Piezoelectric Energy Harvesting in Interactive Environments: A Case Study Using a Playpen-Based Prototype

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ABSTRACT

As modern cities evolve towards sustainable and efficient infrastructure, implementation of micro-energy harnessing technologies caught the attention of researchers. This is mostly because non-renewable energy sources are being depleted, and the consequences of them are also marginal to the world. Piezoelectric materials are known for their conversion ability of mechanical stress, such as motion, vibrations, pressure, to electrical energy. This study provides a piezoelectric mechanism-based prototype that demonstrates the suitability of converting mechanical energy to electricity, especially footsteps from people, while being low maintenance and cleaner. In this design, 70 PZT piezoelectric disks are implemented beneath a playpen floor, suspended by a spring mechanism and further suspension components.

Output voltages of 9.2V to 11.4V could be observed from this demonstration, with the help of 2-5kg loads applied. 76 LEDs were used to visualize this power in real-time, which also offers interactive feedback for children. The output analysis shows a low-current and somewhat non-linear power output.

These results validate the possible outcome of deploying a piezoelectric system in high footfall infrastructure and recreational spaces. Even though it is low powered, such systems can enhance built environment functionality, and further improvements in the design can increase the output of such designs. This project represents a small-scale demonstration of this unpopular yet effective technology.

KEYWORDS: *Footstep Energy, Interactive Environments, Kinetic-To-Electrical Conversion, Low-Power Applications, Piezoelectric Energy Harnessing, PZT (Lead Zirconate Titanate), Smart Cities, Sustainable Infrastructure*

INTRODUCTION

The desire for renewable and sustainable energy sources has grown substantially in the 21st century, especially for smart cities. Due to the astonishing speeds of non-renewable energy, such as fossil fuel supplies are being depleted, the energy security in the world is considered in danger. According to the current forecasts, current fossil fuel reserves may significantly run out in the years ahead, if the current rates of consumption continue. Some estimate that Coal may run out in 139 years, Oil in 54 years and Petroleum gas in 49 years, from a 2020 study (METGroup Countries, 2021). This shows the importance of eco-friendly and alternative energy sources in the upcoming future. (Nations, n.d.) (Sorrell, Speirs, Bently, Brandt & Miller, 2010)

Energy extraction from non-renewable energy sources is relatively straightforward, but the negative effects and the inefficiency outweigh the advantages (United Nations, 2015). Therefore, it is crucial for engineers to find, study, develop and implement renewable and sustainable technologies. Even though rarely discussed, piezoelectric energy harnessing stands out among the recent technologies, as a possible solution to generate clean energy (Ghazanfarian, Mohammadi & Uchino, 2021). Piezoelectric materials are known for converting mechanical stress, such as vibrations, pressure, motion, into electrical energy (Rajapaksha, Senevirathne & Fernando, 2025) (Robeldo, 2023). This property is used in piezoelectric technology. The energy harnessed is ideal for low-power applications, such as sensors, LEDs, small electronic devices etc.

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Continuous research and development would help to improve the efficiency of this technology by a considerable margin. The goal of this study is to investigate the usefulness of piezoelectric energy harnessing. Frequent movement can be converted to electrical energy, by integrating this technology into dynamic spaces, such as playgrounds, walkways, roads etc. The aim is to evaluate the effectiveness and the potential of applying this technology to help the wider search for renewable and sustainable energy. (Rajapaksha et al, 2025) Our project utilizes a small-scale implementation example to demonstrate this idea.

The diagram below represents how mechanical stress applied on a piezoelectric material converts to electrical energy, and the losses involved with it (Ghazanfarian et al, 2021).

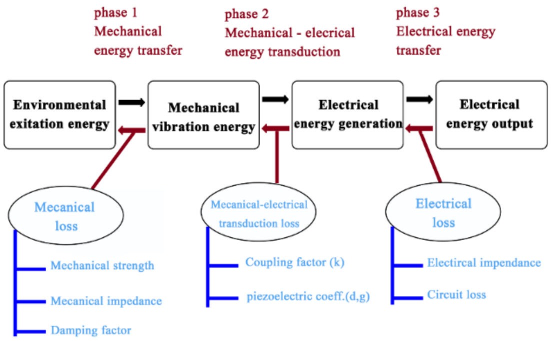

Figure 16 - Three major phases associated with piezoelectric energy harvesting. Retrieved from https://www.mdpi.com/2076-0825/10/12/312

In this demonstration, mechanical energy from footsteps is converted to electricity, with the use of piezoelectric disks beneath a rigid floor construction. When pressure is applied onto the disk, the crystal lattice of the piezoelectric material distorts, which creates an electrical imbalance, thus generating an alternating current between the two terminals.

