A Hybrid Piezoelectric and Inductive Rotational Energy Harvester

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Abstract. This paper presents the development of a rotational energy harvester that generates power based on a combination of piezoelectric and electromagnetic methods. The device utilizes two piezoelectric beams and two inductors and potentially multiple elements on a stationary plate to maximize the harvested energy. The piezoelectric beams generate voltages when deflected with a rotating magnet. In addition, the inductors generate voltages when a magnet passes over them. In order to maximize the harvested energy and frequency, sixteen magnets were embedded in the rotating plate to excite the elements with a higher frequency. A 3D printer was used to make the enclosure, and stationary and rotating components of the device. An assembly of Arduino microcontroller, DC motor, IR sensor and LCD screen was used to test the device. The harvester utilized a closed loop feedback system to monitor rotational speed. The device was tested at various rotational speeds from 130 rpm to 510 rpm. Voltage output versus time graphs were analyzed for each speed. It was determined that raising the number of moving magnets and rotational speed increase not only the frequency but also the voltage amplitude in both piezoelectric beams and inductors. The developed energy harvesting device can be used in any existing rotational system such as vehicle tires, bicycles, rotating machines and exercise equipment.

1. Introduction

Energy harvesting has been widely researched in the past decade due to its great usage for providing energy to remote areas as well as electronic devices [1]. Harvesting energy from piezoelectric beams is a popular form of energy conversion due to the possibility for a high voltage output [2]. Piezoelectric energy harvesting devices have been used for charging batteries [3], wireless remote power supply [4], subsurface ocean/river power generators [5], unmanned aerial vehicles [6], biomedical devices [7], and other portable devices [8]. There have been numerous studies that have focused on producing electrical energy from natural vibration in sources such as the human body and other wearable devices [9].

One of the available energy sources that are already existent and natural is rotational movement. This kinetic energy can be potentially converted into electrical energy to power remote devices and not rely on batteries [10]. This practice of extracting power for every day systems that rotate has been applied to rotational systems such as bicycles. The converted energy from the wheels on the bicycle could be used to power accessories the user has on the bicycle which would remove the need for a battery pack [11]. Many rotational energy harvesting operate at low frequencies such as frequencies between 7-13.5 Hz [12]. They compared two different configurations of magnets at higher frequencies and the power
outputs. In addition, different shaped cantilever beams including rectangular and trapezoidal were compared to find the maximum deflection and potentially highest power output [13].

Piezoelectric based rotational energy harvesters have been demonstrated on systems such as wind systems [14], automotive tires [15], wearable human watches [16], rotary disks [17], rotational sun track solar panels [18] and wireless autonomous monitoring systems [19]. Theoretical and experimental modelling of a piezoelectric based rotational energy harvester with bi-stability and frequency up conversion was demonstrated for applications with wide bandwidth and low-frequency kinetic energy [20]. Furthermore, models have been characterized for energy harvesters in self-powered watches [21,22]. Few rotational energy harvesters have been demonstrated to use multiple PZT beams. For example, a wrist-worn rotational energy harvester was developed that used six PZT beams with four moving magnets [23]. The eccentric rotor-based piezoelectric rotational energy harvester was developed based on the idea adopted from self-winding watches to address low performance challenges in energy harvesting from human motion. The design worked based on both linear and rotational motions and provided several degrees of freedom [24]. In another research, several feasible magnetic plucking configurations were categorized and simulated for eccentric energy harvesters. The work classified in-plane plucking and three different out-of-plane deflection configurations including direct repulsive, orthogonal, and indirect repulsive setups [25]. Rotational energy harvesters utilizing multiple piezoelectric beams and moving magnets were demonstrated [26,27].

An electromagnetic vibration-driven energy harvester was developed using printed circuit board materials to lower the cost and to achieve lightweight device [28]. An electromagnetic energy harvesting technique with an enhanced magnetic flux change was presented based on Faraday’s law to convert mechanical vibration into electrical energy using an array of alternating north- and south-orientation magnets [29]. In this paper, we have added multiple inductors to the piezoelectric based rotational energy harvesters to increase the power output with a hybrid piezoelectric and inductive method. The paper descriptively discusses the design, fabrication, testing and results of the rotational energy harvester actuated by magnetic fields to harvest energy from a rotational movement. In addition, the design uses different elements such as a closed loop feedback system to control the rotational speed of the system. The effect of rotational speed on the harvester performance including voltage amplitude and frequency are discussed.

2. Design

Energy conversion into electrical power using inductive and piezoelectric methods require some type of kinetic energy. The energy in this design is a rotational movement. A spinning plate passes magnets over the two different types of energy generation elements, inductors and piezoelectric cantilever beams, converting a rotational energy into an electrical power. A complete view of the system is depicted in figure 1.

