played by the core die as well as a permanent magnet that is placed on top of this chip. All these coupled elements together form an electrostatic energy harvester in package with magnetically induced resonant movement. The detailed study about the use of the magnetic field generated by a two-wire cord has been carried out. Different numerical calculations and simulations have been performed to find the optimum design parameters and validate the main idea proposed in this work.

Keywords: ENERGY HARVESTING, ENERGY SCAVENGING, PERMANENT MAGNET.

INTRODUCTION

The concept of energy harvesting has received a huge attention during the last years because of the need of find an autonomous way of supplying low-power integrated system. Wireless sensor nodes (WSN) concept is an especially interesting application where avoiding the use of batteries is critical, and the mechanical energy harvesting from the ambient could be a real alternative.

Since the weak point of the vibration-based energy scavengers is the difficulty of having an available ambient vibration with a constant-amplitude, frequency-stable and continuous-time, a new application field has to be exploited to find different ambient energy sources. For instance, the grid power is normally available in a domestic or industrial ambient and it is always generating parasitic magnetic energy which could be used to power numerous self-powered devices.

We have performed an analysis about the suitability of using the resulting force generated by a two-wire cord carrying an AC electric current over a permanent magnet. The sinusoidal magnetic force induced by the wires can be used to excite the resonant movement of a vibrational energy harvester tuned to the grid power frequency (50 and 60 Hz for Europe and US respectively).

FABRICATED DEVICE DESCRIPTION

We need to obtain a device equivalent to a damped mass-spring system capable to get in resonance at the required frequency. The typical approach consists of using a macroscopic piezoelectric beam with a large magnet attached to its tip. The main disadvantages of this system are the large size and the impossibility of putting the device close to the wires. In order to solve these problems, the concept of energy harvester in package (EHiP) presented in [1, 2] could be used.

In these previous works, the concepts of using a whole energy scavenging chip as inertial mass and maximizing the transduction area were introduced. In this case, the role of inertial mass is played by the core die as well as the permanent magnet that is placed on top of this chip. All these coupled elements form a micro-scale electrostatic energy harvester integrated in a package and with a magnetically induced resonant movement.

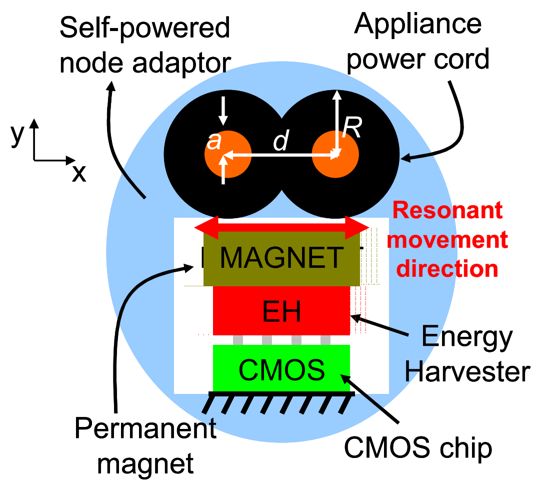

Fig. 1: Diagram of a magnetically-actuated Energy Harvester in Package (EHiP) attached to an appliance power cord.

The idea of this paper is to take advantage of the fabricated chip presented in [2] by using it for this new approach. The original main features of this device are a resonant frequency of 265 Hz and maximum and minimum capacitance values of 178 pF and 32 pF respectively.

These values mean an ideal maximum power around 20 µW, i.e. 1.5 mW/cm^3, with an initial and final voltage of 10 V and 55 V respectively and an effective quality factor of 50. The required acceleration magnitude to reach the maximum capacitance position is around 0.4 m/s^2.

