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A Review of Piezoelectric Energy Harvesting for Low Power Applications: From Infrastructure to Wearable Devices

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Abstract:

The increasing interest in sustainable energy has sparked a surge in research focused on piezoelectric energy harvesting as a renewable way to power low-energy devices. Piezoelectric materials have amazing ability to turn mechanical stress/vibrations into electricity, making them perfect for distributed systems where traditional power sources just won't cut it. This review brings together experimental findings from various fields, including tiles/stairs that harness energy from human footsteps, vehicle suspension systems, wearable tech, civil infrastructure monitoring, and water-flow energy harvesters. The main goal is to assess their performance, pinpoint effective methodologies, and find the most practical and cost-efficient solutions for real-world use. The methods differ based on design: tile and stair harvesters use arrays of PZT sensors to capture energy from people walking; vehicle systems convert suspension movement into energy using rack-pinion or ball-screw mechanisms; wearable devices incorporate PVDF films into shoes or fabrics to harness energy from walking; civil structures use piezo-beams with proof masses to monitor vibrations; and water-wheel harvesters utilize magnetically triggered systems to boost the conversion of fluid energy into electricity. The results of various papers show that individual piezo elements only produce a few milliwatts, but when combined in arrays and optimized for mechanical coupling, the output significantly increases. A comparative analysis of various review papers reveals that tile-based harvesters in busy areas, like campuses or streets, are the most viable option for powering streetlights or wireless sensors due to their ease of manufacturing, durability, and scalability. While vehicle and wearable harvesters show promise, they struggle with varying input conditions and long-term reliability. Civil and water-flow systems are useful for specific applications but are less flexible for urban settings. This review paper suggests by stating that piezoelectric harvesters are best suited for distributed low-power systems, particularly with infrastructure-integrated tile designs.

Keywords: Piezoelectric Energy Harvesting; PZT Sensors; PVDF Films; Energy Harvesting Tiles; Vehicle Suspension Systems; Wearable Devices; Low-Power Applications



1. Introduction

The environment depends on energy production, whether it comes from renewable sources like solar and wind or non-renewable ones like coal and petroleum. Toxic chemicals and hazardous gases are released by non-renewable sources. Wind tunnels and solar panels are examples of renewable energy sources that are limited for remote locations and require frequent maintenance. For remote locations, piezoelectric sensors or devices provide affordable, simple-to-install, low-power energy solutions.

Piezoelectric Sensor or Energy Harvester is a Device that is used to convert mechanical vibration (usually in form of force) into electrical energy. This Technology usually works on converting any form of ambient energy in atmosphere and in our daily life to useful electric energy that can power low energy consuming applications. This Generation of electric charge by PEH is based on direct effect of piezoelectric sensors [1]. According to [2] the power Generated by a single Piezoelectric sensor (PZT Disc) is 17.6 mW and the table published by [3] Show the amount of power consumed by low power applications which are shown in **Table 1**.

Table 1. Some Low Power Applications and their Power Consumption.

Device	Voltage	Power
Hear Pacemaker	2.5 V	33 μ W
GPS Tracker	3 V	Medium
ZigBee	3 V	60 mW
Timer Set	2.5 V	88 nW
Bluetooth Device	2-3.6 V	45 mW

Apple Watch	3.76 V	52 mW Average
Analog Watch	2.8 V	2.8 μ W

According To **Table 1**, Piezoelectric Sensors can easily Fulfil the energy requirement for low power applications and can run these applications without the need of battery replacement or complex design due to their simple structure.

Piezoelectric Sensors Generally works on two effects known as direct and indirect piezoelectric effect. The Direct Piezoelectric Effect states that when mechanical stress is applied to a sensor , energy is produced and the amount of energy production is directly proportional to the force being applied on the sensor [4].

This review Paper conclude all the major developments in PEH world including use of Piezoelectric Sensors in Shock Absorbers of Vehicles, Footwear and Wearable Harvester, Energy Tiles etc. This Paper Evaluates which approach is suitable for specific Application including its integration, maintenance, cost and its applications that include Street Lights, Wireless Sensors, Light Truck Digital Board, Temperature Sensors, Railway Health Monitoring etc.

2. Materials and Methods

Several approaches for energy harvesting using piezoelectric materials, including lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF), and their composites, are demonstrated in this review literature. The implementation of these materials into various mechanical or structural systems—

where flow, vibrations, or external forces are converted into electrical output—is the main goal of each study. The following is a grouping of the methodologies by application domain:

2.1. Infrastructure Based Piezoelectric Energy Harvesters (Tiles)

Materials Used: PZT Sensors (Disc) and Ceramic Tiles.

Method: In these systems, high-traffic areas like streets or building entrances are equipped with piezoelectric tiles. The embedded PZT sensors are subjected to stress due to the impact and cyclic loading caused by human footsteps. Bridge rectifiers are used to correct the produced alternating voltage, which is then stored in capacitors or batteries. The Energy produced successfully by this approach and is verified by voltage and current production [6]. The **Figure 2** shows the Installation of PZT Sensors on Ceramic Tiles.