There are two plates in the device, rotational and stationary. The top plate, the one rotating, has two rings of magnets at different radii. The inner ring with a 23 mm radius has eight 4.8 mm diameter magnets which pass over the piezoelectric beams. In addition, the outer ring with a 47.5 mm radius has eight 12.7 mm diameter magnets for the inductors. The number of magnets increase the operational frequency that acts on the elements. Instead of one pass per revolution there are eight passes per revolution simulating a faster rotational speed by eightfold. The polarity of all the magnets are in the same direction north to south and perpendicular to the plate surface. Figure 2 shows the top and bottom plates in detail, including the two rings of magnets in the top plate, and the PZT beams and the inductors in the bottom plate. The bottom plate houses the energy conversion elements, two piezoelectric beams and two inductors. The 34.85 mm long, 2.50 mm wide, 0.30 mm thick cantilever beams are made of lead zirconate titanate (PZT). The two PZT beams which are 90° apart have a neodymium magnet on one end, therefore when the top plate magnets pass by, the repulsion between two magnets causes a deflection in the beam. The distance between the two magnets is a crucial part of the system. If the distance is too large, the beams do not bend enough to generate a voltage while if it is too small the repulsion force largely bends the beam and breaks it.
**Figure 1.** Complete view of the inductive and piezoelectric rotational energy harvester.

**Figure 2.** (a) The top rotating plate including two rings of magnets, eight 12.7 mm diameter magnets centered over inductors and eight 4.8 mm diameter magnets centered over PZT beams. (b) The bottom stationary plate including the PZT beams and the inductors. A small magnet is attached to the end of each PZT beam.

Working principle of the piezoelectric and inductive energy harvesting is illustrated in figure 3. The piezoelectric actuation is based on repulsive force between two magnets on the beam and rotating plate. As the rotating magnets rotate along with top plate, they line up with the magnet on the PZT beam at some point and deflect the beam downwards. As the rotating magnet gets away from the beam magnet, the beam deflects back to the original position. The beam will continue deflecting upwards in negative direction due to spring elastic forces. The signal generated by the PZT beams is a sinusoidal
pulse and the voltage output is related to the beam deflection. When the beam reaches its max point of deflection, the voltage is at its greatest.

![Diagram of piezoelectric beam energy harvesting](image1.png)

*Figure 3.* Working principal of piezoelectric beam (a) and inductive (b) energy harvesting.

The inductive energy harvesting principal is based on Faraday’s law which states that an electromotive force is induced in a conductive coil by time varying magnetic flux though the coil. The change in magnetic field in this device is made by moving the magnet on the rotating plate over the inductor. The vertical gap between the rotating magnet and the 10mH inductors needs to be at the minimum possible value to receive the highest voltage. This gap is designed to be about 1 mm. The inductors are designed to be 7.2 mm diameter to ensure that the 12.7 mm moving magnets completely cover the inductors when passing over them.

### 3. Fabrication

The design was realized using SOLIDWORKS®. The device frame, holding the rotating magnets, PZT beams, inductors, DC motor and IR sensor was fabricated using an Athorbot® A-01 3D printer using poly-lactic acid (PLA) filament (Hatchbox®). The utilization of 3-D printing allowed for features and components to be modeled with little down time. A complete overview diagram of the fabricated device and its accessories is shown in figure 4.
The rotating magnets were adhered to the underside of the rotating plate in which its vertical distance from the harvesting elements could be adjusted. This was done by adding or subtracting 0.1mm thick shims to move the shaft that the rotating wheel was fixed to up and down. The 6 mm diameter shaft was held in place by three ball bearings, two of which were pressed into the plate that mounted the inductors to ensure that the magnets rotated perfectly parallel and at a constant distance from the surface of the inductors. The driving motor was mounted above the shaft and a torque was transmitted via an aluminum flexible shaft collar to ensure that the motor did not bind due to any misalignment.

The two piezoelectric beams were laminated to a thin piece of narrow copper sheet on the upper side of the piezoelectric beam. There was a magnet mounted on one end of the beam via the copper sheet using an epoxy. The beams were bonded into a well inside the 3D-printed base plate with the PZT beam facing down to ensure that it was firmly fixed to the base. This forced the beam to deflect both the copper and the PZT material when a magnet passed over the end of it. Wires of the off-the-shelf inductors and PZT beams were soldered to the outside of the bottom plate through the designed holes. Figure 5 shows a PZT beam and an inductor fully fabricated and in place on the bottom plate.
Figure 5. Close-up image of a PZT beam and an inductor fully fabricated and in place on the bottom plate.

A closed-loop feedback control system was used to control the rotational speed of the top plate. An Arduino Uno and a DC motor driver board acted as the controller and the actuator, respectively. The DC motor connected to a shaft and spun the top plate. A pulse-with-modulation (PWM) output signal was used to control the DC motor driver. A set rotational speed was measured from a potentiometer and the Arduino converted the analog input signal to a set speed range. An infrared (IR) sensor was used to measure the actual rotational speed and the PWM signal were all displayed on an LCD utilizing I2C communication. A code was programmed in Arduino to control the PWM based off the set speed and the measured speed. Arduino used library references to set up the known functions in a script.

