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Piezoelectric Output Analysis

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ABSTRACT

This study explores the utilization of mechanical energy generated from human footsteps as an alternative energy source through energy harvesting technology using piezoelectric materials. The designed system takes the form of a ceramic tile floor composed of four tiles arranged longitudinally, with each tile containing 30 piezoelectric elements, each 35 mm in diameter. The configuration consists of six piezoelectric units connected in series and five rows arranged in parallel, resulting in a total of 120 piezoelectric units in the entire system. The voltage, current, and power output depend on variations in body weight (60–94 kg), foot size, and the anatomical shape of the user's foot, which affect how many piezoelectric elements receive sufficient pressure during each step. The generated electrical energy is stored in a 12 Volt, 12 Ah battery for subsequent power use. Experimental results show that the system can produce varying amounts of energy depending on user physical parameters, indicating its potential for small-scale implementation in renewable energy applications within urban environments.

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1. INTRODUCTION

The rising population rate results in heightened electricity demands to satisfy everyday necessities. The rapid population growth has created a significant challenge with the depletion of natural resources in many countries worldwide[1]. The urgent demand for green energy arises from increasing global energy needs and climate change challenges. To protect our planet and foster human development, it is crucial to generate and utilize green energy[2]. With the increasing severity of global warming and the shortage of fossil fuels, the search for sustainable and green renewable energies has become a common theme advocated by countries all over the world. In the process of exploring new energy resources, there is a vast amount of untapped clean energy within the road or pavement areas, including mechanical energy, thermal energy, solar energy, and wind energy[3]. In recent years, piezoelectric materials have become a central focus of scientific research due to their potential for efficient, sustainable, and versatile energy harvesting. These materials are capable of sensing surrounding energy from the environment (such as vibration, human motion, wind, and ocean wave movement) and converting it into usable electrical energy. This electrical energy can then power devices without the need for an external power source [4]. These materials exhibit an interesting property known as the piezoelectric effect. When mechanical stress or strain is applied to these materials, electric charges flow through them, thus converting mechanical energy into electrical energy[5]. Piezoelectric materials can generate the electric charges due to the distortion of the internal dipoles when external mechanical strain is applied on them, achieving the conversion of mechanical energy into electrical energy[6].

Several prior studies have explored different approaches to improve the performance of piezoelectric energy harvesting systems. In [7], Zhang et al. proposed an electromechanical model of an L-shaped energy harvester combining bending and torsional modes. The study analyzed the structural dynamics and the influence of geometric configuration and loading conditions on energy harvesting efficiency. Lee et al. in [8]introduced a tire-based energy harvesting system using piezoelectric polymer films blended with carbon nanotubes. The system converts mechanical deformation of the tire into electrical energy. The incorporation of nanomaterials was shown to significantly enhance both sensitivity and output voltage. Moreover, Ryu et al. conducted a comprehensive review in[9] on the development of piezoelectric nanogenerators for mechanical energy harvesting. They emphasized the role of advanced materials and fabrication methods in increasing device efficiency and adaptability for portable and self-powered electronic applications.

In general, PZT has proven capable of generating substantial voltage and power, whether in medical applications, urban infrastructure, or aeroelastic energy conversion. The power output can range from the micro to milliwatt scale, depending on the configuration and operational conditions. However, challenges such as material brittleness, rigidity, and environmental concerns due to its lead content remain key issues. Therefore, despite its superior performance in energy efficiency, PZT must be complemented with energy management technologies and system designs that prioritize long-term sustainability [10], [11], [12].

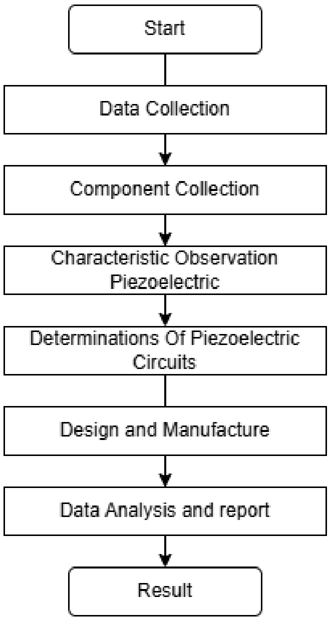

Fig. 1. Block diagram research

2. METHODS

This research was conducted based on the flow shown in the Flowchart Fig. 1. The process begins with collecting data through a reference search to design a piezoelectric system as an energy source that utilizes the pressure of human footsteps. After that, data collection was carried out on all components needed in the manufacture of the tool. The next step was to observe the piezoelectric characteristics to determine the optimal pressure between the piezoelectric element and the foam. Then, the circuit selection was carried out through a series of trials to determine the most suitable circuit design to be applied to the floor media. After the design was determined, the process continued with the assembly of the device. The final stage of this research is to analyze the power generated from the test to be compiled in the form of a report.