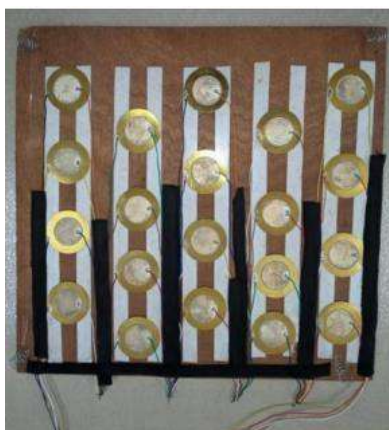


Fig.2. Bottom View of Tile with PZT sensors Installed.

2.2. Vehicle Shock Absorbers

Material Used: PZT Stacks.

Method: In this System, Specially Designed Shock Absorbers are used that convert mechanical induced vibrations from road into electrical energy. The Shock Absorbers used Ball Screw inside them which convert linear motion into Rotational motion which rotates the bevel gears And the Gear train that is designed. The Gear Train rotates the Rotor that is equipped with Multiple PZT Stacks that Vibrate due to rotation and this vibration produces energy which is stored in Supercapacitors to further used in Truck Applications which successfully light the Digital Board of Truck [7]. **Figure 2.1** shows the flowchart of this Shock Absorbers system.



Fig.2.1. Flowchart of Shock Absorber System.

2.3. Vehicle Suspension System

Material Used: PZT Bimorph Actuators.

Method: Road vibrations are transformed into electrical energy by the system using a gear and ratchet mechanism. The ratchet rotates the circular shaft with PZT sensors and internal pinion gears during shocks, producing vibration energy [8]. **Figure 2.2** demonstrates this mechanism in which the

fixed PZT Sensors on wall of Shaft are highlighted in blue color.

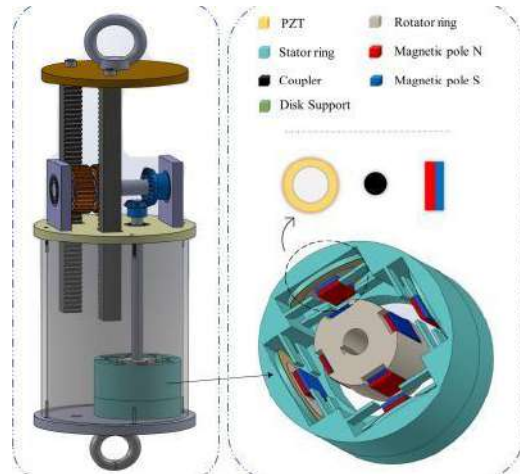


Fig.2.2. Schematic of Magnetically PEH.

2.4. Footwear (Gear and Ratchet Mechanism)

Material Used: PZT Beam.

Method: This System uses a special shoe equipped with Gear and ratchet mechanism in the Heel part of the shoe. When the ratchet is moved linearly due to the mechanical induced force by walking, it moves the gear which further on disrupt the Beam containing PZT Sensors and due to this vibration, energy is produced which is stored in a small battery attached along the Heel of Shoe [9]. **Figure 2.3** demonstrates the complete process of this gear and ratchet mechanism.

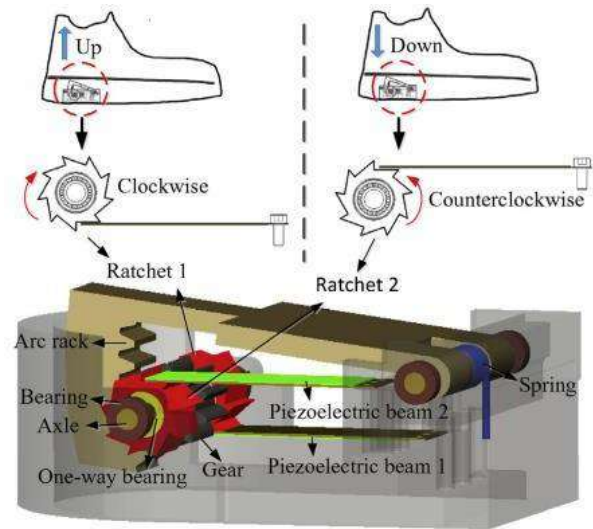


Fig.2.3. Complete Cycle of Energy Production in footwear.

2.5. Footwear (PZT and PVDF)

Material Used: PZT Sensor and PVDF film.

Method: Energy is Harvested from human motion in which the human force directly affect the Piezoelectric sensors i.e. multiple PZT Discs on the Heel Part of the shoe and PVDF films on the Insole part of shoe. Capacitors are used to store the rectified AC output. Subjects are put through walking simulations during testing, and power density and open-circuit voltage are used to gauge performance [10]. **Figure 2.4** demonstrates the installation of PZT and PVDF films on shoe for energy production.

