

# A handy-motion driven, frequency up-converted hybrid vibration energy harvester using PZT bimorph and non-magnetic ball

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**Abstract:** We have presented a frequency up-converted hybrid type (Piezoelectric and Electromagnetic) vibration energy harvester that can be used in powering portable and wearable smart devices by handy motion. A transverse impact mechanism has been employed for frequency up-conversion. Use of two transduction mechanisms increases the output power as well as power density. The proposed device consists of a non-magnetic spherical ball (freely movable at handy motion frequency) to impact periodically on the parabolic top of a piezoelectric (PZT) cantilevered mass by sliding over it, allowing it to vibrate at its higher resonant frequency and generates voltage by virtue of piezoelectric effect. A magnet attached to the cantilever vibrates along with it at the same frequency and a relative motion between the magnet and a coil placed below it, induces emf voltage across the coil terminals as well. A macro-scale prototype of the harvester has been fabricated and tested by handy motion. With an optimum magnet-coil overlap, a maximum 0.98mW and 0.64mW peak powers have been obtained from the piezoelectric and the electromagnetic transducers of the proposed device while shaken, respectively. It offers  $84.4\mu\text{Wcm}^{-3}$  peak power density.

## 1. Introduction

Now a days, low power consuming microelectronic devices and sensors such as accelerometer, gyroscope, proximity sensor, heart-rate sensor, bluetooth, NFC, Wi-Fi, GPS tracker, and many more are being embedded within hand-held or wearable consumer electronics. These embedded devices and sensors consume power from a single power source of the consumer electronics. Use of the embedded sensors allows it to run out of power quickly. Generally, electro-chemical batteries have been using as power source to supply power to these portable and wearable electronic devices. The development of the power sources (batteries) are still slower than that of the device technologies, even though the devices require less power to be operated. Electro-chemical batteries have limited lifetime, needs to be replaced. They require periodic charging which is, sometimes, inconvenient or impossible. Since last few decades, a lots of approaches have been unveiled to sort out this problem. Many researchers around the world have been investigating to use environmental sources as the alternative power source to be supplied to the consumer electronics which is known as energy harvesting. Energy harvesting devices and systems capture physical energy from environmental sources and convert it into electrical energy by means of a number of energy conversion mechanisms depending on the type of energy

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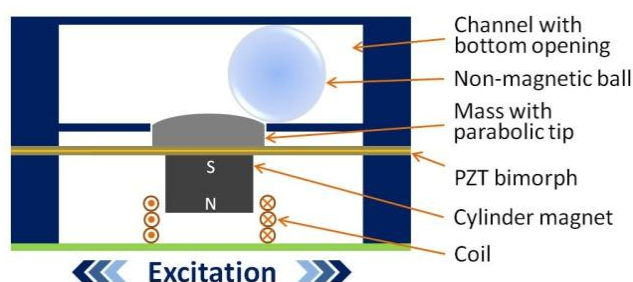


sources. In order to supply power to those electronic devices or recharge their power sources (batteries or super capacitors) in an emergency situation, energy harvesting from environmental sources e.g., mechanical vibration, wind, heat, light, radio wave etc. would have been an effective solution [1]. Mechanical vibration is one of the most attractive physical energy sources due to its abundance in nature and unlimited lifetime [2]. But most vibrations are of low frequencies and large amplitudes with various cyclic movements in different directions [3-5]. Piezoelectric, electromagnetic and electrostatic mechanisms are widely used techniques for harvesting energy from mechanical vibrations [2].

