A WEARABLE SYSTEM OF MICROMACHINED PIEZOELECTRIC CANTILEVERS COUPLED TO A ROTATIONAL OSCILLATING MASS FOR ON-BODY ENERGY HARVESTING

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ABSTRACT

In this paper, we present a compact, wearable piezoelectric on-body harvesting system that uses a small eccentric mass from a common watch movement to mechanically deflect a set of micromachined piezoelectric cantilevers when excited by the low frequency movements of the human body. The piezoelectric cantilevers are directly coupled to the rotating mass via a set of pins located near its rotational center. The energy produced by each pluck of a single cantilever is 545 nJ, corresponding to a maximum output power of 11 µW for continuous plucking; however, accounting for the periodic rest of typical human motion, the average output power over a full day cycle will be considerably less.

INTRODUCTION

Harvesting the mechanical energy of the human body through piezoelectric transduction could provide a means for powering portable and implantable systems. Human motion, however, is irregular and is limited to very low frequencies (a few Hz). Therefore, resonant type devices, where the natural frequency of the harvester is matched to the frequency of ambient vibrations, do not present a viable option. Impact-type harvesting in which the environmental motion is coupled to an inertial object which transfers its accumulated energy to the harvester through physical impacts provides a means of coupling low frequency irregular motion to high frequency piezoelectric oscillators.

Priya *et al.* first presented an impact harvester based on a windmill design in which a wind powered rotating wheel with notches plucks a series of harvesters extending radially outwards from its center [1]. Pozzi *et al.* inverted the windmill design to reduce the dimensions of the harvester in order to extract the energy from a bending knee [2]. Here, we miniaturize this concept using an eccentric mass that oscillates with the movement of the body. The movement of the mass is then transferred to the piezoelectric cantilevers through direct mechanical impact with a set of pins inserted near the rotational center of the eccentric mass.

The presented approach differs from recent work based on magnetic actuation [3] which still requires a relatively large mass, strong magnets and high rotational speeds to effectively actuate the piezoelectric cantilever - the absence of post-excitation oscillations in the case of low-frequency magnetic actuation reduces the electromechanical efficiency of the system. The concept presented here can be used with low frequency movements from a small rotational mass commonly used in a typical wristwatch.

We previously presented a novel efficiency characterization setup for rotational energy harvesters using a flywheel to store and quantify the mechanical input energy and compare energy losses with the electrical output [4]. With this characterization tool, we have demonstrated that the efficiency of mechanical plucking is greater than magnetic actuation for low to moderate frequencies. A potential drawback of a mechanical contact approach, however, is the reliability of the system. Nonetheless, we also demonstrate stable operation of the mechanically plucked cantilevers over long periods through accelerated lifetime tests [5].

Here, we present the design considerations related to developing a rotational micro-energy harvester for on-body applications, taking into consideration the forces available from an eccentric mass from a common wristwatch. We discuss the design and fabrication of the piezoelectric harvesters developed to satisfy the design constraints and we present the results of a demonstrator created to test this micro-energy harvesting concept.

SYSTEM DESIGN

The rotational micro-energy harvesting system is shown schematically in Figure 1. The piezoelectric cantilevers are fixed along the outer diameter of the system such that they extend inward towards the rotational center of the device. In the current configuration, pins, 200 µm in diameter, are inserted into the center ring of the oscillating mass, 3.5 mm from the rotational center.

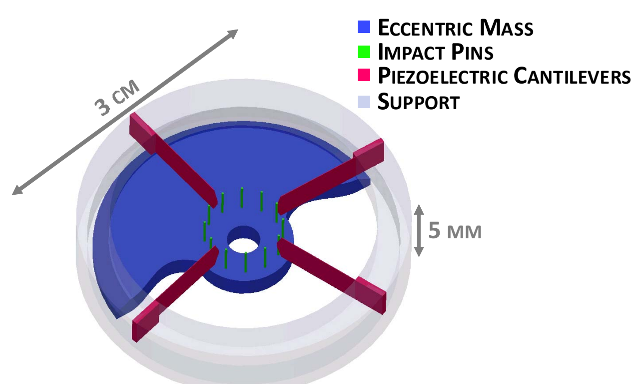

Figure 1: Schematic of the presented concept. Pins inserted into the center ring of an eccentric mass pluck the cantilevers as the mass rotates due to low frequency excitations caused by body movements.

