On the design guidelines for miniaturizing thermo-magnetically activated piezoelectric energy generator

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Abstract. This article deals with experimental testing of a thermo-magnetically activated piezoelectric generator, we provide breakthrough in addressing the miniaturization issue of such power generators by reporting design rules. Three main design parameters were derived: the transducer’s geometry, the gap distance, and the magnetic volume. Special attention was put into the design geometry of the transducer and the magnetic volume. Three different design were tested and compared. These tests revealed that correlated reduction of the transducer and magnets dimensions meant reduction of thermal operating cycles. An increase of 35% in power density is obtained by combining design strategies like to increase the transducer resonant frequency and to uniform distributed strain. An output power density during operating transition of 11.3mW/cm$^3$ is reached.

1. Introduction

Double step conversion methods for thermal energy harvesting such as thermal buckling [1], thermo-acoustics [2], and thermo-magnetic [3], can be considered an alternative solution for miniature thermal energy harvesting. Thermo-magnetic generators rely on the reversible change in magnetization of a suitable material such as the case of iron-nickel alloys, caused by exposing the material to a changing temperature. By utilizing the thermo-manetic field effect described earlier, a new device for generating electric power was previously presented in [4]. In previous work we reported a thermo-magnetic energy harvester able to harness the ambient thermal energy from a variation in environmental temperature and converts it into electrical energy. However, a key limitation of that power generator is that it is too bulky to be integrated into a wireless sensor node. With this goal, the present work seeks to offer design rules for miniaturization. The rest of the paper is organized as follows: the proposed power generator will be discussed in Section 2. The design parameters are presented in section 3. Section 4 shows the experimental measurements of test prototypes. Finally, Section 5 concludes with a summary.

2. Design

As shown in Figure 1, the power generator has two main sections according to their respective functions: the energy transducer and the triggering system. The energy transducer is composed...
of a piezoelectric bimorph-type cantilever beam, namely PSI-5H4E from Piezo Systems, Inc with a series-type polarization. Concerning the triggering system, it consists of two permanent magnets (NdFeB), that is the magnetic volume $V_{\text{mag}}$, that are attached to the free end of the beam, and a soft magnetic material (FeNi), fixed under the free end of the beam, forming an air gap.

2.1. Working principle

The generator has two stable positions: the closed position (B in Figure 2) and the open one (A in Figure 2). In the initial state, at a cold temperature, the soft magnetic material is magnetized so the cantilever beam is pulled-down due to magnetic force. After, when the environmental temperature increases, the magnetic properties of soft magnetic material change from ferromagnetic to paramagnetic, causing the magnetic force to decrease. The beam is pulled back to its initial state because of the spring-back force of the beam. This process of pulling-down and pulling-back of the beam is periodically repeated as long as the energy harvester is placed in an environment with cycled variations in temperature.

3. Design parameters

As can be seen from Figure 2, the cantilever beam has a linear restoring mechanical force $F_{\text{mec}}$, which depends on its geometry. The magnetic force, $F_{\text{mag}}$, is dependent on both the gap distance and temperature. It is trivial to verify that for complete deflection of cantilever, a positive resulting forces sum is expected. We derive three parameters design: the transducer’s geometry, the gap distance, and the total magnetic volume.

3.1. Size reduction strategies

In Figure 3, we report the schematic representation of the overall system operation during 1 thermal cycle versus time. In this figure, a) corresponds to electric current input to change the temperature of FeNi alloy by Joule effect, b) is the temporal evolution of temperature at FeNi alloy, c) represents the actuation forces interaction during the thermal cycle, and d) is the tip displacement response of the transducer. Therefore, the size reduction strategy can be described as follows: the resonant frequency of the oscillation beam is drastically increased when its dimensions are reduced. This results in higher vibration energy of the transducer and better energy harvesting capability. The design geometry of the cantilever beam is geared towards the following goals: (1) Maximize the piezoelectric response for a given input. (2) Minimize the damping associated with the mechanical structure. This can be reached by
reducing the damping ratio of the width-reduced beam; thus, a beam with smaller width vibrates with higher amplitudes and therefore has higher energy harvesting capability. (3) Improve scavenger robustness by producing an evenly distributed strain. This can be realized by having an increasingly triangular profile. In addition, we choose optimal load resistor matching the electrical impedance of the piezoelectric bimorph to maximize power transfer.

