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Modelling and fabrication of a compliant centrally supported meandering piezoelectric energy harvester using screen-printing technology

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Abstract. This paper reports the design, simulation, fabrication, and experimental testing of a low-frequency piezoelectric energy harvester fabricated using screen-printing technology. A centrally supported meandering geometry is chosen to reduce the torsional mode effects during the unit vibrations and to achieve better power efficiency. The design experiences alternating stress along the beams and a strain-matching polarization technique is used to minimize voltage cancellation. The test results are validated against the finite element solution for which there is a good agreement.

1. Introduction

The use of piezoelectric cantilever beams for energy harvesting has been studied extensively and used for wireless sensing applications [1]. One application is the electromagnetic harvesting from current carrying wires. Previous work by [2, 3] demonstrated this capability with a cantilever design with piezoelectric layers and a permanent tip magnet. The maximum power output of such structures occurs when the fundamental frequency of the structure matches the dominant frequency available through the electric current. The major drawback in using cantilevers for MEMS vibrational energy harvesters is their relatively high natural frequency resulting from their short lengths. Work done by [4] for the same application produced a quad-folded cantilevered design to fit within a 100mm^2 area. This design, however, is susceptible to some torsional vibrations and may include several strain nodes throughout the harvester that reduces the overall harvesting efficiency from the bending modes for which more complex electrode configurations have to be used.

PZT components (T_c ~300°C) [5] are often considered for energy harvesting because of their outstanding electromechanical properties compared to those of PVDF [6] or AlN [4]. Although PZT ceramics (>100 µm thick) demonstrate high intrinsic coupling factors and are commercially available, they are relatively expensive and their geometry is often limited to simple shapes which may necessitate additional expensive micromachining steps for specific applications [7]. PZT thin films (<1 µm) are often deposited onto silicon or metallic supports, but are not suitable when large power is required due to their weak electromechanical coupling. PZT thick-films have been found to make good candidates for MEMS applications due to their higher coupling, and can bridge the 1-100 µm gap between thin film and bulk components [8]. They can be formed by screen-printing through a mask. Free-standing thick-film structures can be mass produced and do not need to be assembled manually, like with ceramics. It is therefore possible to create quite complex structures with a series of relatively simple fabrication steps. They can also be integrated with other thin or thick-film layers and microelectronic components, thereby offering an appealing approach for this project.

Free-standing piezoelectric thick-films fabricated on a silicon substrate have been shown to produce ~3 µW from an acceleration of 2.8 m/s^2 at 250 Hz and only up to ~33 µW at about five times the acceleration [9]. For the same 2.8 m/s^2 acceleration thick-films on stainless steel substrates have been shown to deliver power of 240 µW harvested at 66.2 Hz [10].

This paper reports the design, simulation, fabrication, and experimental testing of a compliant centrally supported meandering piezoelectric energy harvester (EH) for current monitoring applications. Future work involves employment of a tip magnet to both reduce the natural frequency of the present unit, and to harvest from the electromagnetic flux around a wire carrying an AC current.

2. Energy harvester design, modelling, and simulation

Compared to a simple cantilever of similar area, a zigzag design reduces the fundamental natural frequency of the structure and helps maintain a high power density [11]. A so-called meandering design uses symmetry about the free end of a zigzag and contains two fixed ends [12]. A centrally supported meandering geometry, used in this paper, is created by mirroring the zigzag design about the clamped beam. This design achieves better power efficiency than a zigzag due to the reduction of the torsional mode effects in the clamped beam, which results in bending modes being dominant during harvesting. The geometry of the harvester is shown in figure 1. Using COMSOL, the simulated strain contour plot for the fundamental frequency is obtained and presented in figure 2.

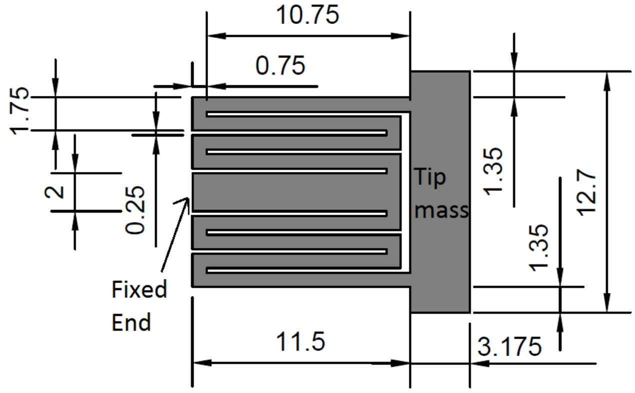

Figure 1. Schematic of the harvester (mm).

