

Innovative Designs in Vibration Energy Harvesting: Performance Evaluation and Comparative Analysis

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Abstract. This paper explores the realm of vibration energy harvesting (VEH) and its potential applications in powering electronic devices. With the increasing demand for constant power supply in various sectors, including medical, transportation, and communication, the drawbacks of traditional battery solutions prompt the exploration of alternative energy sources. Vibration, omnipresent in our environment, presents itself as a promising source of mechanical energy that can be converted into electrical power. This study delves into three distinct VEH designs: a flute-inspired broadband piezoelectric device with mechanical intelligence, an electromagnetic harvester utilizing a magnet-array-based vibration-to-rotation conversion mechanism, and a piezoelectric harvester for ultra-low frequency waves with magnetic coupling driven by rotating balls. Through extensive analysis and experimentation, each design's performance, features, and potential applications are evaluated and compared. While each design offers unique advantages and limitations, understanding their characteristics facilitates identifying suitable scenarios for deployment, thereby advancing the development of self-powered devices.

Keywords: Vibration energy harvesting; piezoelectric materials; electromagnetic induction; self-powering sensors; ambient energy harvesting.

1. Introduction

As automation progresses across various domains, sensors play pivotal roles in numerous applications such as medical treatment, traffic management, and communication systems. However, a consistent power supply is often essential for sensors to function effectively. While batteries are commonly used for power supply, they come with several drawbacks including limited lifespan, environmental pollution, and high costs. Consequently, there is a growing interest in exploring alternative methods for energy collection from the ambient environment to serve as a sustainable power source. Vibration, an inherent phenomenon observed in all moving objects, carries mechanical energy that can potentially power electronic devices. Therefore, the development of vibration energy harvesters presents an attractive approach to achieving self-powering sensors, thereby expanding their applications and promoting environmental sustainability.

Various designs have been proposed to harvest vibration energy and convert it into electrical energy, categorized based on the underlying mechanics involved. Two prominent types of harvesting devices are those utilizing electromagnetic induction and piezoelectric effect. These designs have garnered attention due to their relatively high efficiency and extensive development history [1]. Electromagnetic vibration energy harvesters consist of permanent magnets and coils, forming electromagnetic generators that produce electric potential according to Faraday's Law of Induction. On the other hand, piezoelectric vibration energy harvesters employ piezoelectric materials that generate charges when compressed, enabling the conversion of mechanical energy into electrical energy [1].

Vibration energy harvesters exhibit diverse working environments and performance characteristics depending on their mechanisms and specific designs. This article analyzes, evaluates, and compares several designs, discussing the scenarios in which they may be employed. Additionally, suggestions for potential improvements based on these designs are presented.

2. Innovative Designs in Vibration Energy Harvesting

2.1. Flute-inspired Piezoelectric Vibration Harvester

2.1.1 Mechanism

In this design, vibration is applied to a piece of polyvinylidene fluoride piezoelectric film via a cantilever beam. A sliding mass block, which can be restricted, is attached to the beam, allowing for the adjustment of the system's natural frequency. This adjustability enables resonance with environmental vibrations across a wide frequency range, thereby maintaining high efficiency in energy collection [2].

The flute-inspired mechanical-intelligent energy harvester (MIEH) utilizes the specially designed sliding mass block to transition from a non-resonant state to a resonant state. This mechanical adjustment occurs through the resultant force exerted on the sliding mass by the system. The self-adjusting and self-locking mechanisms are illustrated in Fig. 1.