2.1. Block Diagram of The System

This piezoelectric-based energy harvesting system is designed to utilize the mechanical energy generated by human footsteps. The energy is then converted into electrical energy that can be stored and used for various purposes. To understand the overall workflow of the system, a block diagram is used that illustrates the relationship between the main components in the system. Fig. 2 below shows the block diagram of the piezoelectric energy harvesting system:

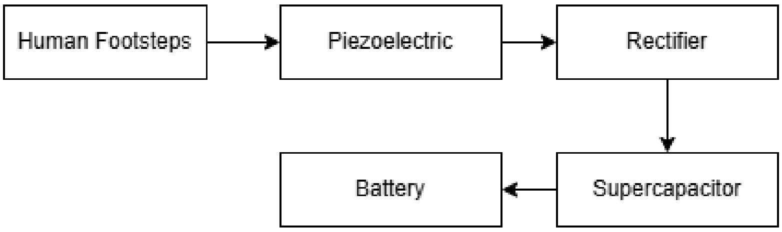

Fig. 2. Block diagram system

Fig. 2 shows the block diagram of a piezoelectric-based energy harvesting system that utilizes the pressure from human footsteps. The system is designed to convert mechanical energy into electrical energy that can be stored and reused. The process starts from human footsteps that generate mechanical pressure. This pressure is received by the piezoelectric sensor, which then converts it into electrical energy. Since the output of the piezoelectric sensor is in the form of alternating current (AC), a rectifier circuit is required to convert it into DC voltage. The resulting DC voltage is then channeled into two types of storage, namely batteries and supercapacitors. Batteries serve as a long-term energy storage medium, while supercapacitors are used to store and release energy quickly and efficiently.

2.2. Design of An Energy Harvesting Prototype

2.2.1 Piezoelektrik

Fig. 3 shows a basic structure of a piezoelectric element made from lead zirconate titanate (PZT). The central white component represents the PZT ceramic, which is responsible for generating electrical charges when subjected to mechanical stress.

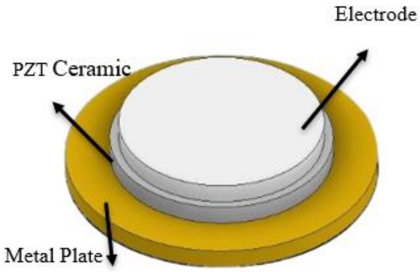

Fig. 3. Piezoelectric

This ceramic is sandwiched between two conductive layers: a metal plate at the bottom and an electrode at the top. The electrode allows for the collection and transfer of the generated electric charge, while the metal plate often serves both as a mechanical support and electrical ground. This configuration is commonly used in applications such as sensors, actuators, and energy harvesting devices, where the deformation of the PZT layer under external forces produces a measurable voltage output. The efficient transmission of mechanical energy into electrical energy is highly dependent on the alignment of these components and the integrity of their interfaces.

Lead zirconate titanate (PZT) is a ceramic piezoelectric material known for its ability to convert mechanical energy into electrical energy and vice versa, based on the piezoelectric effect. This effect occurs when the material generates an electric charge in response to applied mechanical stress (direct piezoelectric effect) or undergoes mechanical deformation when subjected to an electric field (converse piezoelectric effect) [13]–[15]. Chemically represented as $Pb(Zr_xTi_{1-x})O_3$, PZT possesses a non-centrosymmetric crystalline structure that enables ionic displacement under stress, resulting in internal polarization [13]. Due to its high piezoelectric coefficients, good thermal stability, and ability to retain polarization through poling, PZT is widely utilized in various applications [14]. These include transducers, sensors, actuators, and mechanical energy harvesting systems, ranging from microelectromechanical devices to larger-scale implementations [15].

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2.2.2 Piezoelectric circuit in series

A piezoelectric circuit arranged in series involves connecting the first piezoelectric element with the next piezoelectric element according to their respective poles. In a series arrangement, the positive pole of the piezoelectric is connected to the negative pole of the piezoelectric, so that each connection between piezoelectrics requires only one cable. In Fig. 4, the series circuit can be explained by the principle that the total amount of power entering a branch point will be equal to the amount of power leaving each branch point.

