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ELECTROMAGNETIC INERTIAL GENERATOR FOR VIBRATIONAL ENERGY SCAVENGING COMPATIBLE WITH Si TECHNOLOGY

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Abstract: This work reports the design and optimisation of an electromagnetic (em) vibrational generator for energy scavenging applications, compatible with Si technology. The device has a simplified structure formed by a fixed coil and a movable magnet onto a resonant vibrational membrane. The design is based on the calculation of the em damping coefficient [1], performed by Finite elements analysis (ANSYS). The results obtained point out the compatibility of this simple device structure with the generation of powers ranging between some μW's to some hundreds of mW, for f_{res} in the range between 10 Hz and 5 kHz.

Keywords: Power microgenerators, electromagnetic inertial generators, vibrational energy scavenging

1.- INTRODUCTION

The autonomy requirements of modern microsystems for wearable, ubiquitous and self-powered applications have raised an increasing demand for the development of power supplies suitable for their integration with next the generation of micro and nanosensors. For these applications, an interesting option is the use of inertial microgenerators for energy scavenging from the vibration in the environment [1,2]. These devices constitute perpetual energy sources without the need for refilling, thus being well suited for abandoned sensors.

This work describes the design and optimisation of an electromagnetic inertial microgenerator. This device constitutes an inertial velocity damped resonator, which is suitable for harvesting of mechanical energy from vibrations induced by operating machines and engines. These vibrations are characterised by a well defined frequency and low displacement amplitudes [3]. Adjusting the resonant frequency of the system to that of the vibrations allows to amplify these low amplitude displacements. For these applications, the use of an electromagnetic device has the potential advantages of a high level of compatibility with Si Microsystem technology, as well as the possibility of relatively high electromechanical coupling with simple designs.

The device proposed in this work is formed by a fixed coil and a movable magnet mounted on a resonant structure. Figure 1 shows a schematic representation of this design. Assuming a resistive load, the device behaves as an inertial resonator if the inductive component of the coil impedance is much lower than the resistance in the circuit. In this case, the power generated at resonant conditions is given by [1]:

$$P_{res} = \frac{\zeta_g Y_o^2 \omega_n^3 m}{4\left(\zeta_g + \zeta_p\right)^2} \qquad (1)$$

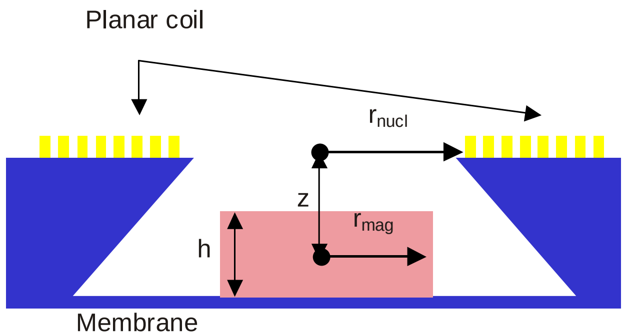

Figure 1. Schematics cross section of the device

where Y_o is the amplitude of the vibrations applied to the device and ω_n is the natural frequency of the resonator with inertial mass m. ζ_g is the normalised electromagnetic damping factor:

$$\zeta_g = \frac{1}{2m(R_C + R_L)\omega_n}\left(\frac{d\phi}{dz}\right)^2 \qquad (2)$$

with R_c and R_L the coil series and load resistances, respectively. ($d\phi/dz$) is the magnetic flux rate through the coil due to the magnet displacement. This model also takes into account the existence of a parasitic damping ζ_p, related to air resistance and hysteresis loss effects in the mechanical resonator. From (2), it can be derived that one condition leading to a maximum value of P_{res}, is $\zeta_g = \zeta_p$. However, the power dissipated in the coil series resistance determines that only a fraction of the power given by (1), P_L, is available at the load resistance. Deriving this power in relation to R_L it is possible to determine the optimum value of R_L which maximizes P_L:

$$R_{Lopt} = \frac{1}{2m\omega_n \zeta_p}\left(\frac{d\phi}{dz}\right)^2 + R_C \qquad (3)$$

which gives the following expression for the maximum power dissipated at the resistive load:

$$P_{Lopt} = \frac{Y_o^2\ \omega_n^3\ m}{16\,\zeta_p}\ \frac{\zeta_c}{\zeta_c + \zeta_p} \qquad (4)$$

where ζ_c corresponds to the electromagnetic damping obtained with R_L=0. This function increases monotonously with ζ_c which, in turn, is inversely proportional to R_C. According to this, the maximum power, obtained when $R_c \rightarrow 0$, is $P_{Lmax} = [(Y_o^2\ \omega_n^3\ m)/(16\ \zeta_p)]$. Then, the optimum design in terms of the generated power corresponds to a minimum value of both R_C and ζ_p.

