A WRIST-WORN ROTATIONAL ENERGY HARVESTER UTILIZING MAGNETICALLY PLUCKED {001} ORIENTED BIMORPH PZT THIN-FILM BEAMS

Tiancheng Xue[1], Hong Goo Yeo[2], Susan Trolier-McKinstry[2] and Shad Roundy[1]
[1]University of Utah, Salt Lake City, USA and
[2]Pennsylvania State University, University Park, USA

ABSTRACT

A wrist-worn eccentric rotor-based energy harvester utilizing multiple magnetically plucked flower petal-shaped bimorph lead zirconate titanate (PZT) thin-film beams was designed and fabricated. The bimorph beams were formed by depositing {001} oriented PZT films up to 5.4 µm in thickness on both sides of a 50 µm thick nickel foil. The prototype was characterized with an analytical system-level model and a bench-top swing-arm test set-up. The prototype can achieve approximately 40 µW power output from a bench-top pseudo walking motion input. Further simulation suggests that improvement can be made by growing thicker PZT layers.

KEYWORDS

Energy harvesting, piezoelectric, wearable, frequency up-conversion, magnetic plucking,

INTRODUCTION

Energy harvesting for wearable wellness sensors provides the potential for continuous 24/7 health monitoring by eliminating the need to replace or recharge batteries. For healthcare, this enables mobility and may provide a safe alternative to hospital-based monitoring, whereas for consumer electronics it improves user experience by minimizing user intervention. Inertial energy harvesters are typically designed to be unidirectional and resonant at a particular frequency to take advantage of the peak dynamic magnification. However excitation from human motion exhibits low and irregular frequencies along multiple axes. Frequency up-conversion is a popular approach to address the issue by transforming the low-frequency excitation into a higher-frequency actuation of the transducer. In a typical implementation, a slower inertial mass plucks a piezoelectric cantilever beam and lets it ring down at its natural frequency; the piezoelectric converts mechanical to electrical energy. Compared to a translational proof mass, a rotational one without intrinsic motion limit caters better to a multidirectional input such as human motion.

Eccentric rotor-based energy harvesters utilizing plucked piezoelectric beams through either pins [1], [2] or magnetic coupling [3]–[5] have been demonstrated in the literature. Magnetic plucking provides better robustness and lower mechanical damping by eliminating mechanical contact compared to its counterpart. Commercial off-the-shelf bulk PZT beams are often used in existing prototypes. However the design space of a wrist-worn device generally allows only one bulk PZT beam due to its higher stiffness. Polyvinylidene fluoride (PVDF) beams are softer than bulk PZT beams but suffer from a poor piezoelectric figure of merit. PZT thin-film beams exhibit a similar amount of flexibility as PVDF beams without the corresponding sacrifice in the piezoelectric properties. It is the ideal candidate for implementing multiple beams in one device to improve power density.

In this paper, a novel wrist-worn energy harvester architecture is proposed with flower petal-shaped beams prepared from PZT/Ni/PZT thin-film bimorphs. Typically piezoelectric beams are designed to be plucked in the plane of the proof mass motion whereas we previously introduced the concept of out-of-plane plucking (i.e., the beam is deflected orthogonal to the plane of proof mas motion) [6]. Out of plane plucking allows for more piezoelectric material without a significant increase in assembly difficulties in the proposed prototype.

DESIGN AND MODELING

Figure 1 illustrates the design of the proposed harvester in an exploded view. Six petal-shape bimorph PZT thin-film beams are mechanically clamped on the casing. The active length of the piezoelectric beam is 14.4 mm while the width is 3 mm and 15 mm at the tip and the base, respectively. The proposed petal shape not only improves the strain profile [7] but also fully utilizes the available area for sufficiently strained piezoelectric materials. The brass rotor is supported by two ball bearings. Tungsten weights are added to the outer rim of the rotor to increase mass and eccentricity which in theory increases the maximum potential power that can be generated [4]. Four cube NdFeB magnets (2mm × 2mm × 2mm) are evenly placed on the rotor. There are identical magnets attached on the tip of the six beams. This mismatch between rotor magnets and beam magnets is a deliberate arrangement to avoid synchronized beam plucking, which is likely to induce a large detent torque on the rotor that inhibits its continuous rotation, especially when the excitation is weak. The magnets are in a repulsive configuration along the direction of beam length with an intentional offset in the out of plane direction to realize the out-of-plane plucking [6].

