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Road Energy Harvesting Using Piezoelectric Technology

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***Abstract*—This study proposes a piezoelectric energy harvesting device designed for urban environments, utilizing vertical spaces such as bridges and roads for energy collection. The device comprises four main components: the piezoelectric unit, the regulation unit, the communication unit, and the energy storage unit. The piezoelectric unit converts vibrations into electrical energy, while the regulation unit adjusts the voltage and circuitry for compatibility with subsequent components. The communication unit monitors the system and communicates with the main computer, and the energy storage unit stores the generated electricity. This modular design enables flexible installation, easy maintenance, and cost-effectiveness. The device offers a sustainable and eco-friendly alternative to traditional energy harvesting methods, addressing the growing demand for clean energy solutions. However, challenges such as improving the efficiency of piezoelectric materials and reducing device costs must be addressed to enable broader commercial applications.**

Keywords—Piezoelectric harvesting; road energy harvesting; urban power generation; environmental protection; AI, backup power

I. INTRODUCTION

With the increasing demand for electricity and growing emphasis on environmental protection, many countries are turning to clean energy. The three most prominent types of clean energy today are solar, wind, and hydropower. However, these energy sources require vast land areas and abundant natural resources, typically installed in remote or sparsely populated regions. Such locations inherently have a surplus of natural energy, but transmitting this energy to urban areas often relies on extensive power grid infrastructure. For instance, China's "West-East Electricity Transmission" project leverages the abundant natural resources and vast unpopulated lands of western China to build large solar and wind power plants, transmitting the electricity to densely populated eastern coastal cities through ultra-high-voltage transmission systems.

This design explores a novel concept: developing a clean energy generation method that can be installed in land-scarce urban areas. Addressing this need, piezoelectric energy harvesting emerges as an ideal solution, leveraging vibrations to generate electricity. The primary advantage of this design is its ability to utilize vertical spaces, such as city bridges and roads, for power generation. Additional benefits include the small footprint of individual devices, enabling the setup of multiple nodes in different directions and locations. All nodes are connected to a central control system for concentrated energy storage, and each node has a unique ID for monitoring operational status. With these features, this product can be applied to bridges, sports stadiums, staircases, and other vibration-prone locations.

II. WHAT IS THE PIEZOELECTIC EFFECT?

The discovery of piezoelectric materials dates to 1880, when Jacques Curie and Pierre Curie first observed the piezoelectric effect in quartz crystals. This effect refers to the phenomenon where a material generates electric charges or potential differences under mechanical stress. Initially, the resulting piezoelectric effect was extremely weak and considered merely the physical property of crystals, garnering little attention for practical applications.[2]

In 1942, research groups in the United States, Russia, and Japan independently discovered ferroelectric ceramics with a perovskite structure, such as barium titanate ($BaTiO_3$). Below the Curie temperature, these ferroelectric ceramics exhibit a tetragonal crystal structure with asymmetric centers and spontaneous polarization. After high voltage poling treatment, the ceramic grains exhibit strong remnant polarization, resulting in a piezoelectric coefficient 60 times greater than that of quartz crystals. This groundbreaking discovery marked the beginning of the development of piezoelectric materials, and $BaTiO_3$ -based ferroelectric ceramics are still widely used today in components like mobile phone and computer motherboards. [1]

With continuous advancements in materials and technology, the efficiency of the piezoelectric effect has improved significantly, enabling its application in numerous fields. For example, piezoelectric actuators in fuel injection systems have replaced traditional solenoid valves, improving fuel combustion efficiency, reducing harmful emissions, and lowering engine noise. High-temperature piezoelectric drilling tools use the piezoelectric effect to generate high-frequency vibrations for drilling, while the same vibration principle underpins ultrasonic devices such as radar and nebulizers, commonly found in daily life. These applications utilize the inverse piezoelectric effect, where materials deform mechanically under an electric field.

Conversely, the direct piezoelectric effect occurs when materials generate electric charges or potential differences under mechanical stress. This direct effect is widely applied in sensors, where vibrations induce electrical signals that are then monitored to determine vibration magnitude. The high working temperature of piezoelectric materials makes them ideal for real-time, dynamic monitoring of internal engine conditions. Piezoelectric-based high-temperature gas and pressure sensors are also extensively used in mobile communications and other consumer electronics fields.