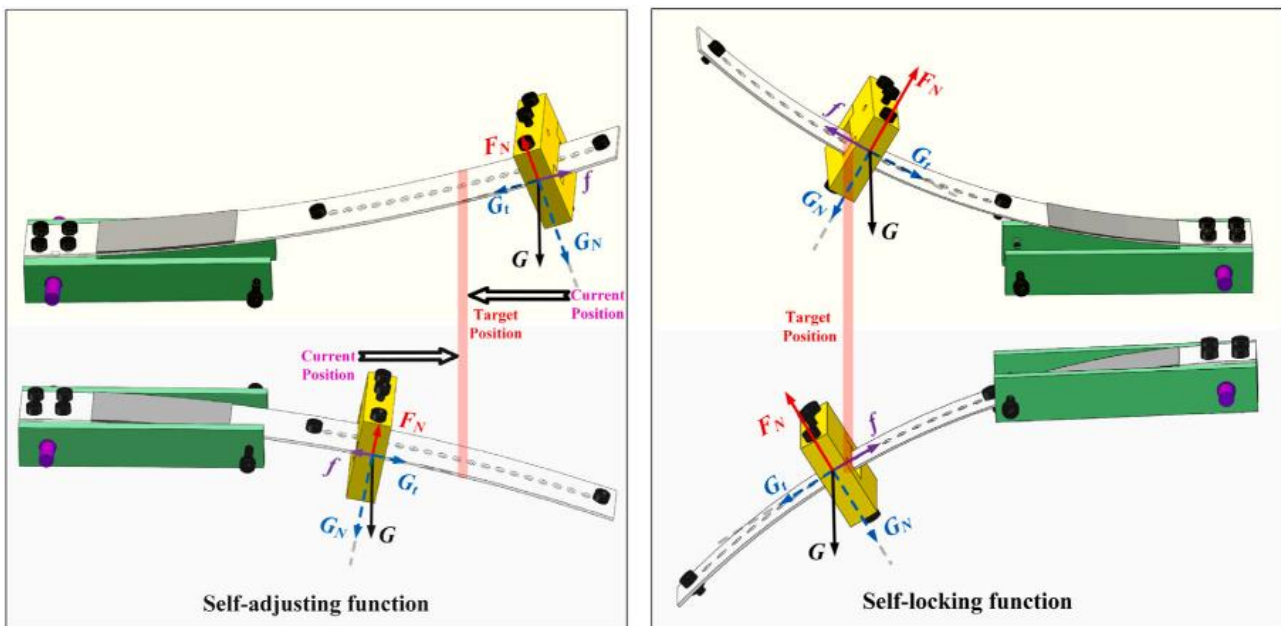


Fig. 1 Self-adjusting and self-locking mechanisms [2].

2.1.2 Performances and features

In lab experiments, fixed-frequency excitation tests, swept-frequency excitation tests, and stochastic excitation tests were conducted on the MIEH, alongside the conventional tunable beam-slider energy harvester without mechanical intelligent design (SEH) and its corresponding linear counterpart (LEH). The displacement–frequency responses, output voltage–frequency responses, and output power density–frequency responses were measured to illustrate the performance of each device.

In the fixed-frequency excitation test, all three devices were initially set to a non-resonant state. Excitations with fixed frequencies of 6, 7, 8, and 9 Hz, each with a 1 mm amplitude, were applied. The performance of the MIEH at each frequency significantly surpassed that of the SEH and LEH. Notably, the output power density of the MIEH at these frequencies (6, 7, 8, and 9 Hz) measured 14.4 mW/m², 22.9 mW/m², 33.0 mW/m², and 31.2 mW/m², respectively, which were substantially higher than those of the SEH (0.5 mW/m² for 6 Hz, 0.7 mW/m² for 7 Hz, 0.8 mW/m² for 8 Hz, and 0.8 mW/m² for 9 Hz) and the LEH (0.4 mW/m² for 6 Hz, 0.3 mW/m² for 7 Hz, 0.2 mW/m² for 8 Hz, and 0.2 mW/m² for 9 Hz) [2].

In the swept-frequency excitation test, a 1 mm amplitude swept excitation with frequencies ranging from 4 to 12 Hz was applied. The results showed that the MIEH vibrated at a large amplitude between 4.4 and 10.5 Hz, while large-amplitude vibrations were only observed in the SEH and LEH when the

excitation frequency ranged from 4.4 Hz to 5.4 Hz. Throughout the frequency sweep, the output power density of the MIEH was significantly higher than that of the SEH and LEH, peaking at 36.2 mW/m² [2].

In the stochastic excitation test, the LEH was excluded, and the acceleration of the vibrating excitation remained constant at 1.3 g, with frequencies varying between 4 Hz and 20 Hz. Similar to the previous tests, the MIEH outperformed the SEH throughout most of the stochastic excitation process, achieving maximum output power densities of 5.0 mW/m² and 2.7 mW/m², respectively [2].

