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Fabrication and characterization of a wrist-driven rotational energy harvester using multiple plucked piezoelectric unimorphs

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Abstract: We present fabrication and characterization of a wrist-worn rotational energy harvester using plucked piezoelectric unimorph beams for wearable applications. It consists of an eccentric rotor containing multiple magnets (at certain angular distance) and multiple unimorph beams (clamped to a central hub) with a magnet at the tip of each beam, in an in-plane plucking configuration. While excited, the unimorph beams are asynchronously plucked by the rotor magnets that generate voltage/power by means of the piezoelectric effect. An electromechanical model has been developed to predict the system performance for different plucking magnet configurations. The unimorph beams (12 mm×3.5 mm) are fabricated by bonding a 25 µm thick nickel (Ni) foil to a 43 µm thick lead zirconate titanate (PZT). In order to achieve the highest yield (~ 91%), a custom fabrication process has been developed that utilizes process steps both inside and outside the cleanroom. Finally, a prototype has been assembled and tested by mounting it on a custom-built driven pendulum to provide a controlled pseudo-walking excitation. The system shows non-linear behaviour with the change in the number of adjacent plucking magnets. The most frequently plucked beam generates a maximum of 6.25 µW average power while plucked by a three-magnet configuration under ±25° and 1.25 Hz pseudo-walking excitation. Experimental results are in good agreement with the simulation.

1. Introduction

Modern wearable consumer devices (e.g., smart watches, body sensors, fitness trackers, etc.) contain a number of fully-embedded wireless sensors with multifunctional and low-power consuming features. However, these low-power sensors still require external power, and are generally powered by conventional electrochemical batteries (e.g., Li-ion, Li-Po, fuel cells, etc.). Batteries for most wearable devices last only a few hours to a few days and require periodic charging. Moreover, since most batteries contain toxic metals (such as lead, lithium, or manganese), disposal of the expired batteries and cells produces hazardous waste that exacerbates environmental pollution and poses threats to both human and animal health. Therefore, there is great interest in developing self-powered electronics for sustainable and long-lasting operation by eliminating the need for recharging or replacing their power sources. Energy harvesting from the human-body (e.g., body motion, body heat, breathing etc.) has attracted considerable research interest to address these circumstances [1]. Kinetic energy generated by human body motion is promising since the energy is readily accessible whereas the other sources impose more requirements and environmental conditions [2,3]. Kinetic energy harvesters are typically designed with an inertial mechanism that takes advantage of peak dynamic magnification at a particular frequency (i.e., resonance) of unidirectional excitation. Human body motion produces multi-directional excitation with low frequency and high amplitude that cannot be effectively coupled to a typical inertial generator [4]. Designing an effective wearable kinetic energy harvester requires careful design choices to determine the best functioning structure since excitations generated at different body locations (e.g., wrist, chest, ankle etc.) for different activities (e.g., walking, running, jogging etc.) have different characteristics [5]. A rotational proof-mass without intrinsic motion limits responds better to a multidirectional input like human motion as compared to a typical translational proof-mass.

Among a number of design approaches proposed by the researchers, mechanical frequency up-conversion has become a common approach and is typically implemented via impact or plucking [6-8]. It allows the transducer element (piezoelectric, electromagnetic etc.) to generate voltage/power at its resonant frequency (typically higher) while excited by a low-frequency vibratory system in response to human motion. Eccentric rotor based energy harvesters utilizing magnetically plucked piezoelectric beams have been demonstrated in the literature [9]. Magnetic plucking has the potential to provide better robustness by eliminating mechanical contact. Recently, our group has demonstrated various magnetic plucking configurations, however, much room for optimization remains [10]. Besides, the power density of a wearable energy harvester for a given structure is dependent on the type and plucking configuration of the piezoelectric transducer. For instance, typically used bulk lead zirconate titanate (PZT) bimorph beams suffer from higher stiffness which limits their use in a multi-beam configuration. Polyvinylidene fluoride (PVDF) beams, on the other hand, are softer than bulk PZT beams but suffer from a poor piezoelectric figure of merit. Thinned bulk PZT unimorph beams could potentially be used to overcome these issues. They exhibit very good flexibility without sacrificing piezoelectric properties.