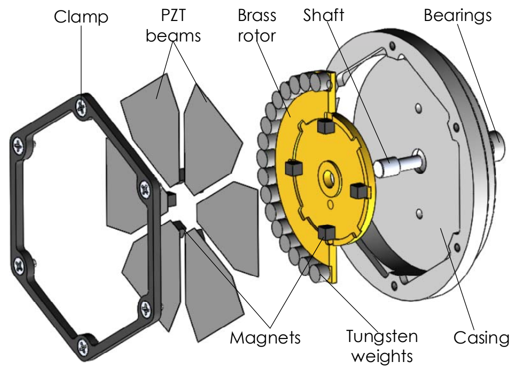

Figure 1: Exploded view of the rotational energy harvester with petal-shape bimorph PZT thin-film beams.

The model for the piezoelectric energy harvester is built upon a generalized rotational energy harvester model previously developed [4], where the transducer is modeled as a viscous damper. The motion of the rotor in a generalized rotational energy harvester constrained in its local plane is governed by

$$\ddot{\phi}_z = \frac{-(b_m + b_e)\dot{\phi}_z + mL[(\ddot{X} - g_x)\sin\phi - (\ddot{Y} - g_y)\cos\phi]}{I_g + mL^2} - \ddot{\theta}_z \quad (1)$$

where m, I_g and L are the mass, the moment of inertia about the center of mass and the eccentricity of the rotor respectively. $\ddot{X}$, $\ddot{Y}$ and g_x, g_y are linear and gravitational accelerations to the casing, respectively in their local coordinates. θ_z denotes the angular displacement of the casing whereas ϕ_z denotes the relative angular displacement of the rotor with respect to the casing. A mechanical damper b_m and an electrical damper b_e are included in the model to represent lost and extracted energy, respectively. To model the proposed petal-shape piezoelectric energy harvester, the electrical damper was replaced with a magnetically plucked piezoelectric cantilever beam model [6]. Given that the system is not only nonlinear due to the trigonometric functions but also numerically stiff in the form of ordinary differential equations because of the implementation of the plucked beam model, the purpose of this model-based simulation is not to obtain an exact match in the time domain. As a matter of fact, the system is highly sensitive to initial conditions. However a good agreement in the average power output over a long period of time lends credibility to the proposed model.

FABRICATION AND ASSEMBLY

Bimorph beams were fabricated by depositing {001} oriented PZT films on both sides of a nickel foil (5cm × 5cm × 50µm). The continuous bimorph PZT films were grown by high temperature in-situ *rf*-magnetron sputtering with {100} textured $LaNiO_3$ (LNO) seed layer and HfO_2 buffer layer described in [8] and [9]. The cross section schematic of the PZT bimorph structure is shown in Figure 2. Strongly {001} oriented PZT films were deposited onto both sides of $LaNiO_3/HfO_2/Ni/HfO_2/LaNiO_3$ foils up to a thickness of 5.4 µm by sputtering at 550 ~ 585 °C from a 10% Pb excess $Pb(Zr_{0.52},Ti_{0.48})O_3$ target. No pyrochlore phase was detected in as-grown films by either X-ray diffraction or scanning electron microscopy.

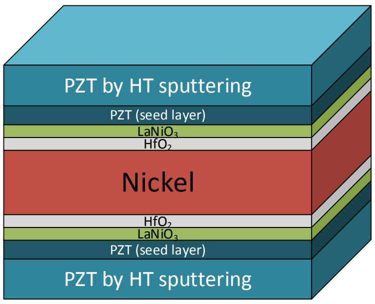

Figure 2: Cross section schematic of the bimorph structure.

A sol-gel PZT capping layer was deposited on top of the sputtered layers to decrease the surface roughness. Both PZT layers exhibited a relative permittivity of approximately 450 with loss tangents less than 0.04 at 10 kHz. Highly {001} oriented PZT films showed well-saturated polarization – electric field hysteresis loops with large remanent polarizations (42 µC/cm^2) at 100 Hz.

The fabrication and assembly process flow is illustrated in Figure 3. Platinum electrodes were patterned on the bimorph PZT films as demonstrated in Figure 3(b) by a standard lithography process. Petal-shape beams were cut with scissors after depositing electrodes by DC-magnetron sputtering on both sides. Wires were bonded onto both the electrodes and the center shim by silver paste and Kapton tape for electrical connection. The bimorph beams were hot poled in opposite directions for series connection before being assembled into the prototype. A high yield (~ 80%) was achieved for the large-area (>1 cm^2) electrodes after using the resurrection treatment described in previous work [9]. Consequently, some beams are electrically functioning as unimorphs despite physically being bimorphs.