Generally, cantilevered spring-mass system with a specific resonant frequency is employed with these mechanisms. Harvested power is maximum when harvester's resonant frequency matches the applied vibration frequency. But employing cantilevered spring-mass system for low frequency (below 10 Hz) energy harvesting is quite challenging due to the size constraints for specific application and, of course, power flow decreases with decrease in resonant frequency [6]. Human motion (e.g., walking, running, shaking limbs etc.) also generates very low frequency (below 6 Hz) vibration which does not allow to employ the cantilever structure conveniently [7]. This is why, mechanical frequency up-conversion mechanism has been employed by a number of researchers [8-10]. Recently, we also proposed an impact based frequency up-converted electromagnetic energy harvester for hand-shaking vibration that employed an FR4 cantilever beam with parabolic-top proof-mass as high-frequency oscillator and a freely movable ball as a low frequency oscillator [11]. But, it was capable of generating a few hundred  $\mu\text{W}$  power, having low power density. In this work, we have approached to hybridize our previous work with a piezoelectric (PE) mechanism in addition to the existing electromagnetic (EM) mechanism without increasing the harvester volume. A PZT bimorph replaces the FR4 cantilever. It uses transverse impact mechanism by a non-magnetic ball that meets the reliability challenge from quick damage of the piezo-cantilever rather than direct impact. This hybrid approach generates significant power that can be supplied (after conditioning) to the portable and wearable consumer electronics from handy-motion vibration.

## 2. Structure of the hybrid energy harvester

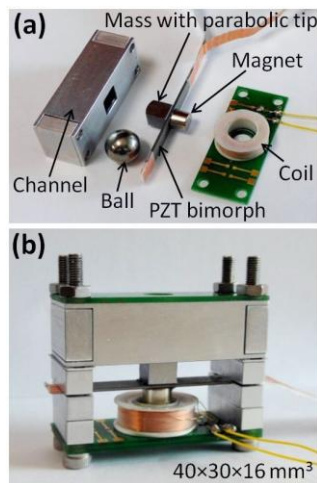
Figure 1 shows the schematic drawing of the proposed impact based, frequency up-converted hybrid type handy motion driven energy harvester. It consists of a freely moveable non-magnetic ball within a rectangular channel with bottom opening at the centre. A proof-mass with parabolic-top is attached to a fixed-fixed piezoelectric bimorph cantilever beam that works as the spring-mass-damper system. The beam is aligned with the channel in such a way that the parabolic-top of the proof-mass can occupy the bottom opening of the rectangular channel so that the ball can slide over it during its back and forth motion in the channel. A cylinder magnet is attached to the piezo-cantilever, opposite to the proof-mass and a coil is also placed below the magnet, on the bottom cover of the device structure. When excitation is given by handy motion, the ball produces transverse impact on the proof-mass allowing the cantilever to vibrate. The piezo-beam vibrates with its resonant frequency in a direction perpendicular to the direction of ball movement and generates voltage due to strain experienced on its surfaces. Accordingly, the magnet attached to the beam also vibrates relative to the coil and induces emf voltage according to Faraday's law of electromagnetic induction. The vibration frequency (resonant frequency) of the cantilever beam is much higher than the applied handy-motion vibration.



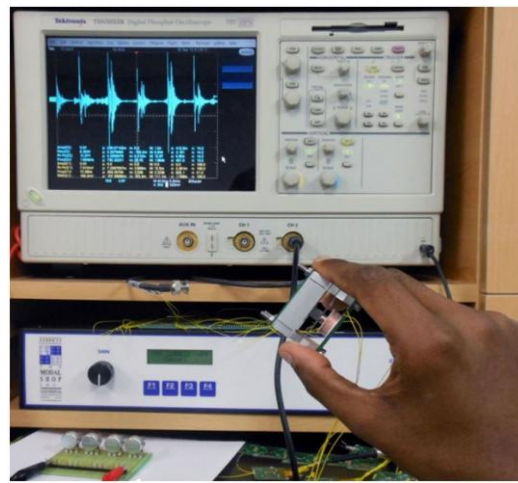
**Figure 1.** Schematic drawing of the proposed hybrid type handy motion driven vibration energy harvester.

