Piezoelectric-Based Energy Harvesting Technology for Roadway Sustainability

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Abstract

The benefits of a roadway energy harvesting system are potentially great, given the lane-miles and high traffic volume in specific areas of state highways. A piezoelectric method of energy harvesting has advantages over other alternative sources, such as solar panels and wind power. The primary goal of this research project is to prove that the piezoelectric method is a viable alternative energy source for roadways. The scope of the research project includes investigation of the energy harvesting method, a feasibility study, the framework of the piezoelectric method, preparation of equipment and materials, conduction of lab experiments, and development of potential design using piezoelectric materials. The lab experiment is to identify magnitude of energy harvesting with piezoelectric materials under asphalt pavements. Preliminary research results indicate that the levelized cost of energy (LCOE) is relatively high, but potential energy generation can be improved by several variables. Thus, there is an urgent need to conduct studies regarding this technology in laboratory conditions with available products in the U.S. Currently, research framework, equipment, hypothesis, and statistical experimental design are prepared to conduct the research. The results of this research project will contribute to the possibility of highways' self-supporting energy capacity. The amount of generating capacity will be recorded and compared with other energy harvesting methods to determine economic competitiveness.

Keywords: Energy harvesting, Piezoeletric Device, Sustainable Highway

1. Introduction

Piezoelectric energy harvesting technology has significant advantages over other renewable energy sources such as solar, wind, and geothermal ("Harnessing Pavement Power: Developing Renewable Energy Technology in the Public Right-of-Way," 2013; Xiong, Wang, Wang, & Druta, 2012). Using the pressure of vehicles caused by gravity, the method generates electric energy from the deformations in the paving materials (Ali, Friswell, & Adhikari, 2011). Although recent research projects have paid attention to this energy harvesting technology, only a few studies have been conducted on-site to determine its feasibility and economic competitiveness. No data are available for highway pavements (Chang-Il Kim & Jong-Hoo Paik, 2011; Huang, Niu, Zhao, & Chang, 2012). Therefore, it is necessary to develop a research framework that enables assessment of the technology of piezoelectric materials on state highways.

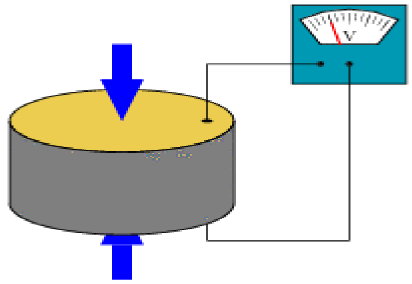

Figure 1: Piezoelectric Generator (Zimesnick, 2011)

This technology can be used for a variety of purposes, including sensors (Gkoumas, Petrini, & Bontempi, 2012; Vijayaraghavan, Kossett, & Rajamani, 2006; Yu, Giurgiutiu, Ziehl, & Ozevin, 2009; Yu, Wu, Giurgiutiu, & Ziehl, 2013), roadway lighting and bridge bearing (Baldwin, Roswurm, Nolan, & Holliday, 2011; Wang, Chang, & Newcomb, 2003), structural health monitoring (Ali et al., 2011; Xiong et al., 2012; Yu et al., 2013), deicing (Symeoni, 2013), and pavement to traffic monitoring (Huang et al., 2012). A privately-owned company applied this technology to a highway in Israel in 2009. It was expected that the four-lane highway could produce enough energy to provide sufficient electricity for average consumption in 2,500 households (Ali et al., 2011). According to a report developed by DMV KEMA under the California Energy Commission, a levelized cost of energy (LCOE) by Innowattech is \$0.11/kWh with an averaged capital cost of \$4000/kW (Hill, 2013). This indicates that piezoelectric-based energy harvesting technology may be more economical than solar panels. In addition, vibration-based roadway piezoelectric technology can be as competitive as wind, nuclear, and coal (Hill, 2013; Jeon, Sood, Jeong, & Kim, 2005; Roundy, Wright, & Rabaey, 2003). However, Table 1 shows the wide variation in magnitudes of power generation that resulted from unknown parameters that may include design of prototypes, vibration or compression, speed, and vehicle weight (Hill, 2013; Office of Research, 2013).

Table 1: Wide Range of Power Generation Using Piezoelectric Materials (Hill, 2013)

Parameter	Genziko	ODOT	Innowattech	Berkeley and Virginia Tech
Power per km (single lane)	13-51 MW	486 kW	100-200 kW	0.0018-0.5 kW
Vehicles per hour (single lane)	600-2250	600	600	600

Despite many advantages with this energy harvesting method, real-world situations typically have inconsistent or varying vibration frequencies, and this requirement severely limits its practicality (Hill, 2013). No research projects in the U.S. have proven in the lab, in asphalt, and in the field that it is reliable, safe, and economically competitive for use in roadways.