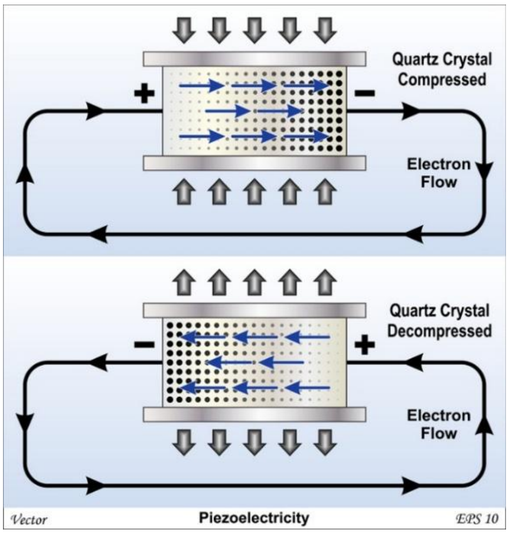

Figure 17 - How piezoelectricity works. Retrieved from www.autodesk.com/products/fusion-360/blog/piezoelectricity/

This current generated can be directly used to power small loads. Here, small LEDs are used as the load, which are then implemented to a play pen (Figure 3). The idea is to create an interactive and attractive environment for children, which also represents a small-scale and practical example of energy generation of this technology with human motion.

Figure 18 – Completed piezoelectric energy harvesting playpen prototype

MATERIALS AND METHODOLOGY

Materials

The main energy harnessing elements were 70 piezoelectric disks, which is constructed from PZT – Lead Zirconate Titanate (Rajapaksha et al, 2025) (Ghazanfarian et al, 2021) (Anton & Safaei, 2022) material, 3.5cm diameter. A metal washer served as a spacer under each disk, to allow some flexibility, and minimize the possibility of cracking under load. As the visual indicators of the generated current, 76 LEDs and 76 resistors (1kΩ) were used. The resistors act as current limiters, to avoid damaging the LEDs.

These piezoelectric disks were installed onto a 0.60m x 0.55m aluminium composite board, which served as the base structure. To spread the force applied evenly, a 0.53m x 0.50m plywood board was used, which acts as the upper flooring layer. PVC tubing, and 90-degree connectors were used, for the construction of the playpen frame, and these frames were covered by a net.

To provide suspension, to cushion the impact from the force applied and secure the floor and frame to the base, springs, hot glue stick pieces, cut to 1cm length and mounting hardware were used. Wiring was used according to the needs for the connection of the circuit. Additionally, for assembly and testing, soldering equipment and basic testing tools, such as a multimeter and an oscilloscope, were used respectively.

METHODOLOGY

The construction of the playpen was divided into three main stages: building the circuit, assembling the mechanical frame, and testing the system. One terminal of the 70 piezoelectric disks were joined into parallel groups and placed on the washers in the first stage. The positive terminal of every LED was soldered with the 1kΩ ohm and connected to the appropriate piezoelectric disk, while the negative terminals of the LEDs and the paralleled piezoelectric terminals are connected to a common ground. This arrangement allows the LEDs to be directly powered by the voltage generated from each footstep. Also, avoiding rectification allows the circuit to be further optimized for this setup, as LEDs do not suffer much from weak alternating current.

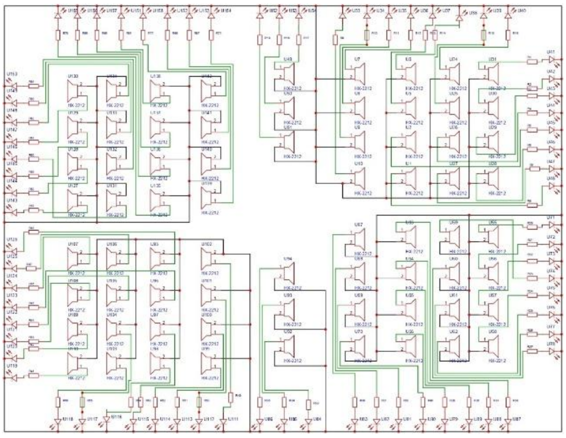

Figure 19 - Connections of piezoelectric disk to LEDs

The plywood board was placed over the disks, which were mounted on the aluminium composite base. The glue stick pieces, 1cm length, were positioned between the disks and the flooring. Springs were inserted between the layers, which serve as the suspension mechanism, further reducing the risk of damage (Figure 5) (Figure 6).