On the other hand, the generated voltage is given by the time derivative of the magnetic flux. At resonant conditions, the voltage amplitude at the load is given by:

$$V_o = \frac{R_L}{(R_C + R_L)}\ \frac{Y_o\ \omega_n}{2\ (\zeta_g + \zeta_p)}\ \left(\frac{d\phi}{dz}\right) \qquad (5)$$

In this case, the voltage increases with the value of R_L, and tends asymptotically to $V_{omáx}$:

$$V_{o\max} = \frac{Y_o\ \omega_n}{2\ \zeta_p}\ \left(\frac{d\phi}{dz}\right) \qquad (6)$$

This implies that, in relation to R_L, the conditions leading to a maximum voltage ($R_L \rightarrow \infty$) do not agree with those corresponding to the maximum output power ($R_L = R_{Lopt}$). In this last case, the amplitude of the generated voltage is half the value of the maximum voltage given by (6). On the other hand, both parameters increase when the parasitic damping decreases. However, in this case one has to bear in mind that decreasing the total damping in the system also leads to a decrease in the range of values of Y_o which are compatible with the device design. This is determined by the existence of a higher limit Z_L for the displacement of the inertial mass in the device, imposed by the potential collision of the mass with fixed parts in the system. For a given value of Y_o, this imposes the need to have a value of total damping $(\zeta_g + \zeta_p) \geq [Y_o/(2Z_L)]$.

2. DESIGN OF DEVICE

The design of the device is based on the calculation of the magnetic flux rate, which has been performed by Finite Elements (FE) analysis (ANSYS). The fixed coil in our first prototype has an area of about 1 cm^2, and is formed by 30 μm wide metal tracks with a separation between tracks of 20 μm. Two different geometries have been analysed, which correspond to circular and square shaped coils, respectively. The permanent magnet is a commercially available NdFeB magnet, with Mz = 954,9 kA/m, 2mm high, and the cross section of the magnet has the same shape as that of the coil. In order to maximize both the power P_L and the voltage V_o, we have investigated the conditions leading to a higher magnetic flux rate.

The FE analysis of $(d\phi/dz)_{max}$ as a function of the separation of the centre of the magnet from the coil plane (z), and of the dependence of on r_{mag} has been performed for both circular and square shaped configurations, and assuming the same value of L_{ext} for the diameter of the outer turn. The results indicate that i) $(d\phi/dz)$ increases with the magnet size, and the optimum case is obtained when the magnet fills the whole nucleus area and ii) that there is a maximum value of the flux rate when the upper surface of the magnet is located in the plane of the coil. This corresponds to z ~ h/2 in fig.1.

Finally, the analysis of the flux rate as a function of the number of turns in the coil is shown in Fig. 2. The value for which the highest flux rate is achieved corresponds to the coils with 29 turns and a nucleus of 8x8 mm^2. This figure also shows the existence of a higher flux rate for the square shaped coil. This has lead to the selection of this design for the implementation of the device prototype.

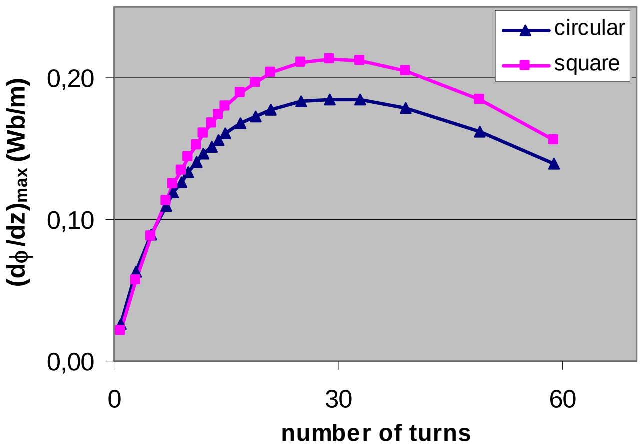

Figure 2: Magnetic flux rate vs number of turns

3. RESONANT STRUCTURE

In a first stage, we have considered the implementation of the resonant structure with a thin polyimide film (Kapton®). This polymer has a Young modulus significantly lower than that of Si related materials (E = 2.5 Gpa), which is better suited for the design of structures with resonant frequencies in the range from few Hz's to few kHz's. A structure formed by a square shaped membrane with an inertial mass corresponding to the magnet filling the nucleus of the coil has been implemented, using a 11x11 mm^2 Kapton® membrane with a thickness of 51 μm. This has been fixed on a PCB square frame and the NdFeB permanent magnet has been glued on the centre of the membrane. To avoid potential collisions of the magnet with the edges of the coil nucleus, a magnet with a size a bit smaller than that of the nucleus has been used (7x7 mm^2).