The superiority of the MIEH over the SEH and LEH stems from its self-adjusting and self-locking abilities. With a variable and self-tuning natural frequency, the MIEH can approach a resonant state even in complex vibration environments. However, it is noteworthy that the maximum output power density of the MIEH during the stochastic excitation test was significantly lower compared to that of the swept-frequency test. This suggests that the self-tuning process of the device occurs gradually and may lag behind the alternating excitation frequency. Therefore, although the self-tuning ability is functional, a stable resonant state cannot be expected for the MIEH in normal environments where vibrations are likely to be chaotic.

2.1.3 Applications

Based on the features demonstrated by the MIEH during testing, potential applications can be proposed. Firstly, due to the requirement of a certain length for the cantilever beam in this device, there exists a lower bound on its scale. This implies that the design may not be suitable for powering electronic devices on portable or wearable devices but can be effectively installed on platforms such as vehicles.

The research team of this project has already tested their design on shared bicycles and electric bikes, utilizing the MIEH to charge a capacitor throughout the test. The experiment was conducted under three different road conditions: smooth stone slabs, crushed stones, and grass-planting bricks. Results indicate that the highest maximum voltage of the capacitor was reached on grass-planting bricks, while the lowest was observed on smooth stone slabs. Moreover, the capacitor voltage in bicycle riding scenarios exceeded that in electric bike riding scenarios under the same road conditions. This discrepancy in output characteristics can be attributed to the better shock absorption devices on electric bikes, which effectively reduce vibration. The results suggest that both road surface roughness and vehicle shock absorption have a significant impact on vehicle vibration, leading to notable differences in energy output for the MIEH.

The power-generating ability has been verified to meet the power requirements of certain commercial electronic devices. Since shock absorption devices can greatly reduce the output power of the MIEH, applications on unmanned vehicles, where vibration reduction is typically not a consideration, may be preferable.

2.2. Electromagnetic Vibration Harvester

2.2.1 Mechanism

In this design, linear motion is converted to rotary motion based on magnetic force [3]. The component responsible for converting vibration to rotation consists of a linear vibrating magnet (LMV) and a rotatable cylinder with a magnet array (CMA). The LMV is connected to the excitation source and coupling between it and the magnet array is created when vibrating, thereby exerting a time-varying torque on the cylinder, causing it to rotate. The rotation of the cylinder is then transmitted to a generator, which produces energy output. Fig. 2 shows the principle of the electromagnetic harvester.

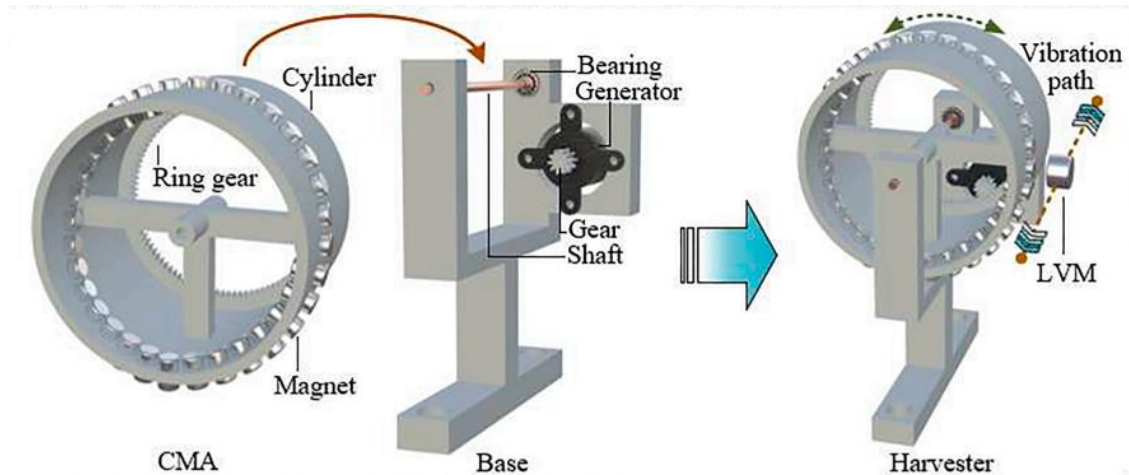


Fig. 2 Principle of the electromagnetic harvester [3].