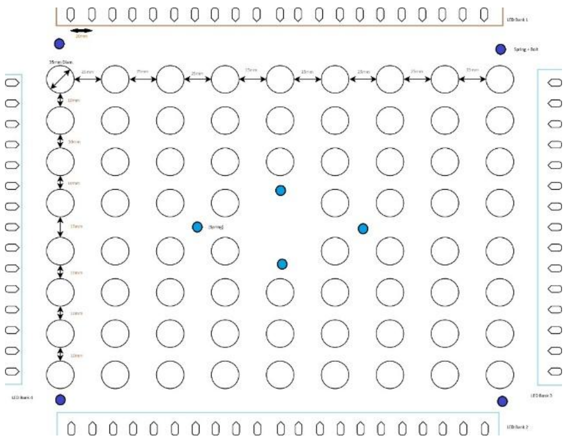

Figure 20 - Piezoelectric disk mounting layout on the composite board

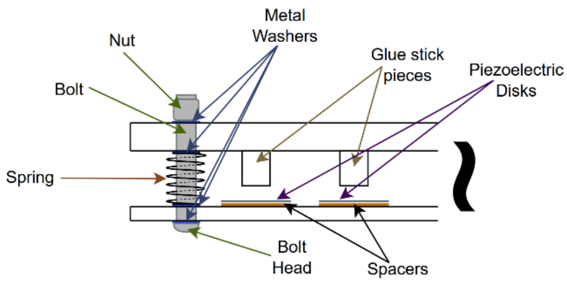

Figure 21 - Diagram of piezoelectric disk mounting (Side view)

PVC tubing was used to build the frame, which was mounted to the base with bolts and 90-degree PVC connectors (Figure 7).

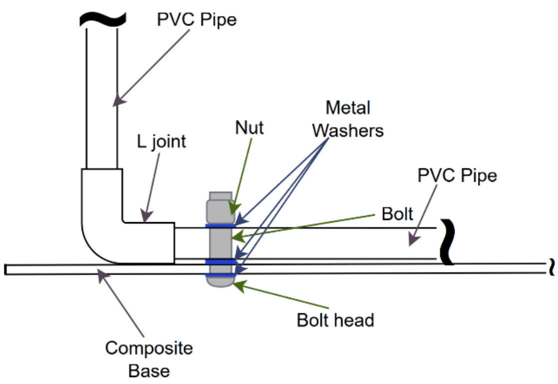

Figure 22 - Playpen frame diagram (Side view)

To simulate footstep pressure, flat objects weighing from 2kg to 5kg were implemented in the final stage. This is done by dropping the objects onto the plywood floor, from a height of ~0.15m. To analyze the output of the project, LED response and oscilloscope output were recorded. The results show reliable voltage generation and visual feedback from the interactive system. The complete project can be explained by the flow chart below (Figure 8).

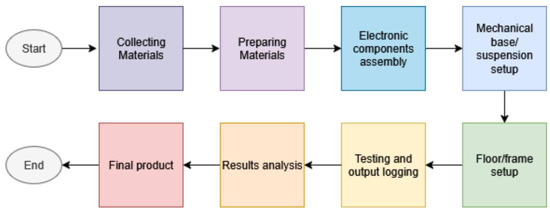

Figure 23 – Flowchart showing the step-by-step methodology followed in constructing and testing the piezoelectric playpen prototype

RESULTS AND DISCUSSION

Sample Collection

After assembling, the project was tested by simulating footsteps, by applying varying loads. Several piezoelectric disks were activated by physically applying load across various sections of the floor, weighing from 2kg to 5kg. Using a digital oscilloscope, the output voltages were recorded, and the LED behavior was recorded simultaneously.

Sample Analysis

Even with relatively smaller loads (~2kg), individual piezoelectric disks presented 9.2V peak-to-peak output on average (Figure 9).

