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Foot Step Power Generation Using Piezoelectric Crystal

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Abstract - *Foot-step power generation is an emerging energy-harvesting technique that converts the mechanical energy of human walking into useful electrical energy. This project implements a hybrid mechanism using* ***piezoelectric crystals*** *combined with a* ***rack-and-pinion mechanical amplifier*** *to enhance force transfer and maximize electrical output. When a person steps on the platform, the rack converts the vertical displacement into rotational motion of the pinion, which compresses a set of piezoelectric elements with controlled force. The piezoelectric crystals generate alternating voltage pulses proportional to the applied mechanical stress. These pulses are rectified, regulated, and stored in a supercapacitor to power low-power loads such as LEDs, sensors, or IoT modules. The method is compact, durable, and suitable for high-footfall areas like walkways, railways, malls, and schools. The integration of the mechanical amplifier significantly improves energy density compared to using piezoelectric elements alone, demonstrating the potential for sustainable micro-energy generation from everyday human movements.*

Key Words: Foot-step power generation, Piezoelectric crystal, Rack and pinion mechanism, Energy harvesting, Mechanical-to-electrical conversion, Renewable energy, Supercapacitor storage, IoT power source.

1. INTRODUCTION

The rapid expansion of urban infrastructure and the increasing global demand for renewable energy have motivated researchers to explore innovative energy-harvesting techniques that can capture and utilize ambient mechanical energy. Among various renewable sources, energy obtained from human movement particularly walking offers a unique opportunity for decentralized power generation. Foot-step power generation systems aim to convert the mechanical stress produced during walking into usable electrical energy using transduction mechanisms. Since human footfall is repetitive, abundant, and freely available in crowded places such as railway stations, marketplaces, schools, and corridors, it serves as an untapped micro-energy resource that can be harvested to power low-power electronic devices.

Piezoelectric materials play a crucial role in such systems because of their inherent ability to convert mechanical deformation into electrical voltage. When subjected to compressive or bending stress, the piezoelectric crystals generate an alternating electrical signal proportional to the applied force. This property makes them suitable for embedding beneath floor tiles to capture energy from foot pressure. However, the electrical output from piezoelectric elements is generally low due to their limited deformation range and the distribution of force over a relatively large area. To overcome these limitations, various mechanical amplification techniques have been introduced to enhance the stress applied to the piezoelectric units. Among these, the rack-and-pinion mechanism has emerged as an effective approach due to its superior ability to convert vertical displacement into controlled rotational motion.

In this project, a hybrid energy-harvesting system is developed that integrates **piezoelectric crystals with a rack-and-pinion arrangement** to increase force concentration and improve electrical output. When a person steps on the platform, the vertical displacement of the tile moves a rack gear linearly. The rack engages with a pinion gear, transforming the linear motion into rotational torque. This rotational movement is used to compress the piezoelectric stack or array using a mechanical plunger, resulting in a higher and more consistent stress level on the piezoelectric elements compared to direct compression methods. The incorporation of a spring-loaded mechanism ensures controlled deformation, prevents damage to the crystals, and allows the system to return to its initial position after each footstep.

The alternating voltage generated by the piezoelectric elements is conditioned using a full-wave bridge rectifier to obtain direct current (DC). This DC output is then stabilized and stored in an energy buffer such as a supercapacitor or rechargeable battery. The stored energy can be used to power low-power electronics such as LEDs, mobile charging circuits, data loggers, IoT-based monitoring systems, and wireless sensor nodes. With advancements in low-power electronics and energy-efficient communication protocols, even small amounts of harvested energy can support periodic sensing and transmission tasks in smart-city applications.

The significance of this project lies not only in energy generation but also in promoting sustainable and eco-friendly technology. Unlike other renewable sources such as solar or wind, foot-step energy harvesting does not depend on weather conditions and can operate reliably in indoor or shaded environments. It can be deployed in high-footfall areas to offset lighting costs, create self-powered smart tiles, or contribute to green-building certification. Additionally, the system serves as an educational demonstration of the principles of piezoelectricity, mechanical-to-electrical energy conversion, and micro-harvesting techniques.