In this work, we demonstrate a wrist-driven magnetically plucked rotational energy harvester utilizing a multi-magnet plucking configuration that asynchronously plucks multiple custom fabricated (nickel) Ni/PZT unimorph beams. Numerical analyses are done to predict the electromechanical behavior of the proposed system. Up to three adjacent plucking magnets are utilized in the eccentric rotor that are able to pluck multiple unimorph beams clamped to the hub. An assembled prototype energy harvester is then tested on a mechanical swing-arm at different pseudo-walking excitations.

2. Harvester structure and operation

A schematic design of the proposed wrist-driven rotational energy harvester is shown in Figure 1. It consists of an eccentric rotor (made of brass) and ten Ni/PZT unimorph piezoelectric beams that are mechanically clamped to a central hub. The eccentric rotor is supported by a shaft and two ball bearings. A tungsten weight is added to the outer rim of the eccentric rotor to increase its mass and eccentricity. The outer rim of the rotor has 8 slots to place plucking magnets (1 mm × 1 mm × 1 mm). This configuration allows multiple magnet arrangements in terms of size, number, and gap to tune the system. The rotor has an outer diameter of 36 mm and proof-mas weight of 13 g with 4.63 mm eccentricity and 2663 g.mm^2 moment of inertia about the center of mass. Each unimorph beam has a magnet (2 mm × 2 mm × 2 mm) at the tip and is aligned with the rotor magnet in an in-plane plucking configuration. A printed circuit board (PCB) is placed at the top of the device that serves not only as the lid of the prototype, but also as a robust gateway to data acquisition.

Figure 2 illustrates a multi-pluck operation of the proposed system that uses up to three adjacent plucking magnets in the rotor at 45° angular distance. The angular distance between each unimorph beam is 36°. This deliberate angular mismatch between the plucking magnets and the plucked magnets is arranged to avoid synchronized beam plucking, which is likely to induce a large cogging torque on the rotor that inhibits continuous rotation, especially when the excitation is weak. The magnets are in a repulsive configuration along the direction of beam length with a 1.5 mm air gap between them.

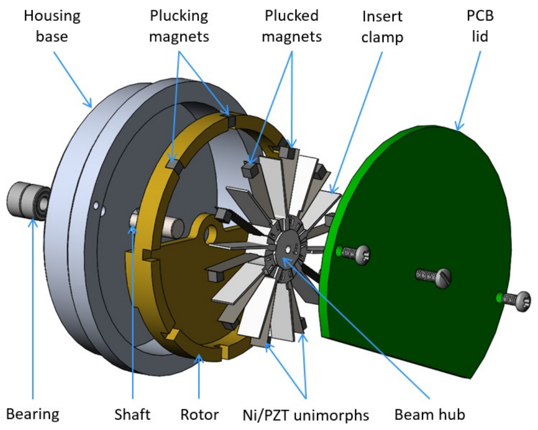

Figure 1. Schematic structure of a wrist-driven rotational energy harvester utilizing magnetically plucked Ni/PZT unimorphs.

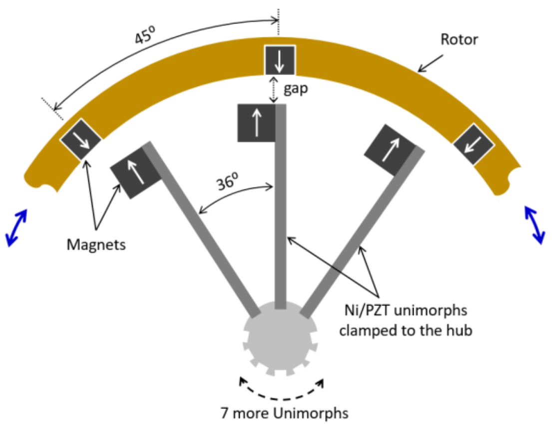

Figure 2. Principle of multi-pluck operation that uses up to three adjacent plucking magnets in an in-plane plucking configuration.