The preliminary characterisation of this structure shows a resonant frequency similar to that simulated by ANSYS (in the range of 300 Hz). The fitting of the experimentally measured resonant peak has allowed to estimate the parasitic damping coefficient in the resonator, to a value of ζ_p= 0,05 for a Kapton membrane fixed to the PCB frame with adhesive tape. Increasing the adherence of the membrane to the frame with a permanent glue allows to obtain a decrease in this parameter, down to ζ_p= 0,023. However, this value is still significantly higher than that previously reported in the literature for devices with a similar design structure [1,4].

4. DEVICE MODELLING AND OPTIMISATION

A device prototype has been fabricated with the design described in Section 2. In this first prototype, the coil has been made with 1.5 µm thick Al metal tracks. This determines a relatively high value of the resistance of the coil, $R_C \sim 910\ \Omega$. The calculation of the power generated at optimum conditions ($R_L = R_{Lopt}$) and assuming the value of ζ_p= 0,023 (experimentally estimated in sect. 2) gives an output power $P_{Lopt} \geq 1$ µW for vibrations with $Y_o \geq 10$ µm and $f_{res} \geq 300$ Hz.
Decreasing the value of R_C can be achieved by using a thicker metal for the coil tracks. For this, the selective growth of 50 µm Cu metal tracks by electrochemical deposition [5] is proposed, in combination with a previous Hot Embossing Lithography process. Figure 3 shows SEM images of the micromould that has been fabricated with Deep RIE, following the same design as described above. The series resistance of this device should drop down to a value of $R_C = 8.4\ \Omega$. This would lead to an increase of two orders of magnitude in the generated power assuming the same conditions as in the previous case, obtaining a value of $P_L \geq 100$ µW.

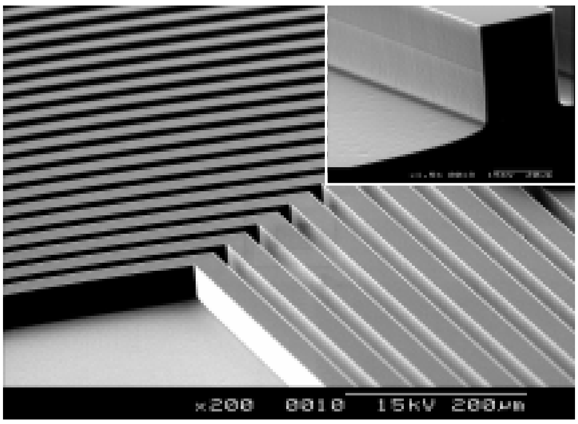

Figure 3: micromould made by DRIE for the fabrication of a coil with 50 µm thick metal tracks using HEL and selective Cu electrodeposition

On the other hand, the analysis of the dependence of the magnetic flux rate as a function of the width of the metal tracks and their separation reveals the possibility to obtain a further increase in the value of the magnetic flux rate by decreasing both the width of the metal tracks and their separation, allowing in our case a value of 6 µm for both parameters compatible with the DRIE processes.

In addition to this, it is important to remark that a critical feature limiting the performance of these devices is the relatively high value of ζ_p= 0,023 found in our structure. As already indicated, this is significantly higher than the value reported by [4] (ζ_p = 0.0037). The higher value of ζ_p encountered in our case could be related to the process performed for the membrane implementation (cutting a piece of polyimide foil and fixing it onto the PCB frame), which could lead to higher residual strain effects and lower membrane adhesion. This suggests the need to improve the technological process for the mechanical implementation of the device. A significant improvement in the parasitic damping effects could be obtained by replacing the polyimide films by membranes made of materials with low mechanical hysteresis losses, such as Si. On the other hand, a further reduction of parasitic damping could still be achieved by performing the encapsulation of the devices under vacuum conditions.
The critical role of the parasitic damping in the characteristics of these devices has been analysed by calculating the maximum output power (i.e. for $R_L = R_{Lopt}$) and the maximum generated voltage (eq. (6)) as a function of ζ_p, for a coil design similar to our first prototype but with lower values of metal track width and separation, assuming in both cases coils formed by 50 µm thick Cu tracks. In these calculations, we have used excitation conditions considered as representative of the low level vibrations typically present in domestic and office environments [3] (Y_o = 4.4 µm, f = 120 Hz and acceleration amplitudes in the range 1 to 10 m/s^2. Assuming the value of ζ_p = 0,0037 reported in [4], the modelling of the device working with $R_L = R_{Lopt}$ gives values of P_L = 81 µW and V_o = 158 mV. Increasing the load resistance to values $R_L > R_{Lopt}$ allows to increase the output voltage to levels more acceptable for practical applications, although this also implies a decrease in the generated power. So, using $R_L = 900\ \Omega$, this calculation gives values of P_L = 40 µW and V_o = 270 mV, respectively.
A significant increase in the generated voltage requires for a further optimisation of the parasitic damping. However, this has also to take into account the minimum value required for the damping compatible with Y_o and Z_L. We have made a conservative estimation of $Z_{L,}$ by fixing the highest position of the base of the magnet with the plane of the coil, which gives $Z_L = z + h/2$ (see Fig. 1). This leads to a limit value for the total damping of ζ = 0,00125 for $Y_o \approx 5$ µm. Assuming this value for ζ_p (which, according to the previous considerations, is compatible with the amplitude of 4.4 µm of the used vibrations), the calculation leads to P_{Lopt} = 385 µW (fig. 4a), and V_o = 469 mV (fig. 4b) for $R_L = R_{Lopt}$ = 285 W. Higher values of R_L allow the generation of P_L = 58 µW with a voltage amplitude V_o=0.9V.