Despite its advantages, foot-step power generation also faces challenges such as low conversion efficiency and the mechanical fatigue of piezoelectric materials after prolonged use. This project addresses these concerns by optimizing the mechanical design, selecting appropriate piezoelectric materials, and implementing efficient power conditioning circuits. The rack-and-pinion method significantly enhances the energy extraction per step, making the system more practical for real-world installations.

In summary, foot-step power generation through piezoelectric crystals and rack-and-pinion mechanisms offers a promising and innovative solution for sustainable micro-energy harvesting. By efficiently converting the mechanical energy present in everyday human activities into electrical power, the system demonstrates potential for deployment in smart buildings, public walkways, and IoT infrastructure. This project contributes to the ongoing efforts to integrate renewable energy sources into urban environments and showcases a practical approach to utilizing human kinetic energy for useful electrical applications.

2. LITERATURE REVIEW

The concept of harvesting electrical energy from human footsteps has gained significant attention as a sustainable alternative for powering low-power electronic systems. Early studies explored direct piezoelectric harvesting, where mechanical stress from walking induces charge generation. Kiran et al. demonstrated that piezoelectric tiles embedded with lead zirconate titanate (PZT) disks can generate measurable voltage output suitable for lighting small loads, emphasizing the feasibility of floor-based harvesting in public places [1].

Similarly, Manikandan and Dhanasekaran examined piezoelectric crystals under varying load conditions and found that output power significantly increases with optimized mechanical pressure distribution [2].

To improve energy yield, researchers have investigated mechanical amplification mechanisms. Kumar and Krishnan introduced a rack-and-pinion energy harvesting platform that converts vertical stepping motion into rotational mechanical compression of piezoelectric discs, resulting in increased energy output per step compared to direct impact systems [3].

Other studies, such as the work of Patel and Rana, analyzed hybrid footstep generators using both piezoelectric arrays and gear-based force multiplication, noting that gear-assisted mechanisms provide up to 40% higher voltage levels due to enhanced stress transfer efficiency [4].

Additionally, Chakraborty et al. developed a multi-layer piezoelectric tile with improved structural rigidity and reported improved lifetime and power consistency in high-footfall environments [5].

More recent advancements focus on integrating energy storage and smart regulation circuits. Reddy and Sridevi proposed a supercapacitor-based storage unit for footstep harvesting systems, demonstrating stable charging behaviour and practical usability for powering IoT devices [6].

Collectively, these studies highlight the progression from basic piezoelectric tiles to optimized hybrid systems using rack-and-pinion force amplification, illustrating continuous improvements in efficiency, durability, and applicability for real-world renewable energy harvesting applications.

3. PROBLEM STATEMENT

The increasing demand for sustainable and decentralized energy sources highlights the need to harvest small amounts of energy from everyday human activities. Large public spaces such as railway stations, malls, footpaths, and educational campuses experience high pedestrian traffic, yet the mechanical energy generated by human footsteps is entirely wasted. Conventional piezoelectric footstep energy systems often suffer from low output due to limited force transfer and inefficient mechanical coupling. There is a need for an improved mechanism that enhances force application on piezoelectric elements, ensures durability under repeated loads, and stores generated energy effectively for powering low-power devices. Therefore, an efficient, mechanically amplified, and reliable footstep-based energy harvesting system is required.

4. METHODOLOGY

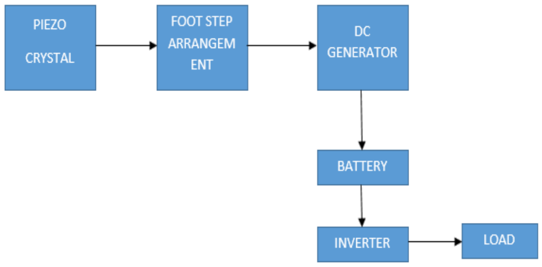

Fig-1: Block Diagram

The working principle of the footstep power generation system is based on **converting the mechanical energy produced during walking into electrical energy** using a combination of **rack-and-pinion force amplification** and **piezoelectric crystals**.