2.2.2 Performances and features

To assess the performance of this design, experiments and simulations were conducted. In the first experiment, a sliding rheostat was connected to the harvester to find out the resistance of the external load that will maximize its power efficiency. Harmonic excitation was employed in this experiment. The results indicate that the root mean square (RMS) of the output power has a positive correlation with the excitation frequency, and a maximum output power of 106.5mW is reached under a 300- Ω external load and a 5-Hz excitation [3].

In the second experiment, hand-shaking vibration was used as the excitation exerted on the harvester when measuring its performance. Hand-shaking vibration represents random vibrations encountered in actual working environments. When conducting this test, one holds the LMV with its hand and shakes it back and forth, imitating periodic-like motions. An acceleration sensing module is attached to the hand holding the LMV to record and analyze the movement of the hand and characterize the excitation source. The results show that the RMS of the open-circuit voltage reached a maximum of 12 V throughout the process. The Fast Fourier Transform (FFT) spectrum demonstrates that the dominant frequency of hand-shaking vibration is about 2 Hz [3].

2.2.3 Applications

The researchers of this project suggested an application scenario for the harvester: the harvester will function as a damper on a train but will not replace the primary shock absorber. The LMVs will be fixed on the bogie, and the CMA will be installed on the wheel frame. When the train is traveling, the vibration of the bogie acts as an excitation exerted on the LMVs, which will ultimately turn into electric power output of the harvester. Since the harvester is merely a prototype, simulations are conducted instead of field experiments due to safety concerns. In simulations, a 300- Ω external load is used to measure the output power. The result of the simulation suggests that when installed on a train that travels at the speed of 80 km/h, this system can perform relatively well, producing an output power of 50 mW. In practice, by installing multiple harvesters one next to another, more energy can be obtained.

Since this harvester is designed to collect energy from linear motion, it may be preferred to apply it on piston structures, apart from the train scenario proposed by the researchers,

2.3. Piezoelectric Vibration Harvester with Magnetic Coupling

2.3.1 Mechanism

As shown in Fig. 3, this design of harvester uses the bending of piezoelectric cantilevers to generate electrical power, with a piece of magnet attached to each piezoelectric cantilever [4]. The component responsible for directly collecting vibration energy in this design is a circular frame with magnets attached to it and a metal ball restricted within it. The metal ball moves around a circular rail. When external excitation is applied, the metal ball rolls and pushes the circular frame to rotate.

The magnets moving with it will exert magnetic forces on the magnets on the piezoelectric cantilever, causing them to oscillate and produce output voltage.

