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# Impact-based piezoelectric vibration energy harvester

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## HIGHLIGHTS

- An indirect impact-based piezoelectric vibration energy harvester presented.
- Impact of the springless proof mass and housing generates electrical power.
- Maximum power of 963.9 μW and 11.9% power decrease after 489,600 cycles obtained.
- Analytical model developed and compared with experimental results.

## ARTICLE INFO

*Keywords:*
Energy harvesting
Indirect impact
MFC (Macro Fiber Composite)

## ABSTRACT

This paper presents an indirect impact-based piezoelectric vibration energy harvester using a freely movable metal sphere as a proof mass and an MFC (Macro Fiber Composite) beam as a piezoelectric cantilever. The impact of the spherical proof mass and both end walls of the channel generates MFC cantilever vibration in response to low-frequency external vibrations such as human-body-induced motion. Size and position of the proof mass on an MFC beam have been optimized to generate higher output power effectively. A proof-of-concept device has been designed, fabricated and tested using vibration exciter. An analytical model has been developed by examining the behavior of indirect impact system and MFC cantilever. Moreover, the vibration mode of the MFC cantilever has been analyzed with finite element analysis and frequency domain analysis. With the developed model, theoretical open circuit voltage has been compared with experimental results. Maximum peak-to-peak open circuit voltage of 42.2 V and average power of 633.7 μW have been obtained at 3 g acceleration at 17 Hz. Long-term reliability of the device has been verified by cyclic testing. After the measurement of fundamental characteristics, we have proposed a new device with improved output performance which generated maximum average power of 963.9 μW at 3 g acceleration at 18 Hz. To improve the long-term reliability, a modified device with titanium alloy housing has been fabricated, which provided 11.9% power decrease after 489,600 cycles of operation.

## 1. Introduction

Recently, research interest in micro power generation using energy harvester has been growing steadily for applications such as wireless sensor nodes, implantable devices, health monitoring devices and wearable devices [1–11]. In some of these applications, autonomous power supply unit is preferable when the device is unsuited for a conventionally wired supply of power or is completely separated from the outside world. Utilization of primary battery cell can be the most straightforward choice in specific devices at the cost of limitation in lifetime and need for a periodic replacement. Also, repeated charging can be an issue for devices with secondary batteries. Therefore, harvesting energy from renewable energy sources such as wind, heat, sound, light, and vibration could be an attractive solution for a low power consuming device with difficulties in battery replacement or charging. Among the various energy sources, environmental vibration has drawn considerable attention from the researchers due to the advantages such as high accessibility, ease of device volume reduction and fabrication, availability of straightforward energy conversion mechanisms, and abundance in nature [12–16]. Vibration energy harvesting has been an interesting and promising research topic up to the present [12,17–34]. General overviews of the field are given by Beeby et al. [35] and by Cook-Chennault et al. [36] with a comparison to non-regenerative power supply systems and a focus on piezoelectric devices. Kim et al. focused on piezoelectric MEMS (Micro-Electro-Mechanical Systems) devices [37] and work on design considerations and optimization of the power output have been introduced by Roundy et al. [38,39].

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Various research has been conducted to harvest energy from environmental vibration, which utilized one of the three primary transduction mechanisms based on piezoelectric [12,17,19,22–28], electromagnetic [18,20,21,29–31], and electrostatic power generation principles [32–34]. Although high-frequency vibrations with regular amplitude originating from specific vibration sources, such as machinery and vehicles, could be utilized as the energy source, many of the vibration energy harvesters are targeting low-frequency vibration of random nature. Human-body-induced vibration which can be characterized by very low frequency, high amplitude, and randomness in both frequency and amplitude is a good example [12,17–26]. After the successful verification of applicability of various power generation mechanisms in miniature and micro scale, different types of approaches have been proposed to overcome the limitations of typical spring-mass-damper-based harvester designs. In addition to the improvement of power conversion efficiency, lowering the resonance frequency and widening the bandwidth have been the major concerns for small-scale vibration energy harvesters which utilized the spring-mass-damper-based architecture. Frequency-up-conversion [17–19], increased frequency bandwidth [20,21], utilization of bistable or tristable responses [12,22,23], impact-driven power generation, and utilization of springless proof mass [24–26] are some of the most widely used techniques to overcome these issues.