### 3. Prototype fabrication

A macro-scale prototype was fabricated that consists of two transduction parts. The PE transduction part of the prototype comprises a  $\text{Ø}6 \times 5 \text{ mm}^2$  NdFeB cylinder magnet and a cubic Fe mass of 6 mm length having a parabolic extension of 1 mm height at the top, both attached at the middle of either sides of a PZT bimorph ( $36 \times 6 \times 0.5 \text{ mm}^3$ ) cantilever beam. A suitable assembly of the magnet and a 1000-turn coil (0.1 mm copper wire) of 8 mm bobbin diameter assembled on a printed circuit board (PCB) constitutes the EM transduction part. Along with those, a  $\text{Ø}10.3 \text{ mm}$  non-magnetic steel (type 316) ball that vibrates inside the rectangular channel (inner area  $10.5 \times 10.5 \text{ mm}^2$ ) with opening ( $7 \times 7 \text{ mm}^3$ ) at the centre of one plane, is assembled within an aluminium structure to constitute the overall ( $40 \times 30 \times 16 \text{ mm}^3$ ) prototype as shown in figure 2. The PZT beam was assembled in such a way that the channel opening is occupied by the parabolic-top of the cubic mass with a 0.4 mm overlap with the ball inside so that the ball can slide over it and produce a transverse impact while an excitation is given to the prototype by handy-motion.



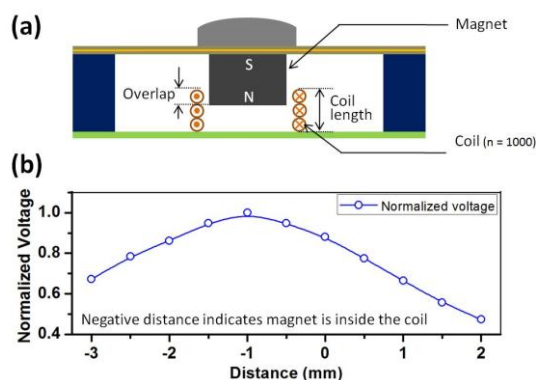
**Figure 2.** Photographs of the (a) components and (b) assembled prototype.



**Figure 3.** Photograph of the test setup while the fabricated harvester prototype was driven by handy-motion.

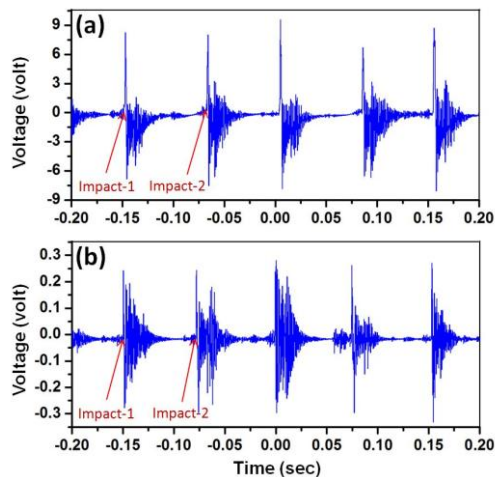
### 4. Experimental results and discussion

To date, most of the vibration energy harvesters have been characterized using electrodynamic shaker. In this case, our harvester prototype was tested by handy motion vibration, as we were intended to. Figure 3 shows the photograph of the test setup where the harvester outputs were connected to a digital storage oscilloscope (TDS 5052B) via continually adjustable load resistor (to measure load voltage and power) in order to observe (and record) the output response instantly.

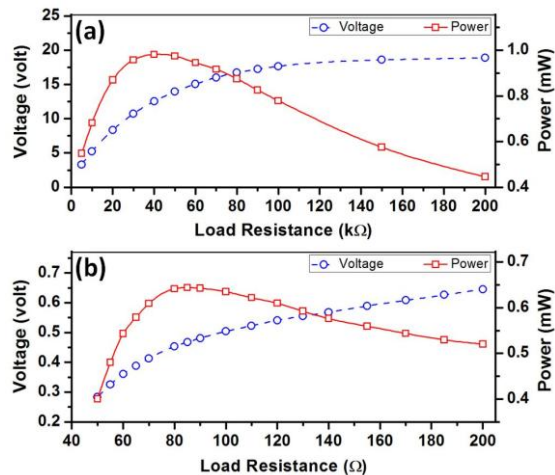


**Figure 4.** Optimization of magnet-coil overlap distance: (a) schematic structure, (b) Normalized voltage versus overlap distance.