2. Research Objective and Scope

The first phase of this research project is to determine the most economical piezoelectric product available in the U.S. The research project is to be accomplished in multiple phases: Generated energy with piezoelectric materials under asphalt pavement will be measured in the lab so that its economy and feasibility can be determined prior to field experiments. Asphalt pavement is the most popular and flexible pavement material, which is used for 94 percent of the surface of U.S. highways (NAPA, 2014). (2) LCOE, \$/Kwh of each piezoelectric material, will be determined based on the energy generated under lab conditions.

2.1 Preliminary Date Collection and Analysis

A preliminary lab experiment was conducted to develop the framework of this research project and to test equipment and materials, including the asphalt analyzer (\$40k), the electricity measurement device (\$13k), and commercially available piezoelectric materials (\$8k) (See Figure 2). Using equipment at Georgia Southern, voltages from two leading piezoelectric material companies were measured, and possible power and energy values were calculated. This experiment was conducted under the assumption of 600 vehicles per hour at 45mph. Loads on the asphalt mix from each vehicle were 50, 100, and 200 lbs (See Figure 3). As a result, computed power and energy were 2.67 mW and 2.67 mWh, respectively.

This requires approximately 7 wafers to generate a 60 wh-light at 14$ where the price of wafer is 2$ each. In this case, the estimated LCOE ($/kwh) is 52 $/Kwh. Currently, with the raw materials provided by manufacturers, the LCOE of piezoelectric materials should be higher than other ambient sources.

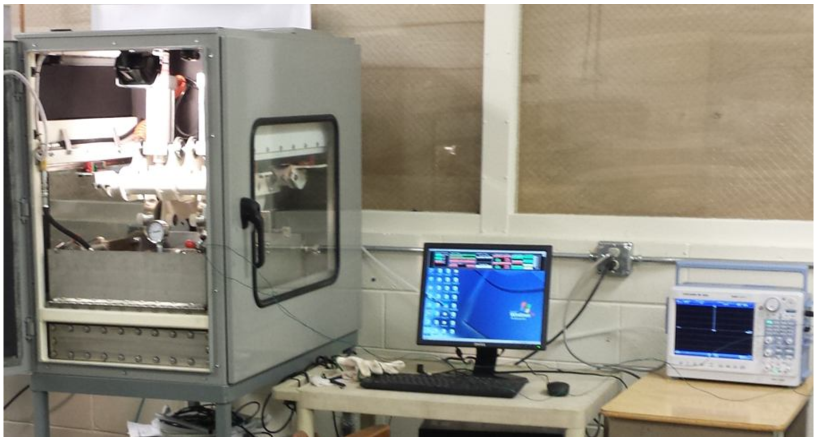

Figure 2: Equipment

Loads (lbs)	Noliac		Kinectic Ceramic	
	Voltage			
	Min	Max	Min	Max
50	-5	5	-10	5
100	-5	5	-20	10
200	-15	15	-40	20

Note: 60HZ

Figure 3: Preliminary data (Roundy et al.)

Several companies have been developing power generation using alternative methods. A report funded by the California Energy Commission indicated that depending on the method of generation with piezo material's shape, size, vibration form, etc., energy can vary significantly. (See Figure 4)

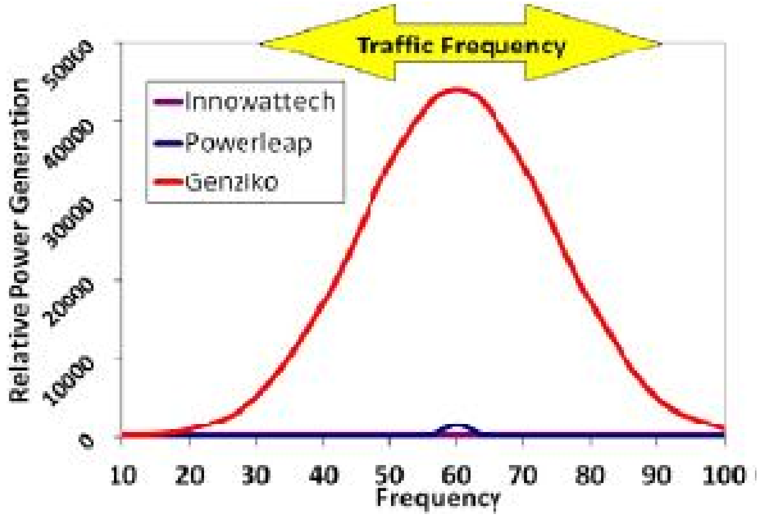

Figure 4: Significant Power Density over Competing Technologies (Hill, 2013)

2.2 Circuit Diagram for Measuring Generated Voltage form the Piezoelectric Devices

The GSU research team developed the research framework (Figures 5 and 6). Figure 5 shows the block diagram of piezoelectric based sensor voltage measurement. A Pre-amplifier is required for piezoelectric sensing electronic circuit.