The electromechanical model of the proposed rotational energy harvester is built upon a generalized harvester model we developed previously in which the transducer is considered as a viscous damper [11]. In a generalized rotational system, the motion of the eccentric rotor is constrained in its local plane and is governed by

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

where m, I_g and L are the mass, 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 housing, respectively in their local coordinates. θ_z denotes the angular displacement of the housing whereas ϕ_z denotes the relative angular displacement of the eccentric rotor with respect to the housing. b_m and b_e indicate mechanical and electrical damping coefficients representing lost and extracted energy, respectively which determines the instantaneous power as

$$P = b_e\dot{\phi}_z^2 \tag{2}$$

In this case, b_e is determined by a magnetically plucked piezoelectric cantilever beam model [10]. The system is nonlinear and is highly dependent on the initial conditions as well as the number of plucking magnets. An increasing number of plucking magnets introduces an increasing amount of detrimental cogging torque. Figure 3 shows the simulated output voltage waveforms generated by a single unimorph beam while plucked by different plucking-magnet configurations at ±25° and 1.25 Hz pseudo-walking excitation. The three-magnet configuration seems to balance out the negative effect of the cogging torque with the fact that more plucks per oscillation should result in a higher power output.

3. Unimorph fabrication and assembly

Ni/PZT unimorph beams were fabricated by bonding 43 µm thick Ni coated bulk PZT (CTS Piezo) to a 25 µm thick bulk Ni foil (Alfa Aesar). Figure 4(a) shows the schematic of the fabrication process steps conducted both inside and outside the cleanroom. The bulk PZT sheet (15 mm ×8 mm) was first bonded to a 3 inch silicon (Si) wafer using photoresist (S1813). A similar sized Ni foil was bonded on top of the PZT sheet by non-conductive epoxy (EPO-TEK OE145-6). A small portion of the top PZT electrode (coated Ni) was left open for electrical connection. Conductive epoxy (EPO-TEK H20S) was used to make a better electrical connection between the coated Ni and the bonded bulk Ni (since non-conductive epoxy keeps them electrically isolated). The sample was then diced to the desired size (12 mm ×3.5 mm), each sample makes two Ni/PZT/Si stacks. Finally, the Si substrate was released from the stack by soaking it in acetone. Figure 4(b) shows the photograph of a number of fabricated Ni/PZT unimorphs having capacitance measured in the range between 9.7 nF and 11.2 nF. We were able to

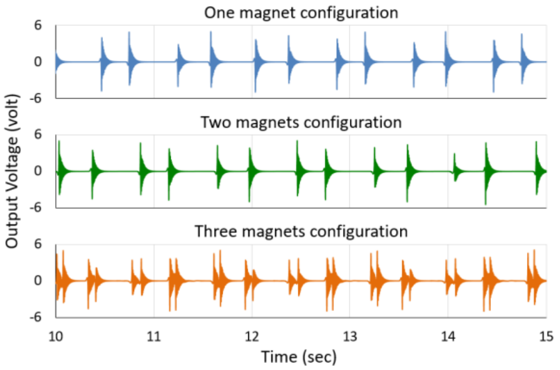

Figure 3. Simulated output voltage waveforms generated by one unimorph beam while plucked by a different number of adjacent plucking magnets.

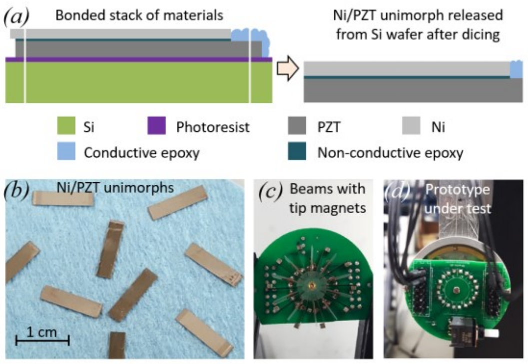

Figure 4. (a) Ni/PZT unimorph fabrication process steps, photographs of the (b) fabricated unimorphs, (c) assembled unimorphs in the hub and (d) assembled prototype.

achieve 91% yield by implementing this custom fabrication process.

A plucking magnet was glued to one end of each unimorph beam and the other end was clamped to a central hub (attached to the PCB lid) using insert clamps, as shown in figure 4(c). The electrical connections from both beam surfaces were made through conductive copper tape placed on both the beam hub and the insert clamps. For a robust connection, silver epoxy was applied at the contact edge between the copper tape and the beam electrodes. Wires were soldered to the copper tapes for connection to the PCB. A photograph of a fully assembled prototype, mounted on a mechanical swing arm (i.e. a driven pendulum), is shown in figure 4(d).

