The 6th International Conference on Sustainable Energy Information Technology (SEIT 2016)

Energy Harvesting from Roadways

A.T. Papagiannakis\textsuperscript{a,}* A. Montoya\textsuperscript{c} and H. Roshani\textsuperscript{d}

\textsuperscript{a}Professor, Dept. of Civil and Envir. Eng. Univ. of Texas at San Antonio, USA 78249
\textsuperscript{b}Associate Professor, Dept. of Civil and Envir. Eng. Univ. of Texas at San Antonio, USA 78249
\textsuperscript{c}Assist. Professor, Dept. of Civil and Envir. Eng. Univ. of Texas at San Antonio, USA 78249
\textsuperscript{d}PhD Student Dept. of Civil and Envir. Eng. Univ. of Texas at San Antonio, USA 78249

Abstract

This paper presents a preview of an ongoing study to develop an energy harvesting system based on piezoelectric elements embedded into the pavements structure. The system development involved designing and testing a number of prototypes in the laboratory under controlled stress conditions. In addition, it involved numerical modeling of the stress distribution in the power generation module and economic analysis of the value of the electric power generated, under a given traffic composition scenario. The results available to date suggest that this technology shows promise in powering LED traffic lights and wireless sensors embedded into pavement structures.

Keywords: Energy, harvesting, roadways, piezoelectricity.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>electrical charge</td>
</tr>
<tr>
<td>$P$</td>
<td>electrical power</td>
</tr>
<tr>
<td>$E$</td>
<td>electrical field</td>
</tr>
<tr>
<td>$d_{33}$</td>
<td>piezoelectric charge constant</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>dielectric constant</td>
</tr>
</tbody>
</table>

* Corresponding author. Tel.: +1-210-458-7071; fax: +1-210-458-6475. 
E-mail address: at.papagiannakis@utsa.edu
1. Introduction

In recent years, there has been increasing interest in energy harvesting through transduction. Three technologies have been used for this purpose, namely electromagnetic, electrostatic and piezoelectric. Piezoelectric transduction appears to be the most promising, given its widest power density versus voltage envelop, as shown in Fig. 1. A number of recent studies explored the use of piezoelectric transduction for harvesting energy from roadways. Work by Xiong at Virginia Tech produced a piezoelectric harvesting system consisting of multiple cylindrical piezoelectric elements that are compressed by the action of traffic tires (Fig. 2). Under a traffic volume of 4,000 vehicle per day (167 vehicles/hour), this system generated voltage ranging from 400 to 700V and electric currents ranging from 0.2 to 0.35 mA. The corresponding power output was obtained by multiplying voltage by current, yielding a power range between 0.08 and 2.1 Watts per system.

![Fig 1. Power Density versus Voltage for various Energy Harvesting Technologies](image1)

![Fig. 2. Piezoelectric Energy Harvesting System Developed By Xiong (2014)](image2)

Work by Kim et al. at Georgia Southern University involved laboratory testing using an Asphalt Pavement Analyser (APA). Two piezoelectric materials were tested one manufactured by Noliac and the other by Kinetic. APA wheel loads at three levels were applied, namely 50, 100 and 200 lbs. The maximum resulting voltages for the Noliac were
5, 5, and 15 Volts, respectively, while for the Kinetic were 5, 10 and 20 Volts, respectively. Assuming a traffic level of 600 vehicles/hour at a speed of 45 mph, such a system could produce up to 2.67 mW of power.

Zhao et al. at Tongji University studied power generation form several types of piezoelectric sensor configurations. These included multiple lead zirconate titanate (i.e., PZT) prismatic elements referred to as “piles” with circular, square or hexagonal cross sections, as well as commercially available cymbal-shaped and bridge-shaped elements. They performed finite element analysis to study the effect of the shape of the PZT piles in producing electric power output, concluding that the circular cross section piles were preferable. Power generators involving multiple piles were analysed (Fig. 3). Stress analysis combined with theoretical calculations established that generators with 8-16 piles each can be used to harvest significant amounts of electrical power under heavy traffic.