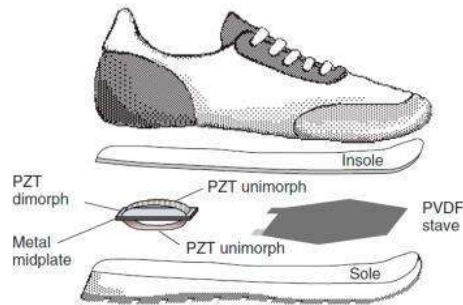


Fig.2.4. Piezoelectric sensors installed inside Shoes for Energy Production.

2.6. Wearable Harvester (Human Motion)

Material Used: PVDF Films.

Method: These Systems uses PVDF films that are installed on the arms and due to the induced vibration produced by the running or walking of human, energy is produced which can be further used for energy production or for health monitoring sensors [11].

2.7. Water-Flow-Based Piezoelectric Harvesters

Material Used: PZT bimorph cantilevers coupled with magnetic triggering.

Method: Water wheels with hydropower-inspired designs have magnets that cyclically excite piezoelectric cantilevers while they rotate due to the water energy. An alternating voltage is created when the wheel's mechanical torque causes the piezo strips to undergo repeated stress cycles. Various flow rates and resistive loading scenarios are used to test the output [12].

2.8. Civil and Railway Health Monitoring Systems

Material Used: PZT patches and PVDF strips mounted on beams and bridge decks.

Method: Surface-bonded piezoelectric patches are used to capture vibrational energy from bridges and railroads. To increase strain transfer to the PZT, a proof mass is frequently added. Rectifiers and storage capacitors make up circuits. Scaled models of railroad tracks and bridges or simulated train loads are used for testing. These systems serve as structural health monitoring tools in addition to energy harvesting [13][14]. **Figure 2.5** demonstrates the implementation of Piezoelectric sensors on railway tracks for health monitoring of railway tracks.



Fig.2.5. Green railways and PZT Stacks on Railway Tracks.



3. Results and Discussions

Different prototypes and mechanisms from the reviewed studies are compared in order to assess the potential of piezoelectric energy harvesting (PEH) techniques. Each method's

performance is examined in terms of power generation, cost, viability, and applicability to practical settings in Table 3.

Table 3. Comparative Analysis of All Systems using PEH.

Approach / Prototype	Power Output (Range)	Advantages	Limitations	Feasibility (Cost/Manufacture)	Best Application
Piezoelectric Tiles / Stairs	10–20 V per step; ~0.01–0.02 W (per sensor/tile under 60–75 kg load) [Ref: Energy Harvesting Tiles, Street Lighting Papers]	Direct use of human motion; simple integration into stairs/flooring; scalable	Limited energy per step; requires many sensors for higher load	Medium cost; tiles are easy to install in public areas	Powering LED street lights, emergency lights, low-power IoT devices
Vehicle Suspension (Rack & Pinion / Ball Screw Absorbers)	1–5 W per suspension cycle depending on road profile [Ref: Shock Absorber, Rack & Pinion Papers]	Large force input → higher power; uses wasted vibration/impact from roads	Complex fabrication; higher mechanical wear	Higher cost due to custom suspension design	Suitable for electric vehicles auxiliary systems, street lighting from road vibration
Water Wheel with Magnetic Excitation	~0.5–1 W under continuous water flow [Ref: Water Wheel Harvester]	Uses renewable water flow; continuous input source	Needs flowing water; bulky system	Medium fabrication cost; limited to specific sites	Remote sensing stations, bridges, off-grid lighting
Railway Track Monitoring Systems	~20–50 mW per passing train axle (enough for sensors & wireless units) [Ref: Railway Papers]	Harvests from high load impacts; integrates with structural monitoring	Only active when train passes; not continuous	Medium cost (piezo beams embedded in sleepers)	Railway health monitoring & IoT sensors
Footwear (Gear/Ratchet + PVDF/PZT)	1–10 mW per step; wearable harvesters [Ref: Footwear with Gear Ratchet, PVDF Shoes Papers]	Wearable, portable energy source	Very low output; cannot power high loads	Low cost, easy to prototype	Charging wearables, fitness trackers, BLE devices
Wearable Harvesters (Body Motion)	<5 mW average	Flexible PVDF; integrates with clothing	Very low output; irregular source	Low-medium cost; experimental stage	Self-powered sensors, medical devices



Tile-based Street lighting systems are clearly the most feasible when considering cost and viability. They can be installed in high-traffic areas like sidewalks or stairs, use commercially available PZT discs, and have

4. Conclusion

Technologies for piezoelectric energy harvesting have shown promise in a variety of applications, including civil infrastructure, automobile suspensions, and pedestrian walkways. Tile-based Street lighting systems stand out among the reviewed applications as the most practical for practical, affordable implementation, especially in urban areas with regular pedestrian traffic.

PZT-based harvesters inside stairs or floor

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