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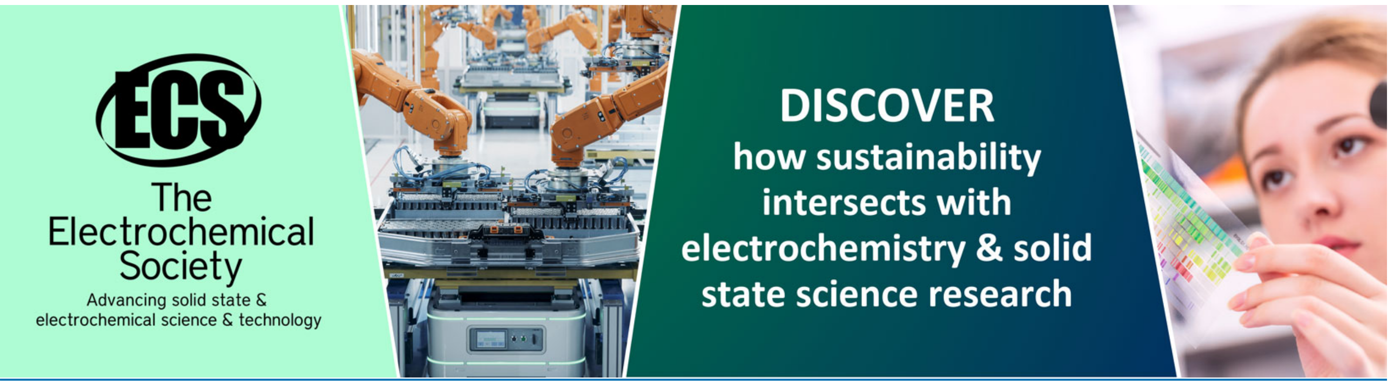

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Scaling effects in a non-linear electromagnetic energy harvester for wearable sensors

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Abstract. In the field of inertial energy harvesters targeting human mechanical energy, the ergonomics of the solutions impose to find the best compromise between dimensions reduction and electrical performance. In this paper, we study the properties of a non-linear electromagnetic generator at different scales, by performing simulations based on an experimentally validated model and real human acceleration recordings. The results display that the output power of the structure is roughly proportional to its scaling factor raised to the power of five, which indicates that this system is more relevant at lengths over a few centimetres.

1. Introduction

The energetic self-sufficiency of body-worn sensors is an important matter to enhance usage convenience and durability. In certain applications such as sportswear and smartwatches, one relevant approach consists in converting a small fraction of the user's mechanical energy into the required electrical energy. In a previous study [1], we proposed an original optimization method for an inertial generator whose structure is well-known and studied in several works [2-4]. A prototype roughly the size of an AA battery (15mm Ø x 52mm length) carried in an armband by a subject running on a treadmill produced high power densities, up to 550µW/cm^3 in a resistive load.

This type of inertial harvester complies well with several wearable systems requirements, such as low cost and easy hermetic packaging. However, the comfort of the solutions remains a challenge, because of their inherent rigidity and volume, and pushes towards the continuous reduction of their dimensions. Therefore, we examine in this paper the impact of the down-sizing of the previously studied structure.

2. Generator structure and model

The generator is composed of a magnetic mass moving between two repulsive magnets inside a straight-lined tube, around which are wrapped several identical and independent coils to enable Faraday's induction (*Figure 1a*). The moving mass includes several magnets with alternate polarities, separated by ferromagnetic spacers. This configuration aims at providing high electromagnetic damping levels [4].

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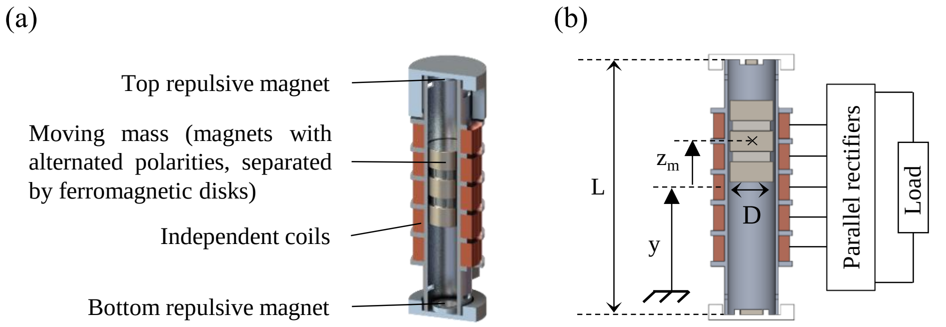

Figure 1 – (a) Structure of the non-linear harvester. (b) Model parameters

Model parameters for this structure are illustrated in *Figure 1b*. The evolution of the position of the moving mass m in the reference frame of the generator when the latter is subject to an exterior stimulation $\ddot{y}$, and the instantaneous dissipated electrical power P_e are expressed in equations (1) and (2), respectively. c_m is the constant mechanical damping coefficient (fixed at 0.01 N.s/m for all this study). c_e is the electrical damping coefficient, approximated by a periodic function of the mass position z_m, with an amplitude A_{Ce} and a spatial period p equal to the magnetic period of the multipolar mass (3). F_{rep} is the magnetic repulsion force estimated numerically (for both top and bottom repulsive magnets). The complete model for this system and its experimental validation are detailed in [1].