A report was recently completed on behalf of the California Energy Commission (CEC) to independently evaluate the feasibility of piezoelectric technology in harvesting energy from roadways and establish if this technology warrants further study. It evaluated some of the pilot systems developed by Universities, as well as commercially available harvesting systems. Three commercially available systems were evaluated in terms of their vendor output claims, namely, Treevolt, Genziko and Innowattech. The first two of these three vendors appear to continue development of this technology. The Treevolt harvesters, marketed in the USA under the POWERLeap name, consist of recycled butyl-propylene membranes sandwiching sheets of harvesting devices are embedded under the top layer of asphalt concrete and are activated in compression. The vendor claims that 1.0 km length of roadway equipped with 6,000 Treevolt harvesters and carrying 600 vehicles per hour can generate approximately 720 kW of power. Genziko claims that under the same traffic level, their vibration-activated harvesters have the potential to generate a considerably higher 13,600 kW of power, an amount that was considered “optimistic” by the CEC report. Innowattech claims that their harvesters can generate 200 kW under similar traffic levels, assuming that harvesters are placed under both wheel paths. The CEC study observed that there are considerable differences in the energy output claims made by different vendors, especially with respect to the assumptions made for the number of sensors involved and the traffic level. It was recommended adopting a standardized way of reporting power or energy output by piezo unit surface area, referred to as power or energy density (i.e., W/unit area or Wh/unit area, respectively). In evaluating the cost effectiveness of these systems, the CEC report recommended using the levelized cost of energy (LCOE) produced by the various harvesting systems varies. The LCOE is defined as the average total life–cycle cost to construct, operate and maintain a power-generating system divided by its total energy output over its service life. This report concludes by recommending further field testing of this technology.

2. Objective

The objective of this paper is to further explore the application of piezoelectric technologies for harvesting energy from the action of traffic using the roadways. It provides a brief overview of piezoelectricity fundamentals, a review of the pertinent literature and a preview of our efforts to develop and test several prototypes for harvesting energy. The most promising prototype will be refined and integrated into a series of modules laid down in the wheel path of roadways for harvesting energy. They are referred to as the HiSEC (Highway Sensing and Energy Conversion) modules.
3. Principles of Energy from Piezoelectric Transduction

Piezoelectric materials generate electricity when subjected to stress or vibration. They are crystalline ceramics (e.g., lead zirconate titanate, abbreviated as PZT) or polymers (e.g., polyvinyl fluoride abbreviated as PVF) heated above their Curie temperature and subjected to a magnetic field to orient their electric dipoles in the same direction. Stress/strain parallel to the poling direction of a piezoelectric material generates an electrical charge. Conversely, an electric charge generates stress/strain across a piezoelectric material. For simplicity the physics governing piezoelectric power generation are explained below in uniaxial terms (i.e., strain/stress in a single direction only). A complete treatment of the subject can be found in the literature\(^9\).

Consider the piezoelectric element of dimensions \(a\), \(b\) and \(c\) shown in Fig. 4 and assume that the direction of polarization is vertical. A force \(F\), parallel to the polarization direction will generate an electrical charge \(Q\) (Coulombs) given by:

\[
Q = F d_{33}
\]  

(1)

Where, \(d_{33}\) is the piezoelectric charge constant (Coulombs/N). This mode of loading is referred to as 3-3 loading.

Equ. 1 can be normalized with respect to the area \(A = ab\) as follows:

\[
D = \frac{Q}{A} = \sigma d_{33}
\]  

(2)

Where \(\sigma\) is normal stress (Pa) and \(D\) is the charge density (Coulombs/m\(^2\)), which is related to the electric field \(E\) (Volts/m) through:

\[
D = \varepsilon_0 \varepsilon_r E
\]  

(3)

With \(\varepsilon_0\) and \(\varepsilon_r\) the dielectric constant of the air (8.85 x 10\(^{-12}\) Farad/m) and the relative (dimensionless) dielectric constant of the piezoelectric material, respectively. Equating Equ. 2 and 3 gives:

\[
\varepsilon_0 \varepsilon_r E = \sigma d_{33}
\]  

(4)

Which reduces to:

\[
E = \sigma g_{33}
\]  

(5)

Where \(g_{33}\) is the piezoelectric constant of the material (Volts/m/Pa) related to the earlier defined constants through:

\[
g_{33} = \frac{d_{33}}{\varepsilon_0 \varepsilon_r}
\]  

(6)

The \(V\) (Volts) produced from the piezoelectric element of thickness \(c\) (Fig. 4) is given by:
The corresponding electrical power $P$ generated over a time period $t$ is:

$$P = \frac{VQ}{t}$$  \hspace{1cm} (8)

Which allows computing the energy output by substituting Equ. 1 and 7 into Equ. 8 as:

$$Pt = F d_{33} c \frac{F}{ab} g_{33} = d_{33} g_{33} \left(\frac{F}{ab}\right)^2 abc$$  \hspace{1cm} (9)