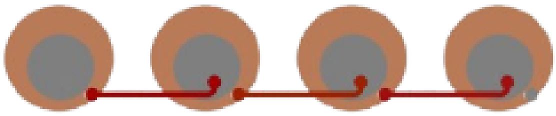

Fig. 4. Piezoelectric circuit in series

2.2.3 Piezoelectric circuit in parallel

A piezoelectric circuit arranged in parallel involves connecting the first piezoelectric element to the next one according to the respective poles, as shown in Fig. 5. This means connecting the positive pole of the first piezoelectric element to the positive pole of the next element, and likewise, connecting the negative pole of the first piezoelectric element to the negative pole of the next. As a result, each connection between piezoelectric elements requires two wires. When piezoelectrics are arranged in parallel, the current increases because the total current is summed.

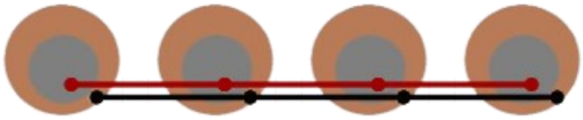

Fig. 5. Piezoelectric circuit in parallel

2.2.4 Piezoelectric Circuit In Series Parallel

A series-parallel circuit is a configuration designed to increase both the current and voltage flowing through a piezoelectric circuit, as shown in Fig. 6. As a result, when a piezoelectric element experiences pressure, it leads to an increase in both the voltage and current flowing through the circuit.

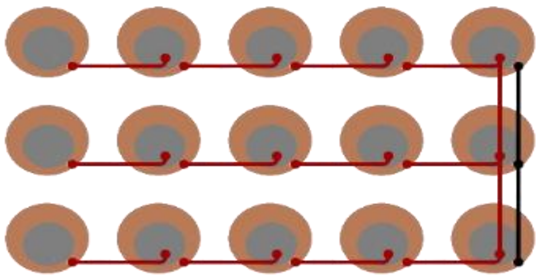

Fig. 6. Piezoelectric circuit in series parallel

2.2.5 Rectifier Circuits

The piezoelectric voltage rectifier circuit uses a bridge rectifier configuration consisting of four diodes, namely D1, D2, D3, and D4, each type 1N4007, as can be seen in Fig. 7. This circuit serves to convert the AC voltage generated by piezoelectric elements due to mechanical pressure or vibration into a DC voltage that can be used to charge batteries or operate electronic devices. AC voltage from piezoelectric is alternating, so it needs to be rectified in order to be utilized effectively. In the bridge rectifier configuration, during the positive cycle, current flows through D1 and D4, while during the negative cycle, current flows through D2 and D3. This allows for a consistent direct current (DC) at the output of the circuit. To flatten the rectified voltage, a 1.6 Farad capacitor C1 is used as a filter to reduce voltage ripple. The leveled DC voltage is then used to charge the B1 battery with a nominal voltage of 12 volts. This circuit is very effective for energy harvesting applications, especially from mechanical sources such as vibration or repetitive stress, as it is able to efficiently channel energy to the storage system.

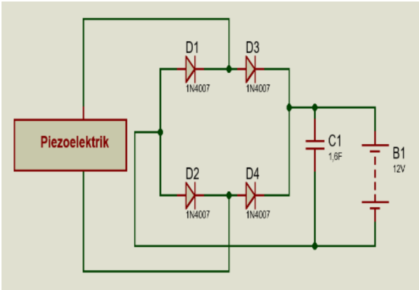

Fig. 7. Rectifier circuits

2.2.6 Design Piezoelectric

In this study, a module was designed using acrylic material in the form of a hollow rectangular cube with dimensions of 1.2 cm × 40 cm × 160 cm. Each inner surface of the module was equipped with piezoelectric elements made from PZT (Lead Zirconate Titanate), selected for its high sensitivity to pressure and stable electrical signal generation. The piezoelectric elements were connected in both series and parallel configurations to achieve a more consistent output voltage. To optimize pressure detection, the 3D structure was coated with a flexible material such as elastic foam, providing the appropriate suspension effect so that the pressure applied on the surface could be accurately detected. 3D design of piezoelectric can be seen in Fig. 8.