Due to the compliance of the polyoxymethylene clamp, the fastening was reinforced with cyanoacrylate as shown in Figure 4(d). To improve robustness six intermediate staging PCBs were placed on the casing as a stress relief for fine gauge wires attached to the PZT beams. Ribbon cable wires were used for final data acquisition.

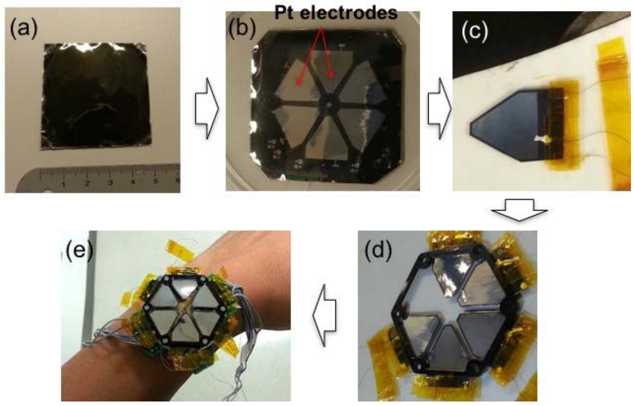

Figure 3: Fabrication and assembly process flow of the harvester prototype with bimorph PZT thin-film beams.

A photo of the fully assembled harvester prototype is given in Figure 4. The diameter of the prototype is 45 mm and the thickness is 8.5 mm, excluding the bearings.

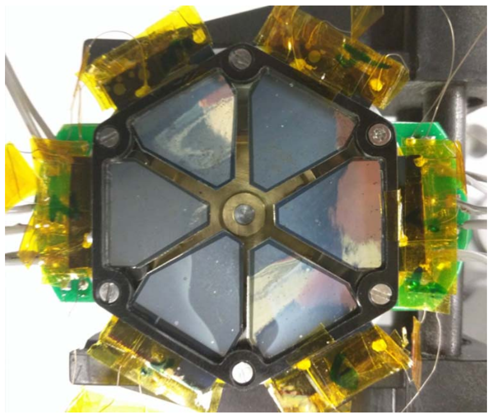

Figure 4: Photo of the assembled rotational energy harvester with bimorph PZT thin-film beams.

After assembly, all the beams maintained their previous integrity without any further damage. However not all the beams perform equally due to manufacturing variation and imperfect yield. In a more mature manufacturing operation, it is reasonable to assume that all beams would perform identically, given the evenly distributed magnet arrangement on the rotor. This assumption allows the simulations to be compared with measured performance by multiplying the power output of the best performing unimorph by 12 to obtain the total power output.

TESTING RESULTS

A bench-top motor controlled swing arm was built as the test set-up to characterize the prototype. As shown in Figure 5, the 50 cm long swing arm roughly mimics the upper limb in human locomotion. The motor creates varying motion profiles in a sinusoidal fashion with different amplitudes and frequencies as an approximation of various walking profiles.

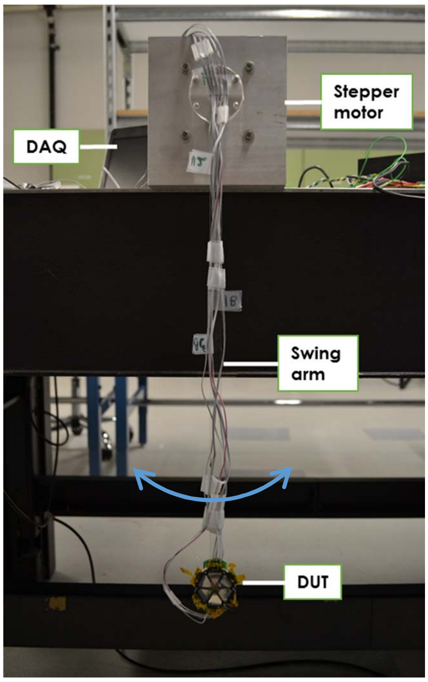

Figure 5: The swing arm test set-up with the prototype attached at the end.

Each beam was terminated with a matching load resistor of values 18 kΩ for de facto unimorphs, and a 33 kΩ for bimorphs. The sinusoidal excitation for characterization tests ranged from 30 to 60 degrees in amplitude and from 0.25 Hz to 1 Hz in frequency. The RMS power was calculated over 20 seconds and the initial power spike during operation was eliminated. As expected the variation among individual beams is significant due to differences in beam properties and assembly tolerances. Thus, the output power was calculated by multiplying the best performing unimorph by 12.