$$m\ddot{z}_m + c_e(z_m)\dot{z}_m + c_m\,\dot{z}_m - F_{rep}(z_m) = -m\ddot{y} \tag{1}$$

$$P_e = c_e(z_m)\,\dot{z}_m^2 \tag{2}$$

$$c_e(z_m) = A_{Ce}\cos^2\left(\frac{2\pi}{p}z_m + \beta\right) \tag{3}$$

3. Method

Using Matlab Simulink, we simulated the performances of the previous modelled system for various generator sizes, with a recorded acceleration sample as the mechanical input $\ddot{y}$ (subject running at 4.8 km/h on a treadmill, with the system fixed at his arm). The ratio between the guiding tube's length L and inner diameter D was kept constant and equal to $L/D=6.25$. The scaling factor k is defined as $k=D/D_0$, where $D_0=8mm$ is the inner diameter of the AA battery-sized reference energy harvester presented in [1]. For each value of k, all other parameters were optimized numerically to yield the maximum electrical power, while preventing shocks between the moving mass and the repulsive magnets. Output voltage was also considered to control the application-readiness. From the value of the optimal electrical damping determined in the power optimization step, the parameters of the multipolar magnetic mass, and the choice of some coils properties (60µm Ø copper wire, 0.5 copper fill factor), we evaluated an optimal number of turns of the coils and the associated electrical resistance R_c. Given that all coils are identical, and considering a unique resistive load R_l at the output of the parallel rectifying circuits, the portion of the electrical power dissipated at the load $\frac{P_l}{P_e} = \frac{R_l}{R_l+R_c}$ is identical for each coil. This configuration allows to calculate the RMS value of the output voltage V_{RMS} from the average dissipated electrical power $P_{e,ave}$, with $V_{RMS} = \sqrt{P_{e,ave} \cdot \frac{R_l^2}{R_c+R_l}}$.

4. Simulation results and discussion

The dimensions of the optimized systems at several different scaling factors k are displayed in *Table 1*. It is worth noticing that the shapes of the optimal repulsive magnets are rather 'flat', leaving a maximum length available for the inertial mass displacement. The simulated electrical performances are plotted in *Figure 2*.

Scaling factor k	L (mm)	D (mm)	Multipolar magnetic mass: Magnet unit (Ø mm x h mm)	Number of poles	Mass (g)	Repulsive magnets: Bottom magnet (Ø mm x h mm)	Top magnet (Ø mm x h mm)
0.38	18.75	3	3 x 3	2	0.34	2.6 x 0.1	0.6 x 0.2
0.5	25	4	4 x 3	2	0.64	4 x 0.6	1 x 0.2
0.63	31,25	5	5 x 4	3	2.2	2 x 1	1 x 1
0.75	37.5	6	6 x 4	3	3.2	6 x 0.5	4 x 0.1
1	50	8	8 x 4	4	7.8	8 x 1.5	4 x 0.5
1.25	62.5	10	10 x 4	4	9.2	10 x 3	10 x 0.5

Table 1 – Parameters of the optimized systems for the considered values of the scaling factor

4.1. Load power
The average electrical power dissipated by the load ($P_{l,ave}$) is plotted in *Figure 2b*. It varies from 38 µW (k=0.375) to 12.42 mW (k=1.25). An adjusted exponential trend αk^{β} with α=4.7 and β=4.8 is plotted alongside the simulated results, and indicates that the down-scaling possibilities of this structure are quickly limited. Several factors can explain this observation. Smaller moving masses obviously provide lower mechanical energy inputs. Besides, it was shown in [1] that limiting the amplitude of motion of the moving mass can also reduce the performances of inertial harvesters, and especially with human-type inputs. Finally, size reduction limits the levels of electromagnetic coupling achievable (*Figure 2c*), as shown in another study [5]. This effect can be observed here with all cases k ≤ 0.75, for which the optimal electrical damping corresponds to the maximum value that can be provided. This “saturation” lessens the power furthermore at the affected scales.

4.2. Output voltages
The calculated RMS voltages at the output load are indicated in *Figure 2d*. A particularity of the “periodic” electromagnetic damping provided by this generator structure is that a given value of its amplitude may correspond to different possible sets of coil parameters (length, number of turns). In particular, coils configurations with greater numbers of turns yield higher voltages. This effect especially visible for the greatest scales (for k=1.25, output voltages range from 0.7 V to 25 V). While the size reduces, the optimum coupling factor becomes equal to its highest value, thus reducing the number of optimum coils configurations and the relative output voltage range. At the lowest dimensions (k ≤ 0.63), levels of output voltages produced by the coils in the optimum configurations become too low to be directly rectified with diodes (V_{RMS}<200 mV, which is the forward voltage drop of a BAS70 diode). Since the coils must be kept independent in this structure to produce a sufficient level of electromagnetic damping, this issue is not easily solvable and requires voltage multipliers circuits [6].