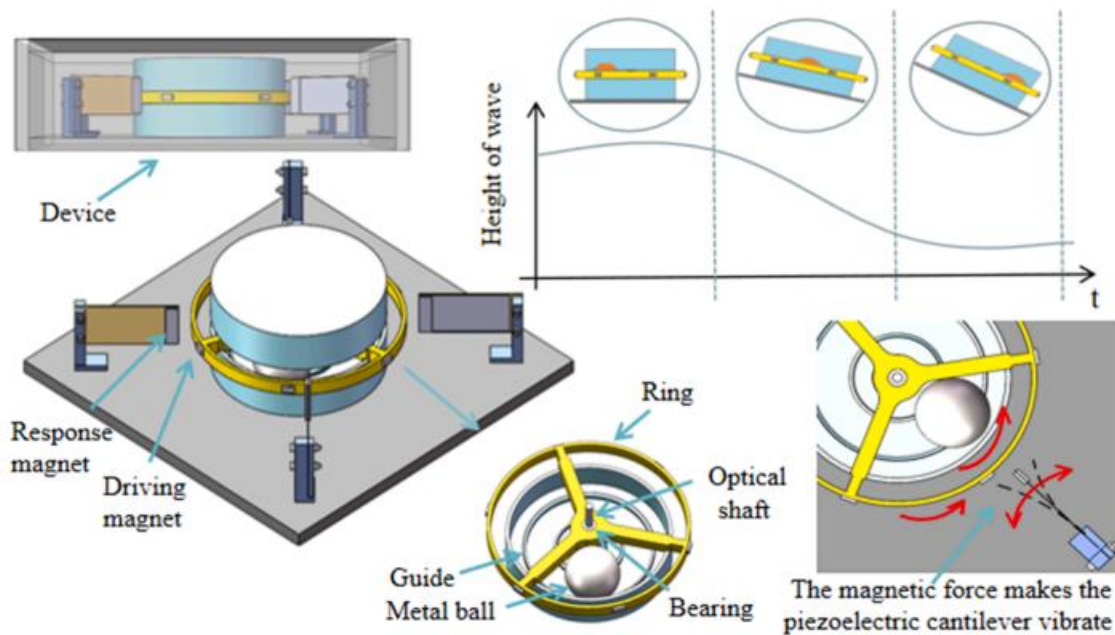


Fig. 3 Principle of the harvester [4].

2.3.2 Performances and features

The output characteristics of the piezoelectric energy harvester is determined by frequencies of excitation. To illustrate the relationship between them, researchers conducted analytical simulations. Excitation frequencies of 0.64 Hz, 1 Hz, 1.27 Hz, and 1.4 Hz were used in the simulations. The results demonstrate that the output voltage of the device exhibits multiple decaying waves, with the maximum output voltage declining rapidly as the excitation frequency increases [4].

2.3.3 Applications

The researchers proposed using this harvester to collect energy from wave vibration and power devices for collecting hydrological information. In field experiments, the harvester is installed in a floating ball that oscillates with waves in water. The output power of the energy harvester is tested by connecting different external resistance loads to the energy harvester. When the external excitation frequency is 0.9 Hz, and the external load is 47K Ω , the device can generate a power output of 6.32 mW, proving that the proposed energy harvester collects energy from ultra-low frequency vibrations at a higher efficiency [4].

The favorable performance of this harvester in low-frequency conditions restricts its application to limited scenarios. Apart from the scenario the researchers proposed, collecting vibration energy excited by wind power may also be a practical application for the harvester.

3. Comparison and Improvement

The different designs mentioned come with distinct characteristics. In general, the flute-inspired MIEH can adapt to random frequency conditions, the vibration-to-rotation conversion harvester performs better under low-frequency conditions (2~5 Hz), and the magnetic coupling VEH works under ultra-low-frequency conditions with multi-directional waves. Despite these differences, what is common among these designs is that they have large sizes, which is typically a drawback in applications. Another notable aspect is the structures of the harvesters. The flute-inspired MIEH has the simplest structure among all three designs of VEH, with a cantilever beam and a sliding mass acting as the only two movable parts. The structure of the vibration-to-rotation conversion harvester is the most complex with multiple rotatable components, and it relies on an electromagnetic generator

to ultimately produce electric power. The magnetic coupling VEH also contains movable components and structures, but it is still simpler than the vibration-to-rotation conversion harvester. Usually, simpler structures imply higher reliability under the same working conditions, so the flute-inspired MIEH has an advantage in stability and reliability, allowing it to be applied in adverse conditions.

Among the three harvesters, the vibration-to-rotation conversion harvester has the highest power output. Conversely, lower power output is found in the other two harvesters. This is due to the fact that piezoelectric materials cannot convert mechanical energy to electric energy as efficiently as an electromagnetic generator does [1, 5, 6]. Therefore, the upper limit of the power output of VEHs using the piezoelectric mechanism is bounded by the development of materials. However, piezoelectric materials are in the shape of thin film in VEHs using this mechanism, which reduces their size and weight compared to electromagnetic VEHs.

4. Conclusion

Vibration is widely found in the ambient environment, and collecting vibration energy holds significant promise. Numerous designs of VEH using varying mechanisms are proposed, each with its own set of characteristics. By analyzing and comparing the performances of these harvesters under various working conditions, potential applications emerge. Identifying the appropriate scenario for each VEH design can maximize their utility, marking a step forward in the quest for self-powered devices.

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