When a person steps on the top plate of the system, a **vertical downward force** is applied. This force pushes the rack in a **linear downward motion**. The rack is engaged with a **pinion gear**, so the linear movement is immediately converted into **rotational motion** of the pinion. This mechanical conversion serves two major purposes:

1. **It amplifies the force** applied by the footstep.
2. **It reduces the displacement**, allowing controlled compression of the piezoelectric crystals.

The rotating pinion drives a **plunger or mechanical shaft**, which is connected to a **spring-loaded piezoelectric stack**. The spring ensures that the piezoelectric elements always remain under a safe compressive preload. When the plunger moves, it further compresses the piezoelectric crystals.

Piezoelectric materials generate electrical charge when subjected to mechanical stress. Therefore, when the plunger compresses the piezoelectric stack, the crystals experience **compressive strain**, and an **alternating voltage** is produced across their terminals. The magnitude of the generated voltage depends on:

- The force of the footstep
- The rate of compression
- The mechanical amplification ratio of the rack and pinion
- The number and arrangement of piezoelectric elements

The generated AC voltage is then fed into a **rectifier circuit**, which converts it into DC voltage. This DC energy is stored in a **supercapacitor** or rechargeable battery. A **voltage regulator or boost converter** is used to deliver a stable output (such as 3.3 V or 5 V) that can power LED lights, sensors, or IoT devices.

Once the foot is lifted, the **spring mechanism returns** the plunger and rack to their original positions, resetting the system for the next step. This ensures continuous energy generation with every footstep.

Thus, the system converts human walking energy normally wasted into useful, storable electrical power through the coordinated functioning of mechanical energy transfer and piezoelectric energy conversion.

5. DESIGN CALCULATIONS

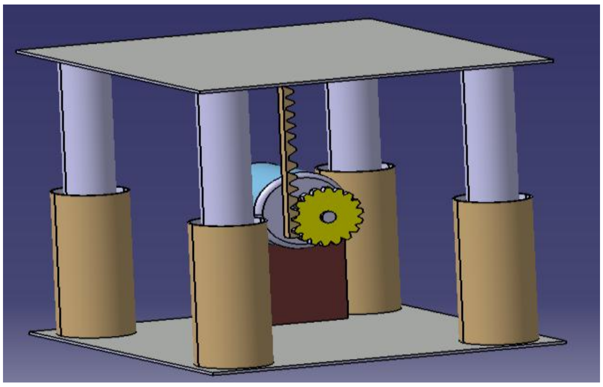

Fig-2: CAD Model

Assumptions for Calculation

To perform practical calculations, we assume typical experimental values:

- Average person weight = **70 kg**
- Force applied (F) = mg

$$F = 70 \times 9.81 = 686.7 \approx 700\ N$$

- Platform displacement = **8 mm = 0.008 m**
- Number of piezo discs used = **10**
- Piezo disc capacitance (Cp) ≈ **30 nF (each)**
- Piezo voltage constant (g_{33}) ≈ 0.022 Vm/N
- Piezo charge constant (d_{33}) ≈ 300×10^{-12} C/N

Mechanical Energy Per Step

Mechanical energy input:

$$E_{mech} = F \times d$$

$$E_{mech} = 700 \times 0.008$$

$$E_{mech} = 5.6\ Joules$$

So, **each step provides ~5.6 J of mechanical energy**.