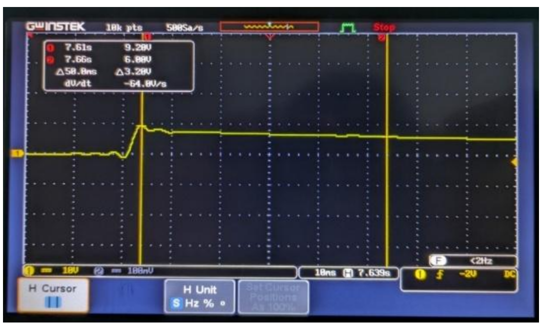

Figure 24 – Voltage spikes generated by piezoelectric discs during simulated footstep testing (oscilloscope output) - 2kg

This shows the mechanical coupling efficiency of this project prototype. High voltage spikes from the piezoelectric disks were verified by the oscilloscope graph, which suggested an effective electrical output from the PZT disks. Though the mechanical dampening caused output gain to become less noticeable with higher loads, the voltage output remained somewhat consistent. Even though the output voltage was considerably large, the current remained low, which proves that powering low-power devices are possible with this mechanism.

RESULTS

Figure below represents the collected output data (Figure 10):

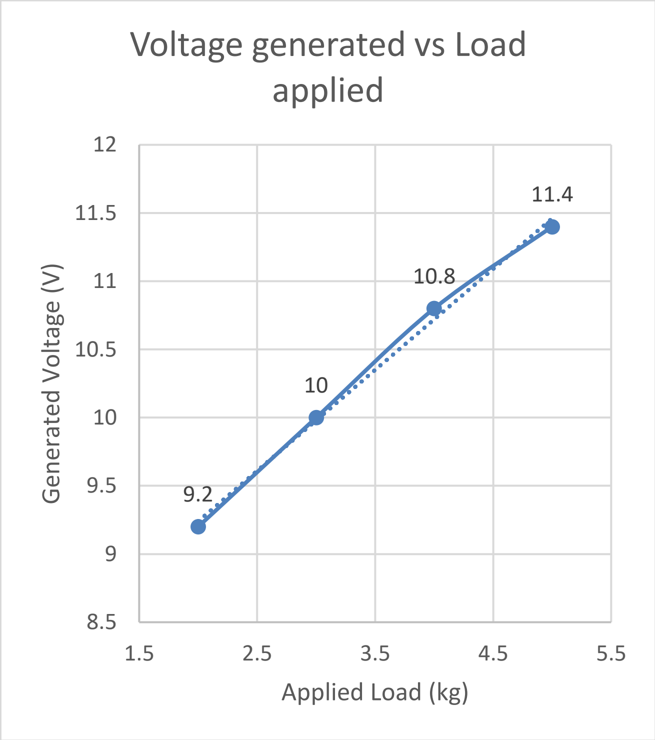

Figure 25 – Graph for Voltage Generated vs Load Applied

Below is an example of LED illumination under a simulated load (Figure 11):

Figure 26 – LED illumination under (simulated) applied footstep load

DISCUSSION

The experimental test findings verify that the piezoelectric energy harnessing mechanism operated with great efficiency, even under light loads. Notably, with 2-3kg load, the peak-to-peak output was ~10V.

The voltage spike pattern occurred during the compression and release of the piezoelectric disks is clearly visible in the oscilloscope output (Figure 9). From these voltage spikes, LEDs can be powered in real time, which also shows the outcome of the energy harvesting of this prototype. Due to energy distribution across multiple contact points and mechanical saturation, the results showed minimal gains, even when higher loads were applied. Even then, the visible light intensity gradually increased with the increase of the load applied.

These results show that this design can provide useful electrical energy, with little mechanical interactions, such as a child's footsteps. This shows the potential for piezoelectric energy harnessing in crowded or low-impact environments, even though this system is limited to low-power applications since piezoelectric elements have inherently low current output.

In future, we hope to improve the mechanical design, such as suspension, coupling, and mounting, to accommodate more load efficiently, while providing exceptional dampening and minimal saturation to the piezoelectric disks. Also, implementing efficient rectification circuits and storage will help this technology to be used in a wide range of applications, such as energy supply for autonomous devices and public lighting. Further long-term testing and improvements will also help this technology to be used in day-to-day life, such as dancing floors, clothing, footwear, road infrastructure etc.

CONCLUSION

This study successfully demonstrates the feasibility of harnessing low-intensity mechanical motion, by piezoelectric mechanisms, and demonstrated using a playpen setup. The LED illumination gave real-time feedback, which effectively visualizes the energy conversion process for demonstrative and educational purposes. The results indicated a considerably reliable mechanical coupling between the floor and the piezoelectric disks and good efficiency under small loads. While the power output is enough only for low-power devices, due to the limited current generated by the PZT elements, the prototype promotes the potential for applying piezoelectric harnessing technology into interactive or public environments, specifically in areas with frequent human movement.

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