4. Experimental testing
The first prototype shows that the gap distance is a key design parameter as reported in Figure 4. In fact this distance plays 4 roles: the first one concerns the thermal hysteresis, $\Delta \Theta$, the second one implies a shift in the temperature thresholds range, $\Theta_{\text{open}}$ and $\Theta_{\text{close}}$, and the third one is associated to the magnetic damping and also the strain energy into the beam. Consequently, the design guidelines shall consider the influence of this parameter. For room temperature applications, having higher gaps is advantageous because it implies a thermal range shift towards these temperatures. Moreover, it increases the strain energy into the transducer. As all of these design parameters are correlated, a tradeoff has to be set for a correct operation of the generator. We constructed three different geometries of transducer, such cases are depicted in Figure 5. Firstly, we reduced the damping associated with mechanical structure by reducing the beam’s width (from case A to case B). An increase of 35% in power density is obtained. Secondly, by reducing the $V_{\text{mag}}$, not only the generator’s volume is reduced but also its resonant frequency is increased (from case B’ to C’). This results in better power density per transition capabilities. Thirdly, using a triangular cantilever rather than a rectangle is to increase by an order of magnitude the power density per transition. This final design is the case C’, which combines these earlier strategies (higher resonant frequency and uniformly distributed strain) to reach an output power density during transitions of 11.3nW/cm$^3$. Figure 6 depicts the typical responses of the design B’ and C’. Table 1 summarizes experimental findings.
Table 1. Experimental results summary.

| Item        | Units | Transducers geometries |
|-------------|-------|------------------------|
|             |       | A | B | B’ | C | C’ |
| Gap         | mm    | 2 | 2 | 1.17 | 2 | 1.15 |
| \(V_{mag}\) | mm³   | 39.2 | 39.2 | 6.28 | 39.2 | 6.28 |
| \(V_{eff}^{\dagger}\) | mm³   | 140.6 | 38.1 | 57.84 | 23.7 | 13.96 |
| \(\Theta_{open}\) | °C    | 67 | 64 | 64 | 57 | 56 |
| \(\Theta_{close}\) | °C    | 34 | 46 | 31 | 32 | 28 |
| \(\Delta\Theta\) | °C    | 33 | 18 | 33 | 25 | 28 |
| \(f_r\) | Hz    | 90 | 85 | 100 | 120 | 250 |
| \(R_{load}\) | kΩ    | 610 | 721 | 740 | 147 | 400 |
| \((P/V_{eff})^{\dagger}\) | mW/cm³ | 0.147 | 0.227 | 0.178 | 7.468 | 11.3 |

\(\dagger\)Effective volume including the transducer’s oscillations amplitude.
\(\dagger\)Considering 40ms as the time period for closing and opening switching.

Figure 5. Photograph of two of the design of piezoelectric transducers: a) rectangular shaped, c) triangular shaped.

5. Conclusion and perspectives
Design guidelines for size reduction of a thermo-magnetically activated piezoelectric energy harvester were presented. Data collected shown that tuning of thermal hysteresis of such devices can be done by modulating the gap parameter. An increase in the power density during transitions was observed with a triangular shaped beam compared with a rectangular one. Current research includes reduction of soft magnetic alloy size to reduce the period time between transitions, thus increasing the generator’s energy harvesting capability.

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References
[1] E. Trioux, S. Monfray, and S. Basrour, “Butterfly micro bilayer thermal energy harvester geometry with improved performances,” *Journal of Physics: Conference Series*, vol. 773, p. 012094, Nov. 2016.
[2] O. Puscasu, S. Monfray, J. Bougahleb, P. Cottinet, D. Rapisarda, E. Rouvire, G. Delepierre, G. Pitone, C. Matre, F. Boeuf, D. Guyomar, and T. Skotnicki, “Flexible bimetal and piezoelectric based thermal to electrical energy converters,” *Sensors and Actuators A: Physical*, vol. 214, pp. 7–14, Aug. 2014.
[3] M. Gueltig, H. Ossmer, M. Ohitsuha, H. Miki, K. Tsuchiya, T. Takagi, and M. Kohl, “High Frequency Thermal Energy Harvesting Using Magnetic Shape Memory Films,” *Advanced Energy Materials*, vol. 4, p. 1400751, Dec. 2014.
[4] A. Rendon-Hernandez and S. Basrour, “Coupled multiphysics finite element model and experimental testing of a thermo-magnetically triggered piezoelectric generator,” *Journal of Physics: Conference Series*, vol. 773, p. 012024, Nov. 2016.