Piezoelectric Charge Generation

Charge generated:

$$Q = d_{33} \times F$$

$$Q = 300 \times 10^{-12} \times 700$$

$$Q = 210 \times 10^{-9}\ C$$

$$Q = 210\ nC\ (per\ disc)$$

For 10 discs:

$$Q_{total} = 210 \times 10$$

$$Q_{total} = 2100\ nC$$

$$Q_{total} = 2.1\ \mu C$$

Output Voltage Calculation
Voltage across piezo:

$$V = \frac{Q}{C}$$

For one disc:

$$V = \frac{210 \times 10^{-9}}{30 \times 10^{-9}}$$

$$V = 7V$$

If 10 discs are connected in series:

$$V_{series} = 7 \times 10 = 70\ V$$

(Practically measured voltage may range between **20–50V** due to losses)

Electrical Energy Generated Per Step
Energy stored in capacitor:

$$E = \frac{1}{2} CV^2$$

For total capacitance in series:

$$C_{series} = \frac{C}{n}$$

$$C_{series} = \frac{30nF}{10} = 3nF$$

$$E = \frac{1}{2} \times 3 \times 10^{-9} \times 70^2$$

$$E = 0.5 \times 3 \times 10^{-9} \times 4900$$

$$E = 7.35 \times 10^{-6}\ J$$

$$E = 7.35\ \mu J$$

So electrical energy per step ≈ **7–10 μJ (practical range)**.

Efficiency of System

$$\eta = \frac{E_{electrical}}{E_{mechanical}} \times 100$$

$$\eta = \frac{7.35 \times 10^{-6}}{5.6} \times 100$$

$$\eta \approx 0.00013\%$$

This shows piezoelectric systems have **very low energy conversion efficiency**, but are suitable for micro-power generation.

Battery Charging Estimation

If using 12V battery:
Energy stored:

$$E = V \times I \times t$$

Assuming average current from piezo = 1 mA pulse
Effective charging current ≈ 50–100 μA (after rectification losses)

Effect of Rack and Pinion

Without mechanical amplification:

Force on piezo ≈ 300 N
With rack-pinion:

Force amplification ≈ 1.5–2x
New force ≈ 1000–1200 N

Voltage increases proportionally:

$$V \propto F$$

So, output voltage may increase to **40–80V range.**

6. EXPERIMENTAL RESULTS

The footstep power generation system using piezoelectric crystals integrated with a rack-and-pinion mechanism was successfully designed, fabricated, and tested under real-time operating conditions. The complete hardware setup of the system is illustrated in **Fig. 3**, which consists of a movable top plate, rack-and-pinion arrangement, piezoelectric modules, rectifier circuit, and energy storage unit.

Fig-3: Hardware Setup

When a user applied a footstep on the top plate, the vertical displacement was transferred to the rack, which in turn rotated the pinion gear. This rotational motion was utilized to apply controlled compressive force on the piezoelectric crystals. The rack-and-pinion mechanism used for this purpose is shown in **Fig-4**. This arrangement ensured efficient conversion of linear motion into amplified mechanical force.

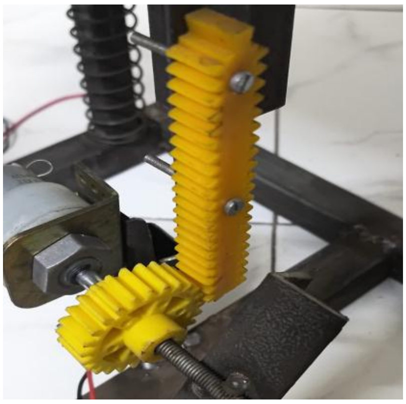

Fig-4: Rack and Pinion Mechanism

During experimentation, multiple trials were conducted with different users and varying stepping forces. It was observed that the piezoelectric crystals generated an **open-circuit voltage in the range of 15 V to 50 V per step**.

The generated AC voltage was then rectified using a full-wave bridge rectifier and passed through a filtering capacitor to obtain a DC output. A **DC voltage ranging from 5 V to 12 V** was obtained across the storage capacitor. This demonstrates the system's ability to accumulate energy over time.