4.3. Power density
Power density is a key parameter to describe the evolution of the performance while down-sizing the structure. To each coils configuration corresponds a given coil thickness. From its value and the length of the system, an estimation of the volume of the harvester and hence of the power density can be determined (Power density = Average load power/generator volume). For comparison, this power density was calculated for the coils configurations corresponding to the extremum values of the output voltages studied previously. The results (*Figure 2e*) show that its value decreases exponentially along with the scaling factor, from 1.586 mW.cm^{-3} (k=1.25) to 44 µW.cm^{-3} (k=0.38). This evolution confirms the limitation of this structure in terms of down-scaling possibilities. Besides, it is worth noting that higher-voltage coils configurations are associated with lower power densities, which may call for a compromise when designing the system, depending on the application.

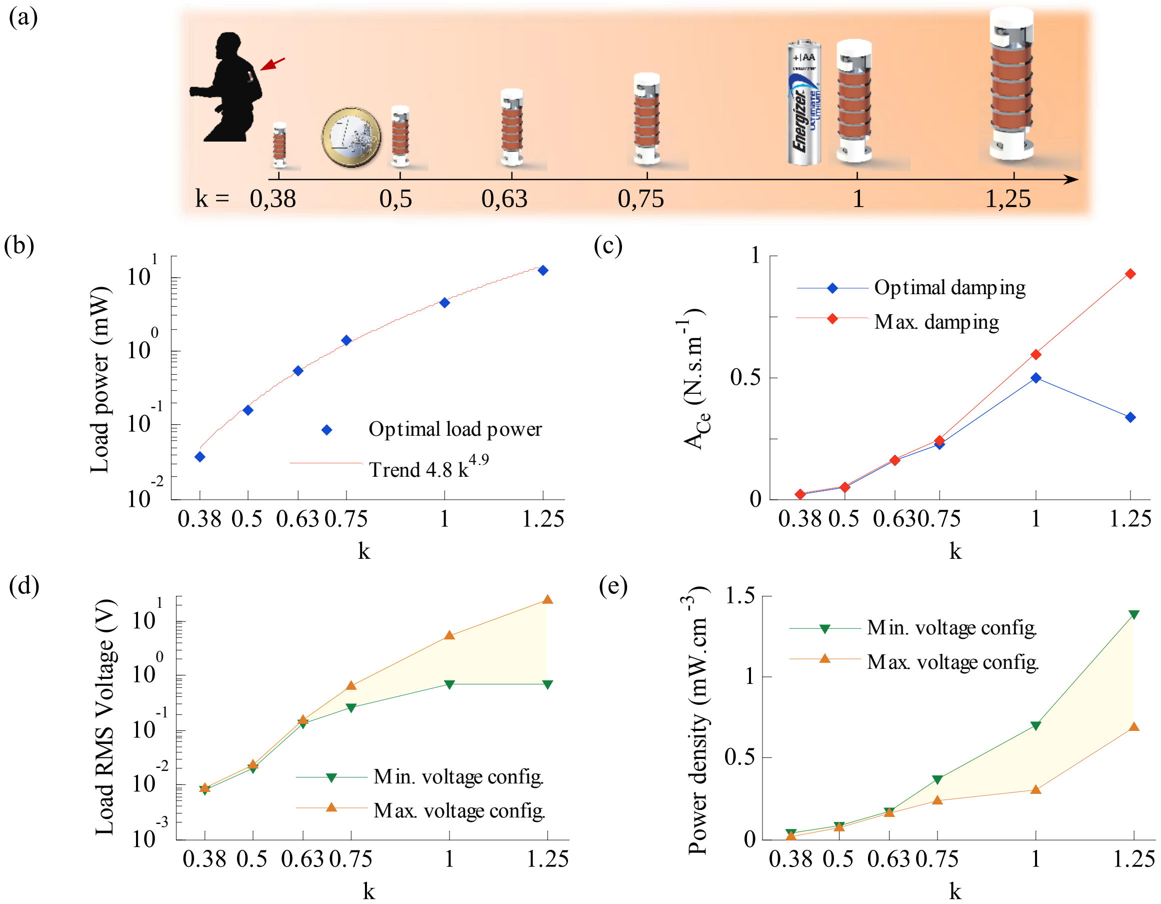

Figure 2 – Simulation results ("4.8 km/h running" input) (a) Computed scales (b) Optimum load power in a matching resistance (c) Electrical damping amplitude A_{Ce} (maximum and optimum). (d) Load RMS voltage and (e) power density, for both the min. and max. voltage coil configurations associated with the optimum load power value.

5. Conclusions

The performances of this type of energy harvester for human motion are strongly impacted by the down-scaling process. Output voltages are the first limiting factor if the device is used with rectifying diodes. In this matter, the critical size appears to be around k = 0.63 (L= 31.25mm D = 5mm), which corresponds to an average load power of 530 µW, but for an RMS output voltage of 150 mV only. More complex power management circuits are thus required to handle the output effectively at these smallest sizes.

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