III. HARDWARE DESIGN

his design is based on the direct piezoelectric effect, meaning vibrations are converted into usable electricity. According to Kim's 2007 conceptualization of energy harvesting, the process involves three main steps: (1) capturing mechanical alternating stress from available sources, (2) converting mechanical energy into electrical energy using direct piezoelectric conversion, and (3) processing and storing the generated electricity. The diagram highlights the major weakness of piezoelectric energy harvesting—energy loss, as significant amounts of energy are dissipated at each step. [4]

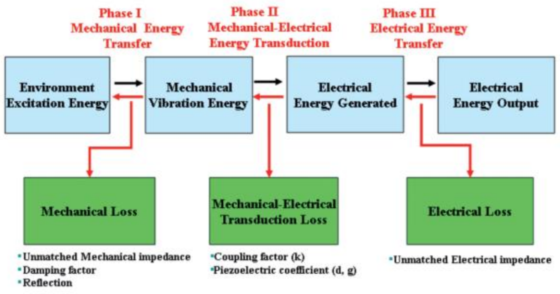

Figure 1. Steps of Piezoelectric Power Generation [6]

In 2004, Hyeoung Woo Kim demonstrated an energy conversion rate of only 7.5% for his PZT ceramic power generator. This means less than 1/10 of the mechanical energy applied is stored as electrical energy, a suboptimal result considering this value reflects mechanical energy directly transferred to the piezoelectric material. In real-world designs, mechanical energy is often more complex and multi-directional. Additionally, frequency is a critical factor for piezoelectric materials; specific materials must operate at frequencies to maximize energy output. Thus, the actual amount of energy converted into usable electricity is significantly lower than theoretical estimates.

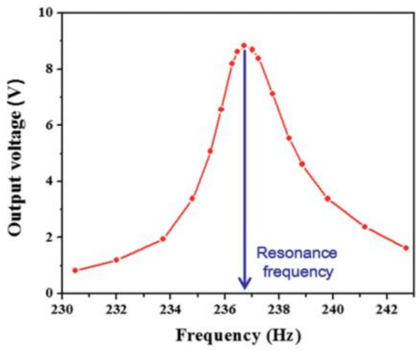

Figure 2. Piezoelectric Effect Frequency Vs Voltage [6]

This design aims to explore the feasibility of leveraging the advantages of piezoelectric effects for road energy harvesting. While enhancing the efficiency of piezoelectric materials remains a scientific challenge, this concept builds on Kim's framework to design a modular, high-tech piezoelectric system that aligns with emerging technologies, such as AI applications, modular power nodes, and new IoT interaction protocols. The system comprises four key components:

A. *Piezoelectric Unit*

The primary function of the piezoelectric unit is to collect vibrations from roads and convert them into electrical pulses through the piezoelectric effect. The piezoelectric device itself is the most critical part of this unit. The mechanical structure can be inspired by Wu's design of a d31-mode cantilever piezoelectric vibration energy harvester. Wu's design incorporated a "hearing tube" to achieve ideal experimental data, which is unnecessary in practical applications. Consequently, piezoelectric sensors are typically thin, and a single vibrator can connect thousands of piezo harvesters.

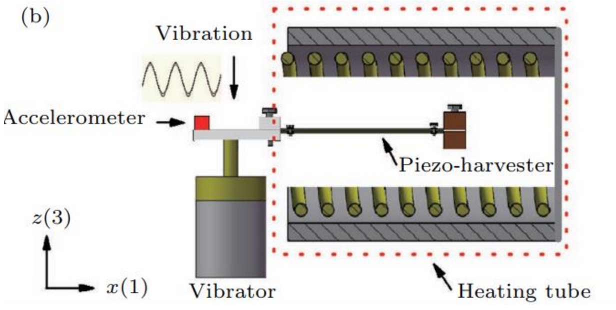

Figure 3. d31 single piezoelectric device [3]

In this design, a single modular unit will house thousands of independent piezo harvesters connected to a vibrator. This approach mitigates the limitations of small current output and unstable power generation in piezoelectric sensors.

What is the d31 Mode?

In piezoelectric materials, the d31 parameter describes the transverse force-electrical coupling effect. It represents the strain intensity generated in the material's orthogonal direction (commonly the 1 direction, parallel to the surface) when an electric field is applied in the polarization direction (typically the 3 directions, perpendicular to the surface).

If the system requires energy harvesting through pressing actions (e.g., foot pads or mechanical impacts), a d33-based design is preferred. For systems generating tension, bending, or shear forces (e.g., vibrating plates or wind-driven sheets), a d31-based design is more suitable. Since this design relies on bending to generate electricity, the d31 mode is prioritized.