Designing the pin / cantilever interaction closer to the center of rotation increases the available torque applied by the eccentric mass, albeit, at the expense of a reduced circumference. The size of the circumference defines the maximum displacement and number of cantilevers that fit within a given system. This is because only one cantilever / pin interaction can occur at any given time due to the limited force available. Therefore, multiple cantilevers must be aperiodically staggered around the circumference of the face, as shown in Figure 1, to reduce the load applied to the mass at any given time. The torque generated by the mass is given by

$$\tau = mgr\sin\beta \tag{1}$$

where $\beta = 180° - \theta$ refers to the angle extended between the gravitational vector and r, the radial line connecting the center of rotation to the center of mass; mg is the weight of the mass (Figure 2). Using a mass from the standard ETA 2824 watch movement, commonly used in many self-winding wristwatches, a maximum torque of $\tau = 0.0001$ Nm is generated when the mass is aligned along the horizontal such that $\theta = \beta = 90°$. At $\theta = 45°$, $\tau = 0.00007$ Nm.

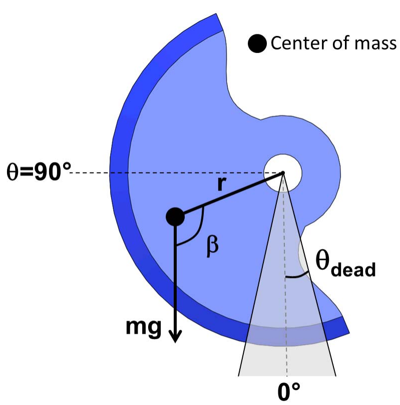

Figure 2: The torque produced by the eccentric mass depends on the angle of rotation. As a result, there is a zone between $\pm\theta_{dead}$ where the force of the mass is too weak to pluck the cantilever.

The required plucking force depends on the stiffness of the cantilever design and the amplitude of the deflection necessary to fully release the cantilever. The deflection amplitude depends on the insertion depth of the cantilevers as shown in Figure 3 and can be approximated by

$$\delta = \sqrt{R^2 - (x - R)^2} \tag{2}$$

where R is the radius of the circle of pins and x is the insertion depth. In order to create a realistic design, an insertion depth of 50 µm was chosen, corresponding to a deflection amplitude of 500 µm. Therefore, taking the available force, the required deflection amplitude and the size of the system into consideration, a cantilever length of 9 mm was selected and the total thickness set to 50 µm: 20 µm of PZT and 30 µm of silicon, satisfying the optimum thickness ratio ($t_r \sim 0.6$) in terms of efficiency for an end-deflected piezoelectric cantilever [6].

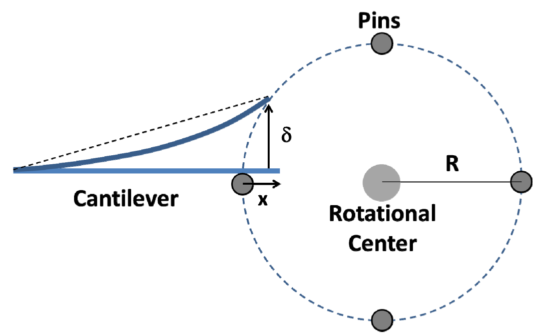

Figure 3: Schematic depicting the cantilever deflection required in order for it to be released by the pin.

As the angle of the mass approaches 0°, the torque produced by the mass vanishes. Therefore, there is a spread of angles around 0° where the mass does not provide an adequate force to fully pluck the cantilevers. The maximum angle in this spread is referred to as the dead angle and can be determined with the following equation

$$\theta_{dead} = \sin^{-1}\left(\frac{k\delta R}{mgr}\right) \pm 180° \tag{3}$$

It is important that the dead angle be small in order to allow the mass to rotate with the motion of the body. Given the designed dimensions of the cantilever, the stiffness, k, is 13 N/m and the dead angle of the presented configuration is $\theta_{dead} = \pm 13°$.

The mechanical plucking of the harvesters in this configuration is bi-directional, meaning rotation of the mass in either direction will excite the harvesters, deflecting them to a maximum amplitude and then releasing them, allowing them to freely oscillate as the stored mechanical energy is converted to electrical energy.

HARVESTER FABRICATION

The micromachined piezoelectric cantilevers are fabricated at the wafer-level by bonding a bulk, 130 µm thick, commercially available PZT-5A sheet onto a silicon substrate and thinning it down to a thickness of 20 µm using an automatic grinder (Disco DAG810) [7]. The cantilever tips are patterned with reactive ion etching and cavities are anisotropically etched into the silicon wafer in a potassium hydroxide (KOH) bath before dicing is used to release the cantilevers. Images of the front- and backsides of a processed wafer before the final dicing step are shown in Figure 4. The dimensions of the fabricated cantilevers are 9 x 3 x 0.05 mm^3. A single cantilever fixed to a brass support is also visible in Figure 4. The support was used to easily insert and fix the cantilevers in the demonstrator presented in Figure 5. The brass support can be adjusted to vary the insertion depth of the cantilevers. The cantilever is fixed to the support with a conductive epoxy that connects to the bottom electrode of the PZT through a via etched in the Si.