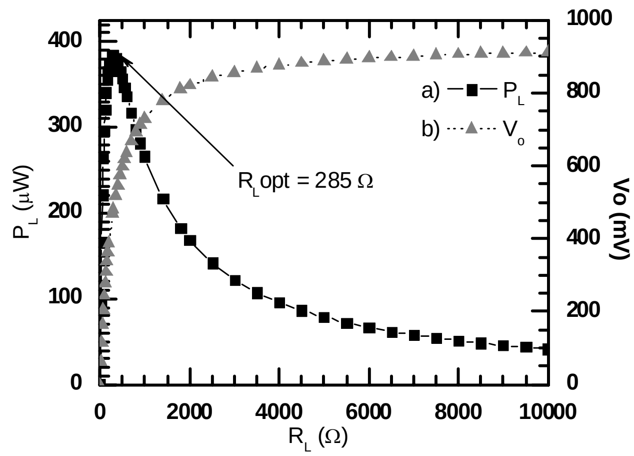

Figure 4: generated power and output voltage vs load resistance (Track width and separation: 6 µm, thickness 50 µm, ζ_p = 0,00125 for $Y_o \approx 5$ µm at 120 Hz).

The comparison of these data with those reported in the literature for the same excitation conditions points out the possibility to generate similar power levels with the electromagnetic device proposed in this work, obtaining higher values than with other approaches such as the electrostatic one. In this last case, Roundy et al have reported a value of 43 µW from the simulation of an optimised design of electrostatic generator [3]. They have also developed a prototype of piezoelectric generator, which gives a higher power of 70 µW/cm^3. Simulations show that an optimised design would be capable of generating a power of 250 µW for the same vibration source, which is still lower than the maximum value of P_{Lopt} = 385 µW simulated for the optimised electromagnetic design. It is interesting to remark that the devices described in [3] correspond to designs with a total volume of 0.5 cm^3, which is of the same order of magnitude of the volume that can be estimated for our device (in the range 0.6-0.7 cm^3).

In relation to previous works proposing electromagnetic generators with a similar structure formed by a fixed coil and a movable magnet [4,6], the simulation of the devices using the same excitation conditions as in these works reveals the possibility to generate much higher (about three orders of magnitude) power levels. This is related to the higher values of the magnetic flux rate achieved with the proposed designs (0.21 Wb/m and 0.721 Wb/m), in front of the values reported of $1{,}5\times10^{-3}$ Wb/m [4] and 7×10^{-3} Wb/m [6], respectively.

5. CONCLUSIONS

In this work, the design of an electromagnetic inertial microgenerator is performed, based on the calculation of the magnetic flux rate by FE analysis, which has allowed studying the effects of different parameters, such as the size of the magnet and the shape of the device. Optimisation of the device in terms of both series resistance and parasitic damping is discussed, and the optimised device is modelled for the calculation of generated power. The values obtained indicate the possibility to obtain power levels up to 385 µW (with voltage amplitudes in the range of 0.5 to 0.9 V) for excitation conditions corresponding to low level vibrations (acceleration amplitude of 2.5 m/s^2 at 120 Hz). This is conditioned to the ability to develop resonator structures with suitable values of parasitic damping. In this sense, the preliminary data obtained with membranes fabricated using thin polyimide foils suggest the interest to replace these films by membranes made of materials with low mechanical hysteresis losses, such as Si.

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