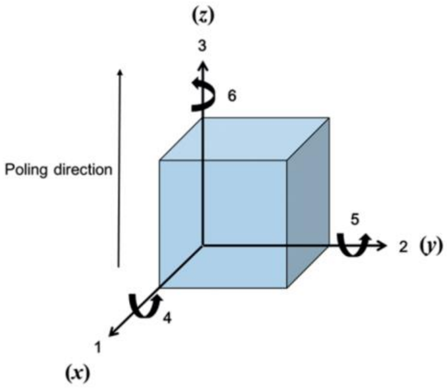

Figure 4. piezoelectric material orientation [6]

B. Rectification Unit

The rectification unit processes the electrical pulses generated by the piezoelectric unit. Piezoelectric sensors do not produce a stable or continuous voltage and current, as illustrated in the voltage-time relationship during sensor operation. The rectification unit collects pulses from thousands of piezo harvesters and converts them into a stable voltage and current to continuously power the system and charge the battery.

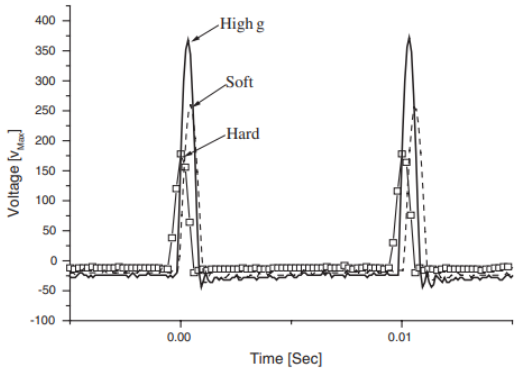

Figure 5. electrical pulses generation [5]

Drawing from Hyeoung Woo Kim’s design, this rectification system requires numerous converters and filters to function effectively. The complexity and variability of the voltage and current output from the piezoelectric unit pose a significant challenge. Designing a reliable and efficient conversion mechanism will be critical to maximizing the overall energy output of the system.

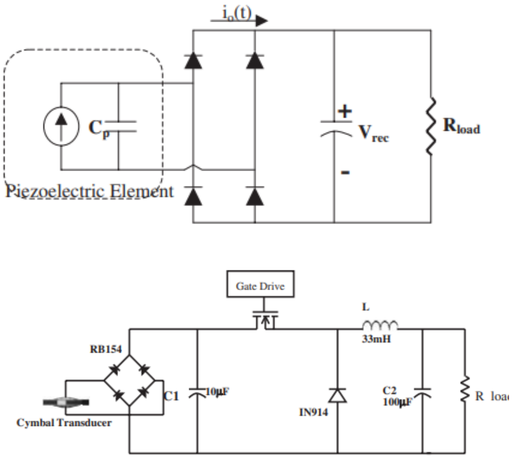

Figure 6. Converter and Filter for the Rectification Unit [5]

C. Communication Unit

The Communication unit plays a pivotal role in ensuring the system operates efficiently. It monitors the operational status of each device in real-time using precise sensors and programs, ensuring all devices function within preset parameters. Additionally, it handles data transmission to and from the host, creating a tightly integrated and orderly network.

Given the modularity and large number of piezoelectric devices, an efficient communication mechanism enhances resource allocation flexibility and significantly improves system efficiency.

The control unit design utilizes microcontrollers (MCUs) as the primary control units, as the main tasks involve reading sensor data and transmitting operational status to the central system without requiring complex computations. This approach reduces costs and minimizes unnecessary features, lowering heat generation and power consumption, thereby enhancing system stability and durability.

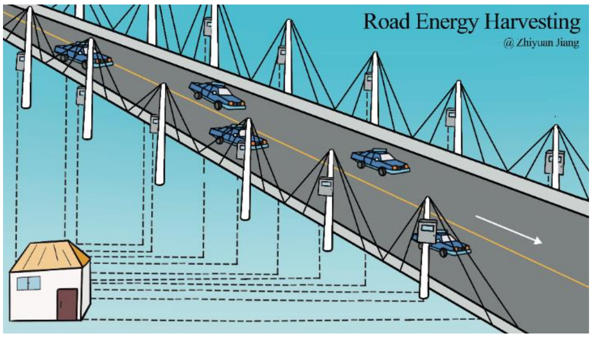

Figure 7. Highway power generation installation

The use of energy-efficient and high-speed MCUs also prepares the system for AI and IoT upgrades. As MCU processing speeds increase (e.g., ESP-32 is widely used in IoT systems), integrating AI to optimize power distribution based on factors such as traffic flow, power generation, power consumption, environmental temperature, and operating time offers significant potential.