A comparison between simulation and measured power output is given in Figure 6. In the simulation a set of feasible initial rotor resting angles were applied to evaluate the effect of sensitivity to initial conditions on long term average power output. The error bars in Figure 6 represent the minimum and maximum simulated power output based on 3 different initial conditions. The result suggests that model is stable in terms of predicting average power output over a long period of time. In general there is a good agreement between simulation and measurement with the simulated power being consistently lower. For instance, the measured power output from the excitation of $30 \sin 2\pi t$ results in a 41.8 µW and the simulated power output averages 37.6 µW. This discrepancy is likely due to the non-smoothness of the motion profile generated by the stepper motor. In fact the energy harvester benefits from any excess non-periodic excitation which is anticipated in a real wrist-worn situation.

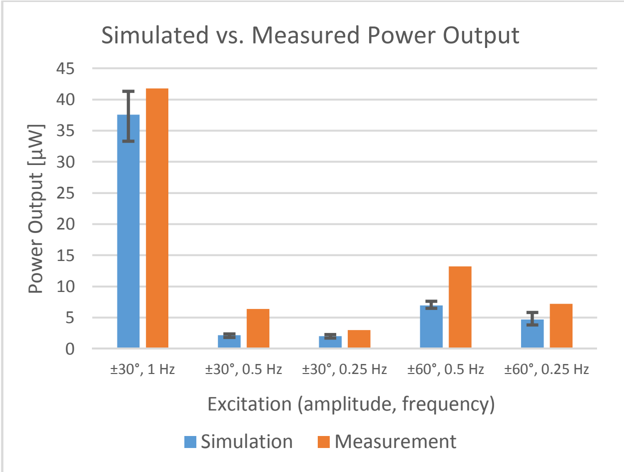

Figure 6: Simulated vs. measured power output from different excitations.

In addition to bench-top controlled experiments, the prototype was tested on the wrist of a human subject with a series of constrained motions including rotating the wrist and jogging in place. By holding the arm horizontally and rotating the wrist from -90º to +90º at approximately 1 Hz, the prototype generates 91.4 µW. In this case, gravitational excitation plays the primary role. A jogging-in-place excitation outputs 156.6 µW. Simply holding the prototype in hand and shaking it generates a similar amount of power. In both cases, the rotor goes into continuous rotation. This prototype was intended to be lightly coupled, i.e., it is targeting weak excitations such as walking or regular office routines. Thus, there is a saturation point for power output once the rotor goes to continuous rotation. Note that the calculations above are all based on the best unimorph assumption made earlier. A sample of instantaneous voltage and power output from one unimorph during an on-wrist test is given in Figure 7.

Further investigation into potential improvement can be done in simulation with the corroborated model. By maintaining the mechanical characteristics of the cantilever beam, a larger PZT to substructure ratio improves the power output since there is more piezoelectric material undergoing the same strain cycles. A bimorph beam with two 10 µm PZT layers will greatly improve the power output to 200 µW in simulation for the same excitation of $30 \sin 2\pi t$.

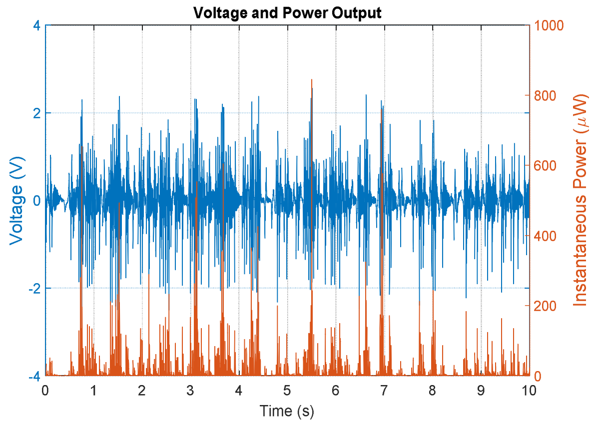

Figure 7: Sample instantaneous voltage and power output from one unimorph across a 27kΩ resistor during an on-wrist test.

CONCLUSIONS

A wrist-worn rotational energy harvester utilizing magnetically plucked {001} oriented bimorph PZT thin-film beams was designed, fabricated, and characterized. A state of the art 5.4 µm thick dense PZT layer on a nickel foil with a high piezoelectric figure of merit for energy harvesting was utilized. The prototype demonstrated approximately 40 µW power output from a bench-top pseudo walking input, which provides potential for a self-powered wearable wellness sensor.

ACKNOWLEDGEMENTS

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CONTACT

*T Xue, tel: +1-801-587-3180; tiancheng.xue@utah.edu