Table 1: Device and power cord features

Parameter		Value
Chip mass	m_{chip}	27 mg
Magnet mass	m_m	800 mg
Magnet remanence	Br	1.22 T
Length of cubic magnet side	l_m	4.85 mm
Conductor wire radius	a	0.65 mm
Distance between center of wires	d	3.6 mm
Radius of wire insulation	R	1.95 mm
Current carried by the cord	i	10 A (AC)

Due to its reduced size, this energy scavenger can be placed close to the wires of the cord to find the point of maximum generated force over the magnet. Fig. 1 shows a proposed adaptor to place the energy harvester in the desired position. The main parameters of this system are described in Table 1.

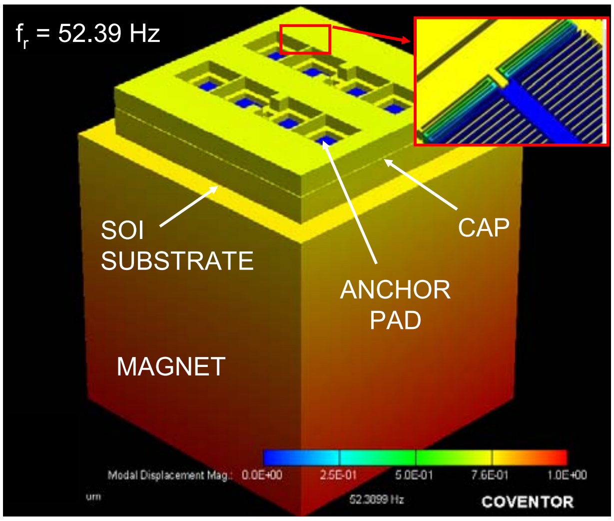

Fig. 2: FEM modal simulation of the first resonant mode. Note that the chip is anchored by the pads. Inset: Detail of compressed suspensions and electrostatic transduction bellow protective cap.

This couple of chip and PCB has a resonant frequency of around 289 Hz (experimentally measured) which drops to 50 Hz by means of adding the mass of the permanent magnet, as shown in Fig. 2.

The resulting total mass of around 827 mg. will displace around 3.9 µm due to the gravity. Since the maximum internal distance to the substrate is 2 µm, it is probably the appearance of an additional friction. Thus a new fabrication with less rigid suspensions for out-plane movements should be taken into consideration.

THEORETICAL FUNDAMENTS

The magnetic field, $\vec{H}$, generated by a current-carried single wire is described by the Biot-Savard Law:

$$\left.\begin{aligned} r > a, \quad \vec{H} &= \frac{i}{2\pi r}\vec{u_t}\times\vec{u_r} \\ r < a, \quad \vec{H} &= \frac{ir}{2\pi a^2}\vec{u_t}\times\vec{u_r} \end{aligned}\right\} \qquad (1)$$

Where i is the current passing trough the wire, r is the radial distance from the center of the wire to the point of interest, $\vec{u_l}$ and $\vec{u_r}$ are unitary vectors pointing to the current direction and the interest point respectively.

From [3, 4] we know that the force applied to a permanent magnet with magnetization, $\vec{M}$, by an external magnetic field, $\vec{H}$, can be calculated by integration of the force density, $\vec{f}$, over the magnet volume, V.

$$\vec{f} = \vec{\nabla}(\vec{M}\cdot\vec{H}) \qquad (2)$$

Since the magnetization of the permanent magnet is constant, the longitudinal forces are given by,

$$F_{xMx} = B_r\int\frac{dH_x}{dx}dV\,, \qquad F_{yMx} = B_r\int\frac{dH_x}{dy}dV \qquad (3)$$

$$F_{xMy} = B_r\int\frac{dH_y}{dx}dV\,, \qquad F_{yMy} = B_r\int\frac{dH_y}{dy}dV \qquad (4)$$

Where the remanence of the permanent magnet, B_r, is uniform and oriented in the positive x-direction (M_x) or y-direction (M_y).

NUMERICAL CALCULATIONS

A MATLAB® program has been created to numerically compute the magnetic force generated by two wires carrying an alternating current. In parallel, several COMSOL® simulations have been carried out to verify the right working of the numerical calculations.