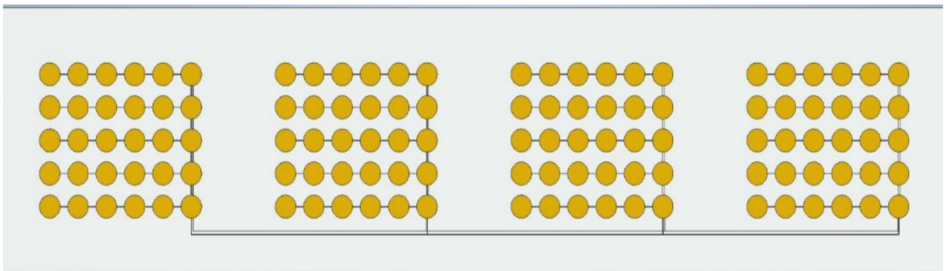

Fig. 8. 3D Design piezoelectric

After the design phase was completed, a hardware prototype (Fig. 9) was tested under real-world conditions to evaluate its performance and reliability. The prototype consisted of a rectangular piezoelectric module assembled from 120 PZT piezoelectric components, which were installed on each internal side of the specified structure.

Fig. 9. Hardware piezoelectric

3. RESULTS AND DISCUSSION

In this section, a prototype of a ceramic floor was developed, in which piezoelectric elements were systematically embedded for the purpose of energy harvesting. The testing procedure involved individuals with varying body weights walking over the floor ten times. The piezoelectric elements were divided into four groups, each consisting of 30 units arranged in a configuration of 6 elements in series horizontally and 5 elements in parallel vertically. The output of each group was then connected in parallel with the others. This testing aimed to evaluate the performance of the piezoelectric energy harvesting system under different pedestrian weight conditions. Each individual applied direct pressure to the piezoelectric module, and the resulting voltage was measured using a multimeter, while the current was measured using an ACS712 sensor.

The power output was then calculated by multiplying the measured voltage and current values. The recorded data are presented in Table 1.

3.1. Measurement Data

In this experiment, the data obtained demonstrates the relationship between body weight, voltage, current, and power used in a system. This data provides crucial information about how changes in body weight can influence the electrical quantities used by the system. Table 1 presents this data.

Table 1. Measurement Data

Body Weight	Average score		
	Voltage (V)	Current (Ma)	Power (mW)
65	10.4	0,98	10.192
69	10.7	1.01	10.807
70	12.7	1.18	14.986
72	13.2	1.26	16.632
73	14.8	1.43	21.164
75	11.7	1.08	12.636
76	15.2	1.41	21.432
80	14.3	1.34	19.162
94	16.4	1.53	25.092

From the table above, it can be observed that there is a tendency for the voltage to increase as body weight increases. For example, at a body weight of 65 kg, the voltage is 10.4 V, while at a body weight of 94 kg, the voltage rises to 16.4 V. This indicates that as body weight increases, the system requires higher voltage. Similarly, current tends to increase as body weight increases, though there are some fluctuations. At a body weight of 65 kg, the current is 0.98 mA, while at 94 kg, the current rises to 1.53 mA. This increase in current may be due to a higher energy requirement or changes in system characteristics. However, the power does not always increase consistently with body weight. For instance, at a body weight of 70 kg, the power recorded is only 1.4986 mW, which is much lower than the power at 73 kg, which reaches 21.164 mW. This suggests that although there is a general trend of power increasing with body weight, other factors such as system efficiency or material properties may influence the power output.

Fig. 10. Chart of piezoelectric

The graph in Fig. 10 shows a general tendency for voltage and current to increase as body weight increases. Data reveals that subjects with higher body weight require more voltage and current to operate the system. For example, at 65 kg, both voltage and current are lower compared to subjects with higher body weights, such as 94 kg. However, the relationship between power and body weight is not as consistent, with some data points showing significant spikes in power, like at 70 kg and 73 kg. These fluctuations might be due to factors like resistance or operational conditions affecting the power consumption, in addition to body weight.

4. CONCLUSIONS

This study demonstrates that piezoelectric-based energy harvesting technology, applied to ceramic flooring, has the potential to serve as an eco-friendly alternative energy source, particularly in areas with high pedestrian traffic. Using a total of 120 piezoelectric devices with a diameter of 35 mm arranged in a configuration of 6 in series and 5 in parallel on each tile, the system is capable of converting mechanical energy from human footsteps into electrical energy, which can be stored in a 12 Volt 12 AH battery.

The system's performance is highly influenced by the user's body weight, the size, and the shape of the feet, as these factors determine the number of piezoelectrics that receive optimal pressure when stepped on. Variations in these physical parameters result in differences in the voltage, current, and power generated.

Overall, this system can be implemented as a small-scale renewable energy solution, particularly for supporting lighting systems or charging low-power devices in public environments such as sidewalks, stations, or shopping centers.

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