4. Experimental results

The performance of the assembled protype energy harvester was verified under pseudo-walking excitation by mounting it on the distal end of a microprocessor-controlled, stepper motor-driven mechanical swing-arm. The swing-arm creates varying excitation profiles in a sinusoidal fashion with different angles and frequencies as an approximation of various walking profiles. The output voltages generated by the unimorph piezoelectric beams under various input excitations were observed and recorded for further analysis. Each unimorph beam was terminated with a 95 kΩ matched load resistance whose value was determined as $R_{opt} = 1/2\pi f_n C$; where C is the capacitance of the piezoelectric material and f_n is the natural frequency of the beam determined by manually deflecting the beam tip and releasing it to undergo a damped oscillation. Tests were done for three different plucking magnet configurations and two different excitation angles at 1.25 Hz excitation frequency.

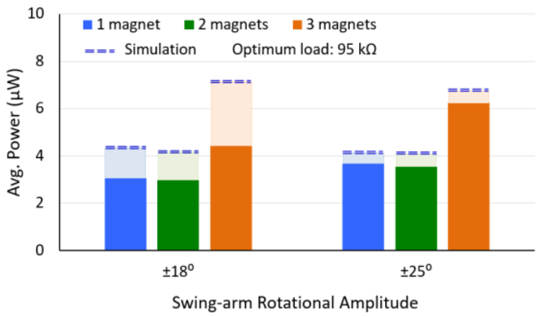

Figure 5. Measured average power output (compared with simulation) by most frequently plucked unimorph beam at 1.25 Hz pseudo-walking excitation frequency.

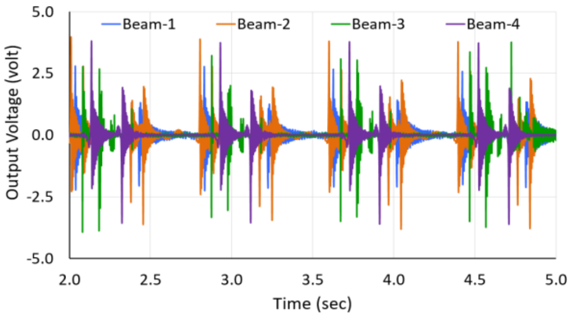

Figure 6. Measured voltage waveforms generated by four adjacent unimorphs simultaneously plucked by three-magnet configuration at ±18° and 1.25 Hz pseudo-walking excitation.

Figure 5 shows the measured and simulated average power output of the most frequently plucked unimorph beam for different plucking magnet configurations. Results show that the average power is reduced with a two-magnet configuration due to an increased cogging torque. With a three-magnet configuration, the amount of average power increases significantly. In this case, the negative effect of cogging torque is balanced with the increase in number of plucks per oscillation. The variations in the simulation and measurements are likely due to inaccuracies in assembly, especially the gap and offset between plucking and plucked magnets which governs the maximum strain in the beam and its voltage output. Figure 6 shows measured voltage waveforms generated by four adjacent beams simultaneously plucked by the three-magnet configuration at $\pm 18^{o}$ and 1.25 Hz pseudo- walking excitation. The data in Figure 6 demonstrate that there is a significant beam to beam variation in terms of voltage (and power) generation. In addition to the fact mentioned earlier, potential differences in degradation among the beams during assembly and testing could contribute to the variation as well.

5. Conclusions

A wrist-driven rotational energy harvester using magnetically plucked Ni/PZT unimorph beams has been designed, fabricated and characterized. It has been modelled in a multi-pluck configuration by varying the number of plucking magnets. A custom unimorph fabrication method is developed to achieve the highest fabrication yield. Numerical analyses are done to predict the electromechanical behaviour of the system. A prototype is assembled and tested by a bench-top pseudo-walking input. Up to three adjacent plucking magnets (at 45^{o} angle) are utilized in the rotor that are able to pluck multiple beams clamped to the hub with a 36^{o} angular spacing. An increasing number of plucking magnets introduces an increasing amount of detrimental cogging torque. A three-magnet configuration introduces more plucks per cycle and balances out the negative effect of cogging torque, resulting in a higher power output.

Acknowledgements

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