Among the various power generation mechanisms, piezoelectric energy harvesting is an attractive energy conversion method due to ease of implementation and high energy conversion efficiency. Among the various piezoelectric devices and systems, generators using the impact-induced vibration of piezoelectric materials have been researched mostly due to advantages such as simplicity of the system and relatively low-frequency dependence compared to other transduction mechanisms. As shown in Fig. 1(a), conventional impact-driven piezoelectric generators generally utilized spring-mass-damper system where a proof mass supported by spring directly impacts the piezoelectric material. This type of vibration energy harvester based on resonant system produces maximum power only within a relatively narrow frequency band near the resonance frequency of the spring-mass-damper system [22,40–44]. Impact based frequency up-converted mechanism has been presented, which utilized a freely movable springless proof mass under random excitation [26,45]. However, a constant collision between the proof mass and piezoelectric material could lead to a catastrophic failure of the device. Therefore, mechanical stability and long-term reliability of the device should be significantly emphasized in the design of a non-resonant system with very small damping to the springless proof mass [26]. As an alternative, piezoelectric energy harvesting device with magnetic plucking has been proposed to avoid physical contact between the piezoelectric material and proof mass [17,19,46]. Although contactless excitation method using magnetic coupling could be a practical approach in some of the applications, improvement of output power and reduction of fabrication complexity need to be considered.

In this paper, we present a vibration energy harvester based on the indirect impact of springless spherical proof mass to harvest energy from low-frequency vibrations such as human-body-induced motion while overcoming the issues of conventional devices using direct impact. To avoid the physical contact of the piezoelectric material and to improve reliability, the kinetic energy of the springless proof mass is conveyed to the piezoelectric cantilever via metal housing during impact. As shown in Fig. 1(b), the proposed design utilizes a metal housing with simple channel structure in which a spherical metal ball can move freely even at very low frequencies with large amplitude. In contrast to the conventional piezoelectric vibration generators where input acceleration has to be applied vertically to the piezoelectric cantilever, external vibration is applied in the length direction of piezoelectric MFC (Macro Fiber Composite) beam, which significantly reduces the device volume.

In addition to the improvement of long-term reliability by protecting the piezoelectric cantilever from making contact with any of the structural materials, proposed design can benefit from an increase of acceleration during the reciprocating motion of the proof mass inside the channel. The proof mass collides with the end wall of the channel at an acceleration higher than that of the external vibration of sinusoidal nature. Also, the fixed end of the MFC has been designed to efficiently deliver the vibration of the housing induced by much larger springless proof mass to the MFC cantilever, which maximizes the output power. Thorough investigation of the operating mechanism has been carried out by comparison between the experimental results and analytical model. A finite element analysis (FEA) has also been performed to confirm the resonance mode of the proposed device.

## 2. Harvester design and working principle

A 3D (3-dimensional) schematic diagram of the proposed vibration energy harvester is shown in Fig. 2. The harvester consists of a spherical proof mass in an aluminum housing and a piezoelectric cantilever beam fabricated by attaching metal blocks at the free end of an MFC beam. Previously, we have reported the feasibility testing results of an energy harvester using indirect impact, where we have analyzed the effect of both the springless proof mass inside the channel and the proof mass attached to the MFC cantilever in improving the output performance [47]. In the experiment, a device with copper blocks attached to an MFC cantilever and tungsten carbide ball as a springless proof mass provided the best results. By utilizing the MFC as a piezoelectric

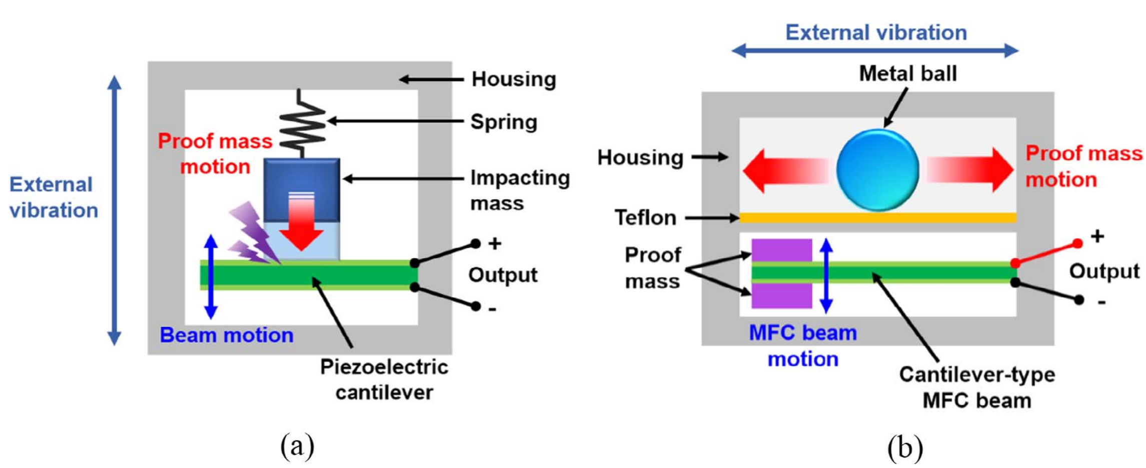


**Fig. 1.** Comparison of impact based piezoelectric power generators: (a) conventional piezoelectric vibration energy harvester structure, (b) proposed energy harvester based on indirect impact.