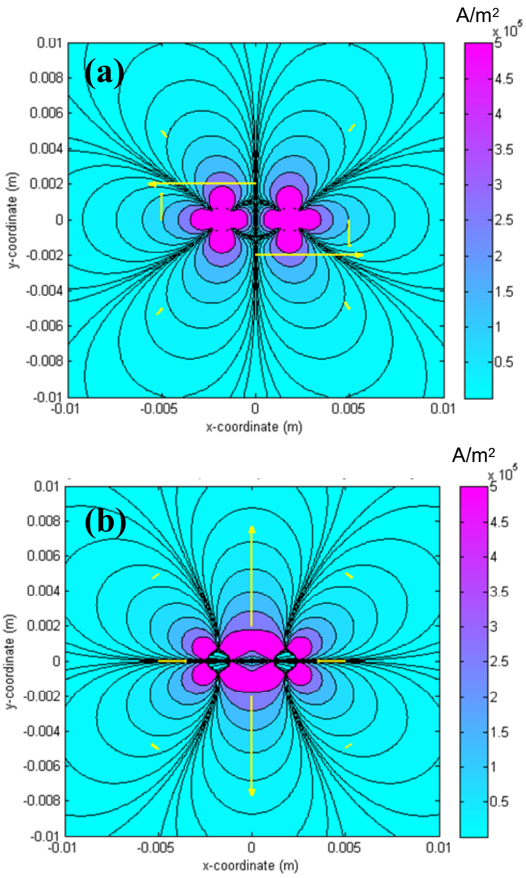

Fig. 3: Magnitude of the horizontal (a) and vertical (b) components of the gradient of the magnetic field in x-axis (a) and y-axis (b) directions. Magnetic force vectors for horizontally (a) or vertically (b) magnetized permanent magnets.

Fig. 3 shows the two components of gradient of the magnetic field generated by the two wires of a power cord. The magnetic force has been calculated by integration of this gradient over the volume of the desired permanent magnet. Several positions for the magnet vertically and horizontally magnetized respectively are represented in the same Fig. 3.

From the analysis of this figure, we can realize that the more interesting working positions of the magnet are through the y-axis, because a force with maximum magnitude and only one direction can be obtained. For our purpose a magnet horizontally oriented is going to be used to get a lateral magnetic force.

PARAMETRIC MODELIZATION

In [3], Leland et al. calculated the expression (5) for the y-direction gradient of H_y along the y-axis line. They found the location when the gradient is maximum and they claim that the magnetic force will be maximum in this position too. However, it is not completely right, because the magnetic force is proportional to the area behind the gradient surface. Hence, the magnet will enclose this maximum of gradient, but the optimum magnet center position is farer from the wires when calculating by numerical methods. It offers us a more profitable working position range.

$$\left.\frac{dH_y}{dy}\right|_{(x=0)} = -\frac{i2yd}{\pi(y^2+d^2)^2} \qquad (5)$$

However, we can use this expression (or the analogous for an x-axis oriented magnet) to calculate the force by supposing that the gradient has the same shape for the whole magnet volume.

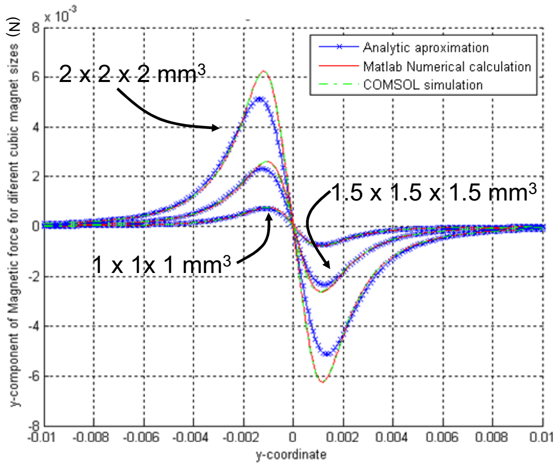

Fig. 4: Comparison between different methods to calculate the magnetic force along the y-axis for three magnet sizes.

