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P4 3 Piezoelectric Power Generation for Street Lights

J. Owusu Boamah, A. Fotedar, A. McCrea
Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH

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Abstract
This study examines the potential of harnessing vehicle traffic in Leicestershire to power street lighting using the direct piezoelectric effect. Our model generated approximately 4.8×10^2 J of energy, which falls significantly short of the estimated energy requirement of 3.3×10^{13} J to meet the full demands of street lighting.

Introduction

Piezoelectric materials are dielectrics that convert electrical energy to mechanical energy and vice versa. They change shape when exposed to an electric field and generate an electric charge when subjected to mechanical stress. A piezoelectric material, placed underneath a road's surface, converts mechanical energy into electrical energy as the weight of a vehicle passes over it. In this paper, we model a direct piezoelectric configuration and implement traffic data to determine whether mechanical stress can power street lights in Leicestershire.

Theory

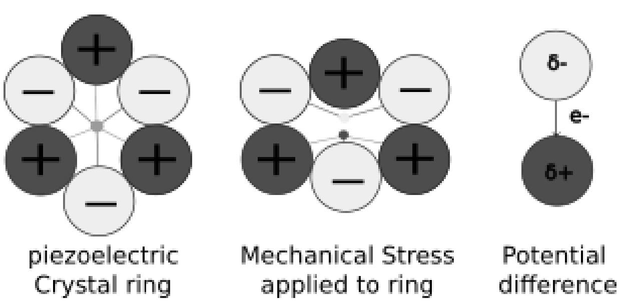

Figure 1: Piezoelectric in SiO_2 Crystal Structure (adapted from animation)[1]

Figure 1 shows a segment of one of the most commonly used piezoelectric materials quartz (SiO_2), where the positively and negatively charged spheres represent Si and O atoms, respectively. These atoms tend to attract or repel electrons when covalently bonded. The centre of charge describes the average position of all the electrical charges within a piezoelectric material. Initially, this centre is located at the core of the hexagonal structure. However, when vertical mechanical stress is applied to the crystal, the system's symmetry is disrupted, leading to a potential difference [1].

As we are dealing with a single-axis force, the constitutive law of piezoelectric materials can be simplified, allowing the induced potential difference to be expressed as:

$$V = \frac{dFL}{\epsilon_0 \epsilon_r A} \tag{1}$$

Where 'd' is the piezoelectric charge constant; 'F' is the mechanical force applied to an area 'A'. The thickness of the piezoelectric material is given by 'L'. 'ε_0' and 'ε_r' are the vacuum and relative permittivity, respectively [2].

Simulation

Researchers at Pennsylvania State University created a piezoelectric road energy harvester using lead zirconate titanate (PZT-5H) due to its physical strength and high operating temperatures.

They proposed a ring configuration of five PZT-5H cylinders that share the weight of a vehicle's tyre [3]. We will use their stress distribution model on each tyre, for our COMSOL multiphysics simulation to calculate the potential difference induced by vehicles in Leicestershire.

Our PZT-5H cylinder has a piezoelectric coefficient of d= 7.41×10^{-10} C/N; a thickness, L of 5 mm; a radius of 5 mm and a relative permittivity of 3400. Considering the stress-distribution model on Asphalt roads, a force of 114 N is calculated for each wheel of an average-sized car (1500 kg) [3]. We can then calculate the potential difference using these material properties and verify our model using a measuring probe to measure the voltage.

Results and Discussion

We calculated a Potential difference of 179 V using equation (1) however, our potential probe only measured 134 V. This discrepancy is highlighted by the 25% error between the two voltages.

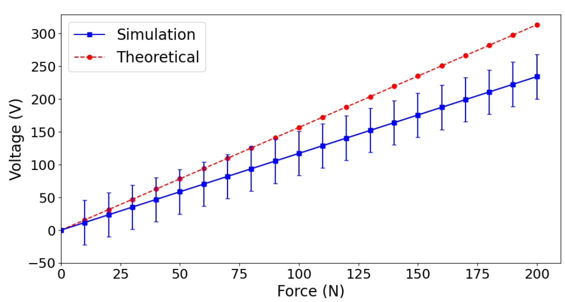

Figure 2: Output Voltage as a function of Force

Figure 2 shows a significant voltage difference for forces over 100 N, indicating that our model is inadequate for large forces. We applied a fixed constraint to the cylinder's bottom in COMSOL to prevent it from moving. However, at high forces the PZH-5H's natural deformation limit is reached, resulting in a weaker piezoelectric response and a lower potential difference.

In 2019, street lights in Leicestershire consumed 3.3×10^{13} J of energy [4]. Using our piezoelectric device with a capacitance of 4.73×10^{-10} F, we calculate the energy per tyre using $E = \frac{1}{2}CV^2$. This is multiplied by 5 for each cylinder; then the 4 wheels per vehicle, and the daily vehicle count of 5,621,141 [5], yielding a total energy of 4.8×10^2 J.

Conclusion

The energy produced by the piezoelectric effect is eleven orders of magnitude too low to power the street lights, making the model impractical. Future work should attempt to mitigate the limitations by spreading the weight of each tyre over more cylinders to lower the forces on each cylinder or consider alternative materials which may exhibit stronger piezoelectric properties.

References

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