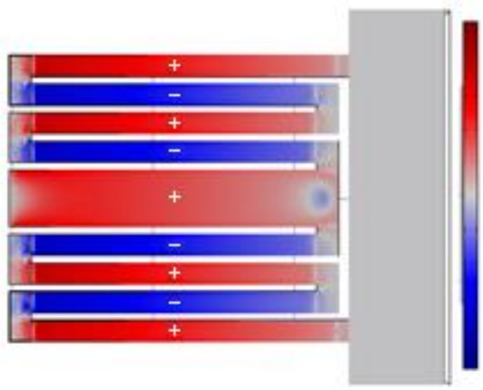

Figure 2. Strain contour plot showing tension (red) and compression (blue).

As shown in figure 2 the adjacent beams experience alternating strains and each individual beam experiences either tension or compression along its entire length during the cyclic motion at its fundamental frequency. This is one of the most attractive features of the proposed design and quite critical as any strain node within the length of the beam would require segmented electrodes to avoid a charge cancellation. The segmented electrode was adopted as a solution in [4].

3. Fabrication process

This screen-printing method is a low-cost alternative process to classical silicon manufacturing. The most valuable advantages of screen-printing are the low investment costs for equipment and choice of materials including the substrate and paste. Screen printing also allows for thicker PZT layers which can be in the range of 1-100 μm.

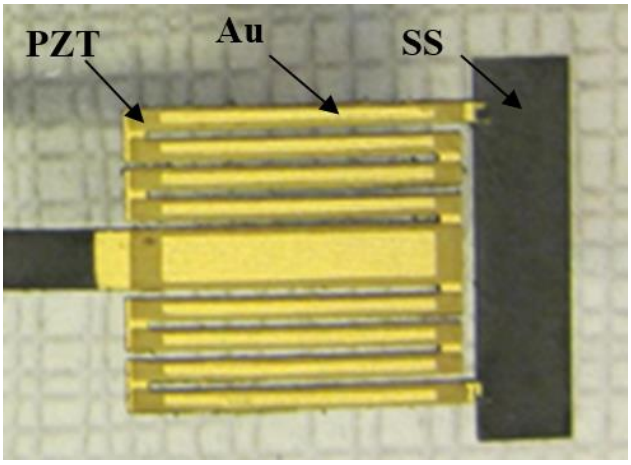

Figure 3. PZT energy harvester fabricated using screen-printing technology.

Figure 3 shows the EH fabricated by screen-printing techniques. It consists of a PZT layer sandwiched between two gold electrodes deposited on a stainless steel substrate. The substrate material is 301 stainless steel (SS) with a thickness of 254 μm and was laser cut according to the design geometry. The SS was selected for its compatibility with the firing temperature required by the screen-printable process and for its low Young's Modulus of 193GPa. The gold ink used for the electrode layer is commercially available (ESL8836 from ElectroScience Laboratories), whereas the PZT is prepared at the IMS laboratory at the University of Bordeaux. The piezoelectric paste is prepared from a commercial piezoelectric PZT powder (PZ26 from Ferroperm) mixed with 3wt% LBCu (25wt% Li_2CO_3, 40wt% Bi_2O_3, 35%wt CuO), blended with ESL4000 organic vehicle from ElectroScience Laboratories [13].

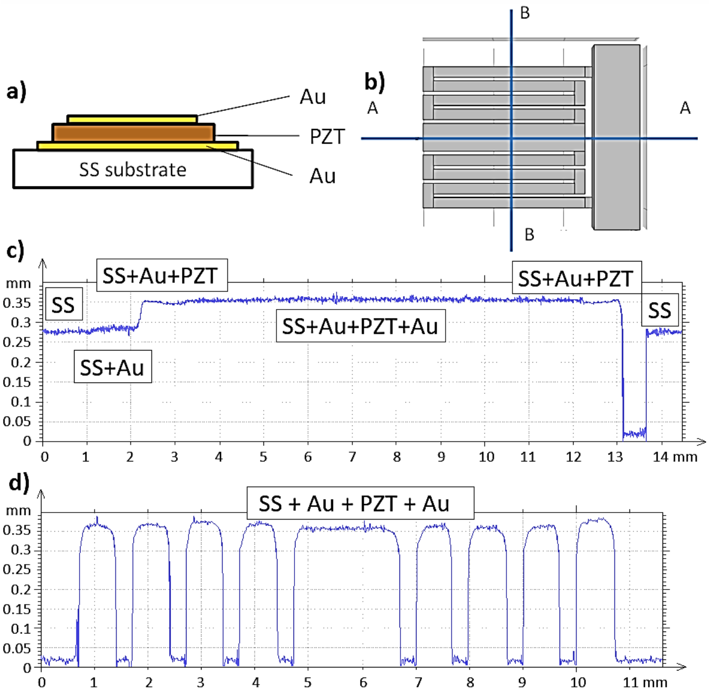

Figure 4. a) Cross section of stainless steel substrate with screen printed layers b) Thickness measurement lines across the sample for optical profiling c) Optical profile along A-A d) Optical profile along B-B