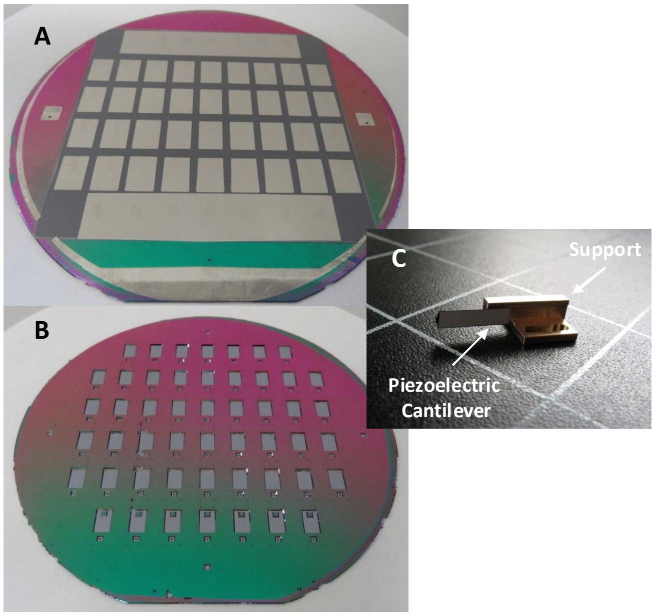

Figure 4: MEMS cantilevers fabricated at the wafer-level: A) a thinned PZT sheet on the frontside of the wafer; B) cavities on the backside of the wafer; and C) a mounted piezoelectric harvester.

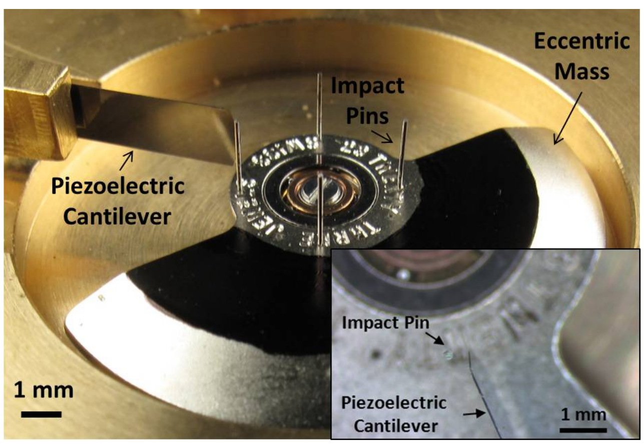

Figure 5: Optical image of an eccentric mass (ETA 2824) with 4 pins inserted in the central ring and a single piezoelectric cantilever mounted. (Inset: magnified view of an impact pin and the overlapping tip of the cantilever).

RESULTS

As the mass turns, the pins strike the tips of the piezoelectric cantilevers producing voltage pulses similar to the one presented in Figure 6; an initial deflection is followed by free oscillations of the cantilever. To measure the voltage pulse from a single pluck, a cantilever was aligned to an angle of 50° and the mass was rotated to 20° such that a single pin was positioned just above the cantilever. Upon dropping the mass, the pin plucked the cantilever once before the mass stabilized at 0°. 545 nJ of energy is generated by a single pluck across an optimum load of 14.5 kΩ. The initial contact between the cantilever and the pin accounts for only 15 nJ while the majority of the electrical energy is generated by the free oscillations after the cantilever has been fully released by the pin as demonstrated in Figure 6.

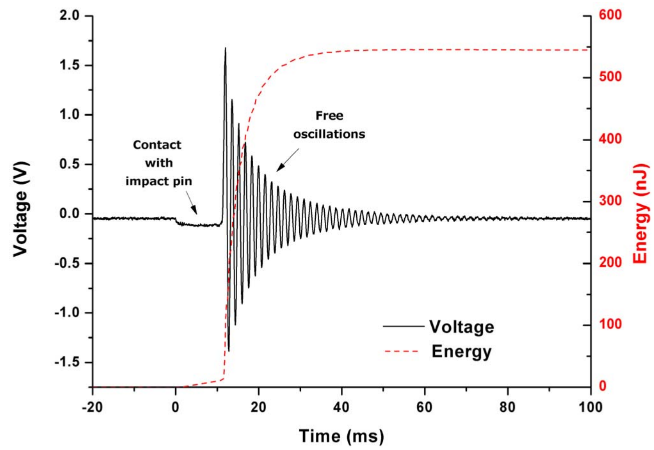

Figure 6: Voltage and energy output from a single pluck when connected to a load of 14.5 kΩ.