4. Testing
The device was run using its aforementioned accessories and tested using a National Instruments USB 6003 Multifunctional Data Acquisition (DAQ) device to make a precise measurement of each energy harvesting element. A LabVIEW software was used to allow for the recording of generated voltages as a function of time. To fully test the system, data was collected at six distinct speeds from 130 rpm to 510 rpm. This range of speeds are available in many applications such as fitness equipment, washing machine, bicycle, motorcycle and car tires.

5. Results and Discussion
In order to analyze changes in the output of each harvesting element, various speed measurements including those at 130 rpm, 250 rpm, 300 rpm, 400 rpm, 435 rpm and 510 rpm were taken with the DAQ card. Figures 6 and 7 show typical generated voltages as a function of time at two rotational speeds, 130 rpm and 510 rpm for PZT beams and inductors, respectively. It is clear that due to the use of eight magnets on the moving plate for both PZT beams and inductors, the frequency of the sinusoidal voltages significantly increased compared with a case if only one moving magnet was used. The cycles were repeated faster by the number of magnets, making the multiple magnet case a significantly higher overall output. In addition, the rounds of cycles were repeated faster with higher rotational speed in which next round of cycles began earlier by a certain moving magnet. The latter effect was enhanced by having eight rotating magnets in a row. Therefore, the higher rotational speed, the higher overall output.
Figure 6. Typical voltages generated by the PZT beams as a function of time at 130 rpm (a) and 510 rpm (b).

Figure 7. Typical voltages generated by the inductors as a function of time at 130 rpm (a) and 510 rpm (b).

Figure 8 compares the average voltage amplitudes as a function of rotational speed for the PZT beams and inductors. The results showed that the average amplitude in both cases increased with the rotational speed. The voltages generated by the inductors were determined to be linearly proportional to the rotational speed while those generated by the PZT beams were found to be increasing with the rotational speed with a polynomial trend. Therefore, it is concluded that the efficiency of inductive energy conversion is higher than that of piezoelectric energy conversion at higher speeds. In addition, the inductors have more potential to generate voltages with higher amplitude than PZT beams in this case.

Furthermore, the harvester in this research was run with two piezoelectric beams and two inductors that increased the overall output. The harvester has a potential to be run with several piezoelectric beams and inductors that increase the overall output to a higher level. This is especially beneficial for applications that require higher voltages or draw a higher currents. In this case, the several piezoelectric beam circuits can be put in series or parallel, respectively in order to meet these requirements. A similar approach can be used for the inductors. Voltage cycles generated by the PZT
beams or the inductors will have the same phases because the number of the moving magnets passing over the beams is even. In other words, when a beam is hit by a certain moving magnet, another beam 180° apart from the other beam is hit by a magnet 180° apart from the other magnet. This fact would be applicable for the inductors.

![Graph](image)

**Figure 8.** A comparison between the graphs of average voltage amplitude as a function of rotational speed for the PZT beams and inductors.

In addition, an AC/DC converter can be utilized to convert harvested voltages in each element to a DC voltage [30,31]. High voltages can be potentially used as a substitute for the grid power where a device requires that level of voltage. The required voltages can be adjusted by including different number of PZT beams or inductors. There are lots of such devices that draw a low current which is compatible with the voltage generated using this energy harvester. As an example, several monitoring devices in electronic screen of a stationary exercise bicycle are utilized to display speed, distance, time, calories burned, etc. An energy harvester can be implemented into the apparatus, and the power output of the user could be used to power the display. Though such an equipment may use internal converters to adjust the required voltages, the generated voltage by the energy harvester can be used to power the whole equipment unit.

### 6. Conclusions

The development of a hybrid piezoelectric and inductive energy harvester was demonstrated in this paper. The two methods simultaneously converted a rotational energy into an electrical one. It was found that the energy harvester’s output increased by using the two alternative methods simultaneously. Using multiple moving magnets passing over the PZT cantilever beams and the inductors significantly increased the overall generated voltage and frequency. In addition, increasing number of the PZT beams and inductors largely increased the power output. Furthermore, efficiency of inductive energy conversion was higher than that of piezoelectric energy conversion at higher speeds. The inductors have more potential to generate voltages with higher amplitude than PZT beams in this case. The device could be utilized in any rotational machines such as vehicle tires, bicycles, watermills, windmills and exercise equipment. A further study could be performed to increase the efficiency of the beams using lead-free piezoelectric materials with the addition of rare earth metal via
a chemical doping process. Furthermore, multiple inductors in different radial rings on the stationary wheel could be utilized to increase the power output.

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