In case of EM transduction part, the highest possible e.m.f. voltage is induced by electromagnetic induction when maximum flux linkage occurs between magnetic flux lines and coil turns. The optimal equilibrium position of the coil with respect to the magnet was measured in order to achieve maximum possible output. Results show that the EM transducer generates maximum open circuit voltage when the magnet (poled in its thickness direction) is immersed 1mm inside the hollow cylindrical coil, as shown in Fig. 4. The air gap between the magnet and coil was 1mm. Since the absolute values are primarily not of interest in determining the optimal equilibrium position of the magnet and coil, they were normalized to the maximum values.

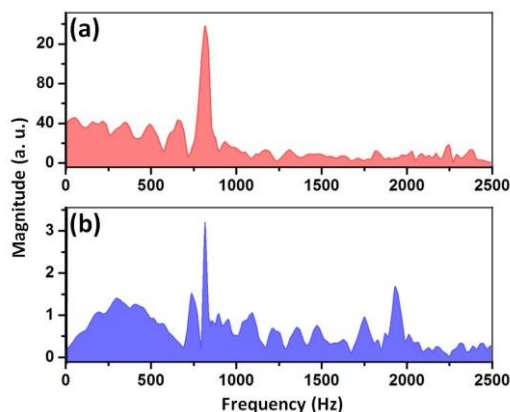


**Figure 5.** Instantaneous open circuit voltage waveforms generated by (a) PZT cantilever beam and (b) magnet-coil assembly of the fabricated prototype.



**Figure 6.** Load voltages (p-p) and powers (peak) versus load resistances generated by (a) PZT cantilever beam and (b) magnet-coil assembly of fabricated prototype.

Open circuit voltage waveforms generated by both PE and EM transduction parts as shown in figure 5, attenuate exponentially with time between two consecutive impacts which cause due to damping. Attenuation is not perfectly exponential due to process variation in assembling the components. Two consecutive maximum peaks were generated in one cycle of the applied vibration because the ball impacted on the parabolic top of the mass twice in one cycle of its back and forth movement. Figure 6 illustrates the peak-peak load voltage and peak power delivered to the load. A maximum 0.98mW and 0.64mW peak powers were generated while PE and EM transducers were connected to 40kΩ and 85Ω matched load resistances, respectively. Since peak voltage amplitudes reduces to almost zero as the time passes, before the next impact occurs, value of average powers reduce dramatically.



**Figure 7.** Frequency components of the voltage waveforms generated by (a) PZT cantilever beam and (b) magnet-coil assembly obtained by FFT.

By applying Fast Fourier Transform (FFT) analysis, frequency of the generated voltage waveforms for both PE and EM transduction parts were found to be 816Hz as shown in figure 7 whereas the frequency of handy-motion vibration was around 5Hz. As both PE and EM transduction parts generate power in this hybrid device, it offers much higher peak power density ( $84.4\mu\text{Wcm}^{-3}$ ) than its EM-only counterpart ( $21.5\mu\text{Wcm}^{-3}$ ). There are still much room for its performance improvement. In order to improve its performance, the damping of the cantilever beam vibration needs to be reduced by proper design choice. Beside this, the shape of the mass's top surface and the overlap area of the mass top and the ball needs to be optimized. Damping matching between mechanical and electrical damping would increase its performance as well.

## 5. Conclusions

We have proposed and demonstrated a handy-motion driven, frequency up-converted vibration energy harvester in which a piezoelectric transduction part and an electromagnetic transduction part have been hybridized. This hybrid approach increases the power density significantly. A macroscale prototype has been fabricated and tested by hand-shaking. The piezoelectric transducer generated 0.98mW peak power whereas the electromagnetic transducer generated 0.64mW peak power across their respective optimum load resistances. Frequencies of the generated voltage waveforms were up-converted by transverse impact mechanism which offers reliable operation of the harvester. The frequency up-conversion feature increased the power flow of the device. Since the output amplitudes degrade with time, average power of the device becomes significantly low which is not good enough to power up an electronic circuit, the test results show its ability to be implemented in powering portable hand-held and wearable consumer electronics from handy-motion with further optimization in design parameters (e.g., stiffness, damping, overlapped contact area). Future work will include more optimized design, miniaturization and implementation of the proposed handy-motion driven hybrid vibration energy harvester.

## Acknowledgements

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