The transduction efficiency of the harvesters to convert mechanical energy into electrical energy can be determined by comparing the mechanical energy input to the electrical energy output. The mechanical energy is simply given by the work required to deflect the cantilever of a given stiffness, $k \sim 20\ N/m$, by a certain displacement, $\delta \sim 500$ µm ($E_M = 0.5k\delta^2 = 2.5\mu J$). The electrical energy per pluck, as shown in Figure 6, was determined by integrating the instantaneous power dissipated by the resistive load over the duration of the pulse. Comparing these two values at the optimum load, the transduction efficiency of the harvester was determined to be ~ 20%.

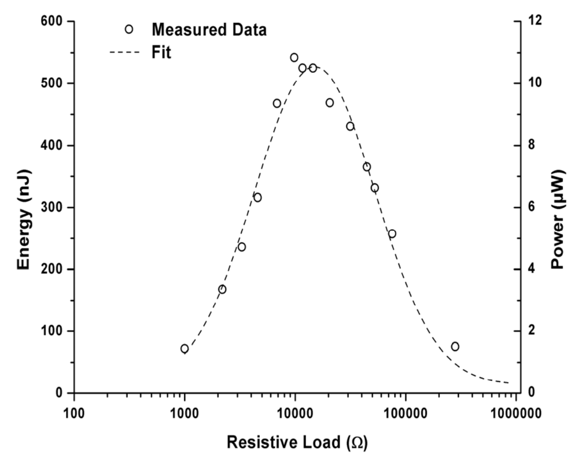

Figure 7: Energy per pluck from a single cantilever as a function of the connected load. The optimum load is 14.5 kΩ.

The optimum load was determined by varying the resistance connected across the electrodes of the harvester and measuring the energy produced for a single pluck. The energy produced per pluck as a function of the connected load is shown in Figure 7. The peak visible at 14.5 kΩ corresponds to the expected optimal load given by $1/\omega C$ where C = 20 pF is the capacitance of the piezoelectric layer and ω is the oscillation frequency, or the natural frequency of the cantilever in this case.

The ideal power for continuous, regular plucking shown on the right-hand axis of Figure 7 was determined using the energy produced and the duration of each pluck. This corresponds to an optimum case in terms of efficiency, but requires regular motion of the mass which is clearly not the case for human motion. An example of human motion is presented in Figure 8. The demonstrator with 4 pins inserted and a single harvester (Figure 5) was strapped to a human arm. The voltage signal produced by the harvester was recorded as the subject walked. Variation in the plucking frequency is clearly visible and the power produced is reduced by approximately half (6 µW) as a result of the gaps that are present between successive plucks. In reality, the human body is at rest for a significant portion of the day, and therefore, the average power produced over a 24 hour period will be considerably less than the power produced during a period of active motion.

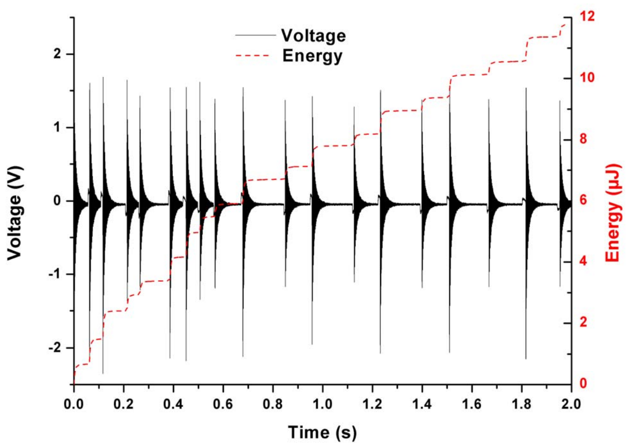

Figure 8: Voltage and energy output by the system while on the wrist of person walking. A 14.5 kΩ optimum load is connected to the harvester.

CONCLUSIONS

We have demonstrated a working concept for a compact, wearable energy harvesting system to convert the mechanical energy of the human body into useable electrical energy to provide a sustainable power source for on-body microelectronics and implantable devices. The system employs piezoelectric cantilevers actuated by an eccentric mass. The piezoelectric cantilever design has been optimized to work with a small mass commonly found in a standard automatic wristwatch and the concept is designed to work with the low actuation frequencies commonly encountered in human body motion.

We are presently working to optimize this concept by increasing the number of pins and the number of cantilevers while improving the compactness of the design. Through optimization, the presented concept could eventually be used to power on-body electronics.

AGKNOWLEGMENTS

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