After aligning the substrate for printing, the bottom electrode is printed, dried for 20 minutes at 120°C then fired for 10 minutes at 850°C. Next, a layer of PZT and its top electrode are printed successively, and dried for 20 minutes at 120°C between each deposition. Then, the dried samples are isostatically pressed for one minute at 40 MPa to improve the densification of the layers. Afterwards, the samples are fired for 2 hours at 900°C in air atmosphere. The densification and firing reduced the thickness of the PZT layer to approximately 55 μm. The thickness profiles of the dried Au/PZT/Au layers on the SS substrate are shown in figure 4.

Polarization is required for the PZT layer to exhibit piezoelectric properties. Polarization of the PZT occurs close to the measured Curie temperature (~280°C) for five minutes at an electric field of 50kV/cm under a dry nitrogen environment. A strain-matched polarization (SMP) technique is used to minimize voltage cancellation across the harvester. As described in [12] the piezoelectric material of each beam is poled such that each adjacent member has the opposite poling direction. By employing this approach all of the electrodes will have the same voltage polarity. This allows for a single continuous electrode to be used across the bottom layer of the EH. A ball-bonding technique was used to make micro-wire connections between the top layers of electrodes. As a preliminary step, only four beams that experienced the same type of strain were poled.

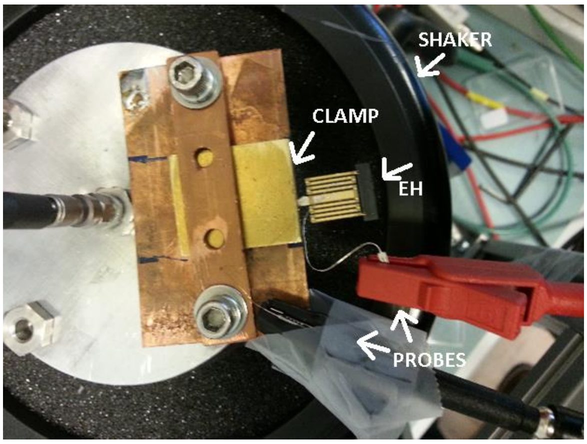

Figure 5. Experimental test setup of the fabricated EH without a tip mass.

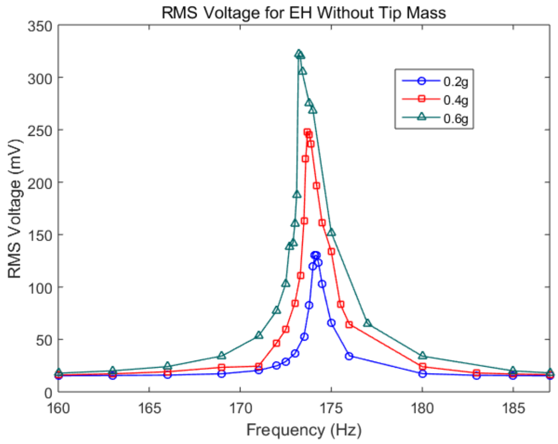

Figure 6. Experimental open-circuit voltage of the harvester without tip mass for various accelerations.

4. Experimental procedure and results

To characterize the PZT parameters, the EH was mounted on an electromagnetic shaker and the voltage readings were taken across the top and bottom electrodes, as shown in figure 5. Figure 6 shows the frequency response of the output voltages for the EH in an open-circuit state for multiple base accelerations.

The maximum RMS voltage produced by the harvester without a tip mass was 322 mV at 0.6 *g* with a natural frequency of 173 Hz. Using COMSOL simulations an eigenfrequency analysis was performed on the same unit. The thickness profile used for the simulation is shown in figure 4. The simulations results predict a fundamental frequency of 171 Hz that is in great agreement with the test results. Future work involves adding the tip magnetic mass to both reduce the natural frequency for the unit and to help harvest from the electromagnetic flux. Further calculation using the model shows that adding a neodymium permanent magnet tip mass of 0.70 g would tune the overall natural frequency to 60 Hz, conforming to the frequency of AC power in the North American power grid.

5. Conclusion

In summary, a piezoelectric EH of MEMS scale has been successfully fabricated using low-cost screen-printing technology on a stainless steel substrate. The centrally supported meandering design experiences alternating strain in the subsequent beams. The PZT is poled according to the strain matched polarization technique to minimize voltage cancellation. The simulation and test results are shown to be in good agreement.

Future work will include improving the adhesion to the substrate and the polarization of all beams. The geometry will also be optimized for greater power density and the EH will be integrated with power conditioning circuitry for the electromagnetic energy harvesting of current carrying lines.

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