Which integrated over time gives the energy output $W_{33}$ of the piezoelectric sensor as:

$$W_{33} = \frac{1}{2} \int_0^t d_{33} g_{33} \left(\frac{F}{ab}\right)^2 abc d\xi$$  \hspace{1cm} (10)

Noting that $\frac{F}{ab}$ represents engineering stress, allows expressing Equ. 10 as follows:

$$W_{33} = \frac{1}{2} \int_0^t d_{33} g_{33} Y^2 abc \int_0^t \varepsilon_{33}^2 d\xi$$  \hspace{1cm} (11)

Where $Y$ is the Young’s modulus and $\varepsilon_{33}$ is the normal strain in direction 3 and $abc$ is the volume of the element. Equ. 11 suggests that the relationship between the strain applied and the amount of electrical energy being generated is non-linear. A similar expression can be derived for a force applied perpendicularly to the direction of polarization (i.e., parallel to direction 1 as shown in Fig. 4). This is referred as 3-1 loading mode and is denoted by subscripts 31 as opposed to 33.

4. Developing the HiSEC Prototypes

In developing prototypes for the proposed HiSEC module, various configurations of boxes containing selected number of PZT elements of various shapes were considered. The analysis involved Finite Element (FE) modeling of the stress distribution inside the boxes, laboratory testing of the power output and durability as well as economic feasibility analysis.

4.1 Finite Element Analysis

The various configurations of the HiSEC prototypes were analysed using the FE model Abaqus®. An example of the FE mesh used to analyse Prototype II is shown in Fig. 5. The FE analysis explored the stresses in the PZT elements, the effect of the stiffness of the box and the effect of the stiffness of the surrounding asphalt concrete pavement. This analysis revealed that the stiffness of the upper side of the box had a marginal effect on the uniformity of the stress distribution in the PZT elements. Furthermore, it determined that the stresses under a moving truck tire are well within the compressive strength range of the PZT elements, which is in the order of 900 MPa\(^a\). In addition, buckling of the elements was not an issue for the prototypes analysed so far under the truck tire service loads anticipated (max dual tire load of 10,000 lbs or 44.4 kN). Additional stress analysis was conducted to ensure that the boundaries of the box do not cause unduly high strains in the asphalt concrete layer that encapsulates them. A depth of 5 cm was selected for installing the HiSEC modules, to allow typical asphalt pavement rehabilitation involving milling of the top 5 cm and overlaying. At this depth, the surface stresses from traffic loads (i.e., approximately 210 kPa from car tires and 700 kPa from truck tires) were relatively undiminished. In addition, statistical analysis was conducted with respect to the width of the HiSEC unit and its optimum lateral placement in the driving lane. It was estimated that a module width of 0.45 m will suffice to fully support the dimensions of standard dual truck tires, which is approximately 0.5 m. The centre of the HiSEC module should be located to maximize the probability of truck tires been located on it. Work by Timm and Priest\(^b\) suggests that this should be about 0.80 m from the edge stripe marking the right hand-
side of the driving lane.

4.2 Laboratory Testing of Power Output

The HiSEC prototype elements were tested in the laboratory using an MTS® Acumen system. Testing was carried by applying a sinusoidal compressive load at a frequency of 10 Hz with a peak-to-peak magnitude ranging from 0.5 to 3.5 kN. Wattage was measured directly using a Watt-meter. Two of the prototypes tested already are described next, namely prototypes I and IV shown in Figs. 6(a) and 7(a), respectively. Prototype I is made of 3 layer connected in series each consisting of 25 PZT prismatic elements of rectangular cross section measuring 3.5mm by 3.5mm. Each layer is 11.7 mm tall and the volume between the PZT elements is filled with epoxy. Prototype IV consists of a stack of six cylindrical PZT-5A element with a diameter 44.5 mm and a thickness of 6 mm, resulting in a cylindrical element of 36 mm in height. This element is enclosed into a commercially available electrical box. The laboratory results of the four other prototypes considered had not been completed at the time this paper was prepared. The laboratory results available are plotted for Prototypes I and IV in the form of power generated (mW) versus the vertical stress applied (kPa) (Figs., 6(b) and 7(b), respectively). These relationships agree with the non-linear form of the energy versus stress/strain suggested by Equ. 11. Following this laboratory testing, these prototypes will be subjected to durability testing by embedding them into asphalt concrete samples and subjecting them to repetitive loading from an Asphalt Pavement Analyser (APA).

Fig. 5. Prototype II; CAD Drawing and Part of the FE Analysis Mesh.