The comparison between this approximation, a COMSOL® simulation and MATLAB® numerical calculation is shown in Fig. 4. We can realize that both numerical approaches to calculate the magnetic force for several magnet sizes have identical shape, but the approximation is not able to fit them perfectly. The differences between them are clearer when the magnet size increases. Nevertheless, it can be certainly useful as analytic approach the early design stages.

Table 2: Scaling of magnetically actuated vibrational energy harvesters.

Physical quantity		Scaling
Remanence of magnet	B_r	1
Resonant frequency ($\omega = \sqrt{k/m}$)	Ω	1
Volume and Mass	V, m	S^3
E.M. force ($F \sim MV\, dH/dx$)	F_{EM}	S^2
Acceleration ($a = F_{EM}/m_{inertial}$)	A_{cc}	S^{-1}
Amplitude at resonance ($z_{dyn} = QAcc/\omega^2$)	z_{dyn}	S^{-1}

We have considered the scaling of all the device parameters when all geometrical dimensions are scaled by a factor S [5]. It is easy to find that the induced acceleration in the inertial mass of the energy scavenger is higher when we scale down and keep constant the resonant frequency. Thus, the design of devices to harvest this kind of parasitic energy with resonant devices has to be oriented toward micro-scale.

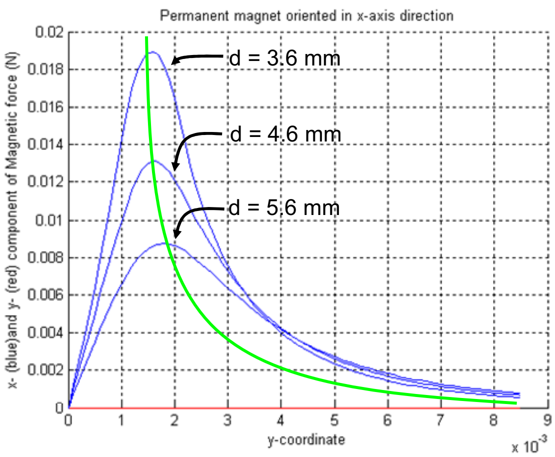

Fig. 5: Parametric study between magnetic force and separation of the cord wires.

A parametric analysis has been made with a magnet size of 1 x 1 x 1 mm^3 and changing the distance between wires. In Fig. 5 we can see that the larger the distance between the wires, the lower the force magnitude. But another interesting effect is taking place, the curve maximum is moving away from the cord insulation layer and it is now possible to place the magnet in this maximum induced force point. In order to take advantage of this positive effect, Fig. 6 shows a new proposal to attach the energy harvester to the power cord.

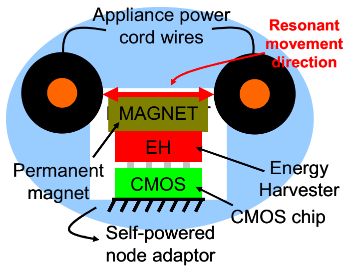

Fig. 6: Diagram of new possibility of attaching the energy harvester to an appliance power cord.

CONCLUSIONS

A deep theoretical study based on a numerical method analysis has been performed concerning the use of the magnetic force generated by a current-carrying cord in a permanent magnet. We have demonstrated that the use of a micro-scale energy harvester attached to a power cord could be advantageous. Due to the EHiP concept presented in [1, 2], we can obtain a reduced size and a high extracted power density.

In order to demonstrate these advantages, the micro-scale energy harvester presented in [2] is being adapted with a permanent magnet to achieve a magnetically actuated resonant device tuned to 50Hz.

ACKNOWLEDGMENTS

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