The main task of this pre-amplifier is to transform the high impedance of the sensor to the low impedance measuring devices. In this project, we will use a charge amplifier as a preamplifier. The major advantage of the charge amplifier comes from the fact that the circuit sensitivity, and therefore, the output voltage is unaffected by the capacitance of the sensor and stray capacitances like the input cable capacitance. Figure 6 shows the pre-amplifier circuitry. The charge q(t) generated from the piezoelectric sensor due to compression/pressure is amplified by the charge amplifier and the output voltage V(t) can be captured for measurement or stored for harvesting. The voltage and current output by the harvester needs to be conditioned and converted to a form usable by the load circuits. There are several methods of conditioning this harvester output voltage. A full wave rectified circuit can be used to harvest the power.

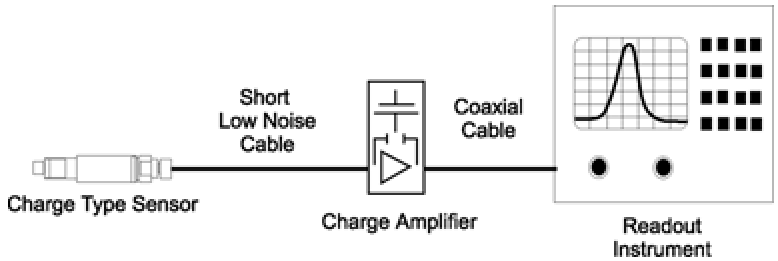

Figure 5: Block Diagram for Measuring Generated Voltage from the Piezoelectric Devices

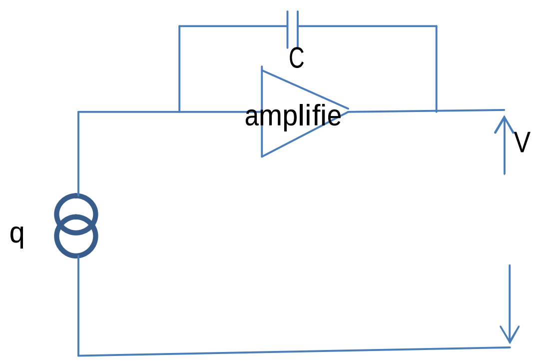

Figure 6: A Charge Preamplifier to Capture Piezoelectric Charge to Form an Output Voltage and Current

3. Data Analysis

3.1 Hypothesis

The Mean of power density generated by piezoelectric materials is compared with the Mean of power density generated by solar panels to determine whether the means of these two groups of data are statistically the same. The construction cost data is the most commonly used construction cost index in the U.S. The null hypothesis and alternative hypothesis for these analyses are as follows:

$$\begin{aligned} H_0 &: \ \mu_d = 0 \\ H_1 &: \ \mu_d \neq 0 \end{aligned} \qquad (1)$$

where μ_d is mean of power generated by piezoelectric material from mean of power by solar panel.

3.2 Normality Tests and Comparison Tests

Two normality tests, the Ryan-Joiner test and the Anderson-Darling test, will be conducted to determine if the experimental data followed normal distribution, as shown in Table 1. A nonparametric test, the Mann-Whiteny test, is utilized to determine whether two populations have the same population median (ƞ) as shown in column 5 of Table 1.

Table 1: Description of Data and Results of Data Analysis

Variable	Number of Data	Normality Test (P value)		Comparison Test (P value)	
		Ryan-Joiner	Anderson Darling	Mann-Whitney	Paired t-test (After Data transformation)
(1)	(2)	(3)	(4)	(5)	(6)
Generated Power	More than 30	NA	NA	NA	NA

4. Conclusions and Future Directions

If further lab experiment data are successfully collected and analyzed, interested parties or users will be able to focus on developing a piezoelectric-based energy harvesting system. The system development, beyond the initial lab work, includes two future phases: 1) determination of whether a prototype generator should be developed with selected piezoelectric materials, and 2) field experiments to be performed on Georgia highways. Completion of these three phased research projects will make several major contributions to the advancement of transportation performance and management, and highway sustainability. Therefore, the research team will propose significant project outcomes that are expected to: (1) increase the self-supporting energy capability of highways, (2) increase the ability of highways to provide electricity to areas that are remote from main electricity lines, and (3) improve the performance of the system to generate energy from both vertical and horizontal forces of vehicles.

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