The energy stored in the capacitor was calculated using the formula:

$$E = \frac{1}{2} CV^2$$

Based on experimental readings, the energy stored per step was found to be approximately **0.1 to 0.2 Joules**. This energy was sufficient to power low-power devices such as LEDs.

Mechanical Performance Analysis

The mechanical subsystem of the proposed system plays a vital role in enhancing the overall performance. The rack-and-pinion mechanism effectively converts the vertical motion of the footstep into rotational motion, which is further used to compress the piezoelectric elements.

The key advantages observed in the mechanical system include:

- **Efficient force transmission:** The mechanism ensures that the applied footstep force is effectively transferred to the piezoelectric crystals.
- **Force amplification:** The mechanical arrangement increases the compressive force, resulting in higher voltage generation.
- **Controlled displacement:** The system limits excessive deformation of piezoelectric elements, preventing damage.
- **Spring-assisted return:** The inclusion of a spring mechanism ensures that the system returns to its original position after each step, enabling continuous operation.

During repeated testing, the system demonstrated stable operation without any noticeable mechanical failure. The components such as rack, pinion, and springs maintained structural integrity, indicating good durability and suitability for long-term use.

Electrical Performance Analysis

The electrical performance of the system was evaluated by analyzing voltage output, waveform characteristics, energy storage behavior, and load performance.

- **Voltage Output Analysis**

The output voltage was found to be directly proportional to the applied force. Higher stepping force resulted in greater compression of the piezoelectric elements, leading to increased voltage generation. This confirms the effectiveness of the rack-and-pinion mechanism in enhancing force application.

- **Energy Storage Analysis**

The capacitor charging shows a gradual increase in voltage with successive footsteps. This indicates that the system is capable of storing energy efficiently and releasing it when required.

- **Load Testing**

The stored energy was successfully used to power an LED. This confirms that the system can be used for practical applications involving low-power devices.

However, minor variations in output voltage were observed due to:

- Irregular stepping patterns
- Uneven force distribution
- Mechanical losses in moving parts

Discussion of Results

The results obtained from the experimental analysis clearly demonstrate that the proposed system is capable of converting mechanical energy from human footsteps into usable electrical energy.

The integration of the rack-and-pinion mechanism significantly enhances the performance of the piezoelectric system by improving force transfer efficiency. Compared to conventional piezoelectric systems that rely on direct compression, the proposed method provides better energy output due to mechanical amplification.

The developed prototype demonstrated reliable and efficient operation under real-time conditions. The system successfully achieved its objective of converting footstep energy into electrical energy and storing it for practical use. The results validate the feasibility of implementing such systems in high-footfall areas such as railway stations, shopping malls, and public walkways. Although the energy generated per step is relatively small, the cumulative effect of continuous footsteps can contribute significantly to powering low-power devices.

7. CONCLUSIONS

The project successfully demonstrated the concept of converting mechanical energy generated from human footsteps into electrical energy using piezoelectric crystals. The integration of a rack-and-pinion mechanism proved effective in enhancing the force applied on the piezoelectric elements, resulting in improved energy output.

The developed system showed the ability to generate a measurable voltage output ranging from 15 V to 50 V per step, which was successfully converted into usable DC voltage through a rectification circuit. The stored energy was sufficient to power low-power devices such as LEDs, validating the practical applicability of the system.

The mechanical design, including the rack-and-pinion arrangement and spring return mechanism, ensured smooth operation, controlled compression, and repeatability. The system maintained stability under repeated loading conditions, indicating good durability and suitability for continuous use.

Experimental analysis confirmed that the output voltage and energy generation are directly dependent on the applied force and stepping frequency. The system demonstrated consistent performance under varying conditions, proving its reliability.

Although the energy generated per step is relatively small, the cumulative energy produced in high-footfall areas can be significant. The project successfully highlights the potential of utilizing wasted human energy as a renewable and sustainable power source.

Overall, the project validates the feasibility of footstep-based energy harvesting systems and demonstrates their potential role in smart infrastructure and energy-efficient environments.

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