D. *Energy Storage Unit*

The energy storage unit stores rectified electricity and discharges it as needed. When selecting a battery, factors such as operating environment, maximum storage requirements, and safety considerations are critical to ensuring performance and reliability. Since all devices share a single energy storage unit, its placement is particularly important. To maintain optimal performance and safety, the storage unit should be installed in a secure, sheltered, and well-ventilated indoor environment.

Among the available battery options, lithium iron phosphate ($LiFePO_4$), vanadium redox flow, and zinc-ion batteries are recommended. $LiFePO_4$ batteries are favored for their safety, long lifespan, and relatively low cost, although they have lower energy density and slower charging rates. Vanadium redox flow batteries stand out for their high safety, long lifespan, and deep discharge capability but require more complex systems and have lower energy density. Zinc-ion batteries excel in safety, cost, and environmental friendliness but need improvements in cycle life and energy density. The choice of battery should be tailored to specific needs and scenarios.

IV. POWER GENERATION CAPABILITY

In Wu et al.'s study, a d31-mode cantilever piezoelectric vibration energy harvester was developed using BS-PT piezoelectric ceramic materials, suitable for high-temperature environments. Under an excitation of 1g acceleration, the device achieved a maximum output voltage of approximately 8 V (peak-to-peak) and an output power of 13.5 µW at room temperature. At 150°C, the maximum output voltage increased to 12 V (peak-to-peak), and the maximum output power reached 23.5 µW. [1]

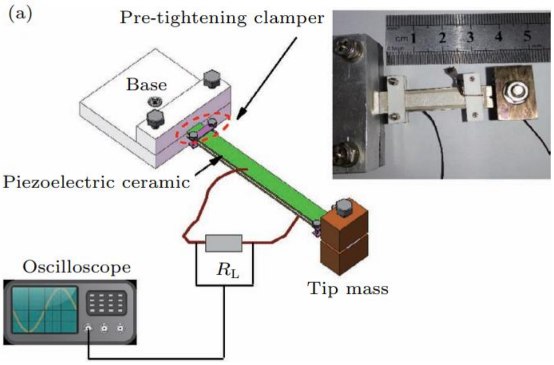

Figure 8. Piezoelectric power generation device [3]

Using the data provided for this device, we performed calculations based on the following assumptions:

The device dimensions, approximated from the study, are 4.17 cm in width, 1.67 cm in height, and 1.5 cm in thickness. This gives a single piezoelectric device a volume of approximately 10.46 cm³.

Assuming our power generation unit is the size of a standard 80 cm × 50 cm × 30 cm suitcase, the unit could accommodate approximately 11,471 devices with a volume of 10.46 cm³ each.

Given that our operating temperatures are generally higher than room temperature, and based on Wu's experimental results, we estimate each device's output power to be 18 µW.

Using these parameters, 11,471 devices, each generating 18 µW, could produce approximately 1.81 kWh of electricity per year. This amount of energy could power a 5 W LED bulb for approximately 362 hours.

V. COMMERCIAL POTENTIAL

Piezoelectric energy harvesting offers substantial commercial potential, leveraging advantages such as high-temperature resistance, durability, and maintenance-free operation. Below are the key advantages of employing modular piezoelectric generators in bridges and roads.

A unique feature of this system is its ability to be installed without any structural modifications to existing buildings. This significantly simplifies the installation process and reduces costs for users, making the system highly accessible. The convenience lowers barriers to adoption, as users do not need to deal with complex construction procedures or incur additional expenses.

The system's flexible installation capabilities also make it suitable for various narrow or complex spaces, such as vertical roads in urban environments, under bridges, or other hard-to-utilize areas. This versatility provides customers with greater choices and convenience, allowing them to utilize existing resources without requiring dedicated land for installation.

In addition, equipped with battery storage and operating independently of external power grids, this energy harvesting system is ideal for commercial backup power applications. In situations where conventional power supplies are unstable or disrupted, it can provide immediate temporary electricity, ensuring continuity and stability in operations. The storage capacity can also be adjusted to meet diverse energy demands by adding additional battery modules.

VI. CONCLUSION

In summary, harnessing vibrations from urban environments for power generation is a feasible application of piezoelectric energy harvesting. The modular design of this system aims to complement traditional renewable energy sources, such as wind, water, and solar power, rather than replace them. As emerging urban centers experience surging electricity demands, the importance of generating electricity within cities will become a key focus for governments worldwide. With commercial adoption and technological advancements, diversified energy solutions will grow increasingly important, positioning piezoelectric energy harvesting as a promising option in the face of rising energy demands.

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