Fig. 6 Prototype I: Configuration (a) and Power Output versus Stress (b)
4.3 Economic Considerations

The capability of electric power production from these devices was studied using the laboratory obtained curves of power versus stress level highlighted above, i.e., Figs. 6(b) and 7(b). These curves were available only for Prototypes I and IV, at the time this paper was completed. For the power production calculations, it was assumed that each HiSEC module measured 0.09 m$^2$ (i.e., 1 foot x 1 foot) and fitted the maximum number of piezoelectric elements possible for each prototype. Prototypes I and IV would allow placing 225 and 25 piezoelectric elements, respectively, per square foot. The traffic volume and composition was considered as an input to the power production analysis. The traffic input assumed for the results presented next is summarized in Table 1 and reflects a moderately busy Interstate highway in the USA. Table 2 shows the calculation steps for the electric power and energy production from the car tires and truck tires expected to pass over a HiSEC module for the traffic composition assumed. It can be seen that Prototype IV module produces approximately 2,100 Watt-hours per year. Clearly, the monetary value of this level of power output is not high compared to the cost of conventional electric grid power. In the USA, this is estimated to range between $0.15 and $0.30 per kWatt-hr ignoring the environmental cost of greenhouse gas emissions resulting from fossil fuelled power plants. Nevertheless, the results to-date suggest that piezoelectric technology can be used to harvest energy from the roadways to power LED traffic lighting or wireless sensors embedded into the pavement structure without the need for external grid power. This is particularly attractive in rural areas, where electric grid power is not available at roadside.

5. Summary

This paper presented a preview of an ongoing study to develop an energy harvesting system based on piezoelectric elements embedded into the pavements structure. The system development involved designing and testing a number of prototypes in the laboratory under stress controlled conditions. In addition, it involved numerical modelling of the stress distribution in the power generation module and economic analysis of the value of the electric power generated, under a given traffic composition scenario. The results available to date suggest that this technology shows promise in powering LED traffic lights and wireless sensors embedded into pavement structure.

Acknowledgements

Funding for this study was provided by the Texas Department of Transportation.
Table 1.
Traffic Assumptions

<table>
<thead>
<tr>
<th>Traffic Property</th>
<th>Assumed Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic speed (m/sec)</td>
<td>22.2</td>
</tr>
<tr>
<td>Average Annual Daily Traffic (AADT)</td>
<td>30,000</td>
</tr>
<tr>
<td>No lanes</td>
<td>4</td>
</tr>
<tr>
<td>AADT/Direction</td>
<td>15,000</td>
</tr>
<tr>
<td>Percent Trucks in traffic stream</td>
<td>0.25</td>
</tr>
<tr>
<td>Percent trucks in right Lane</td>
<td>0.75</td>
</tr>
<tr>
<td>Number of cars in right lane/day</td>
<td>5,625</td>
</tr>
<tr>
<td>Number of Trucks in right lane/day</td>
<td>2,813</td>
</tr>
<tr>
<td>Number of car axles in right lane/day</td>
<td>11,250</td>
</tr>
<tr>
<td>Number of truck axles in right lane/day</td>
<td>14,063</td>
</tr>
<tr>
<td>Car tire load (kN)</td>
<td>6.667</td>
</tr>
<tr>
<td>Truck tire load (kN)</td>
<td>44.48</td>
</tr>
</tbody>
</table>

Table 2:
Energy Output for Prototypes I and IV under the Traffic described in Table 1

<table>
<thead>
<tr>
<th></th>
<th>Prototype I</th>
<th>Prototype IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of elements/module (area of 0.093 m^2)</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>Cross sectional area by piezoelectric unit (m^2)</td>
<td>3.84845E-05</td>
<td>0.001555285</td>
</tr>
<tr>
<td>Stress from car tire (kPa)</td>
<td>769.95</td>
<td>171.47</td>
</tr>
<tr>
<td>Stress from truck tire (kPa)</td>
<td>5136.84</td>
<td>1143.97</td>
</tr>
<tr>
<td>mWatts/car tire pass</td>
<td>34.6</td>
<td>93.6</td>
</tr>
<tr>
<td>mWatts/truck tire pass</td>
<td>1,560</td>
<td>4,098</td>
</tr>
<tr>
<td>Watt-hrs from car tires/year/module</td>
<td>1.58</td>
<td>4.3</td>
</tr>
<tr>
<td>Watt-hrs from truck tires/year/module</td>
<td>90.08</td>
<td>236.65</td>
</tr>
<tr>
<td>Total Watt-hrs per year/module</td>
<td>9.66</td>
<td>240.95</td>
</tr>
</tbody>
</table>

References