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Piezoelectric Energy Harvesting from Traffic Induced Deformation of Pavements

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Abstract: In the last decade, the sensing technology and the concern of the robustness of the roadways have significantly grown. The limit of power source has become an impediment force of the research of sensing technology. Recently, energy harvesting is more proved as a promoting solution. It also provides a new source of clean and renewable energy that can help reduce negative environmental impacts while contributing to improve roadway mobility. In this work, four common energy harvesting approaches are compared and piezoelectric energy harvesting is proposed. It is known as a stable technology converting kinetic energy into electricity. The sinusoidal energy power output from the random external excitation would be rectified and stored by interfacial circuit. Lead Zirconate Titanate (PZT) is widely used in piezoelectric energy harvesting systems due to its high cost-effectiveness. This work presents a maneuver of powering the transportation infrastructural facilities and monitoring electronics using piezoelectric energy harvesting technology. Comparison of coupling configuration, material selection and testing methodologies are also presented.

Key words: *Energy harvesting; Pavement; Piezoelectricity; PZT; Smart transportation infrastructure.*

Introduction

Energy harvesting is a process converting ambient energy into electric energy. The four popular methods of energy harvesting are piezoelectric, thermoelectric, electromagnetic and photovoltaic. One challenge in the studies of micro- and small-scale electronics is the power supply. They cannot be simply powered by batteries due to their special application and limited sizes [1]. Logically, considering the energy consumption of the electronics of micro- and small-scale sensors [2], energy harvesting has received more attention.

Piezoelectric energy harvesting utilizes the effect of piezoelectricity which generates electric potential in response to applied stress along its poling direction. The potential is created by the displacement of the electric dipoles. Piezoelectricity is a reversible process. Applying electric field on piezoelectric material will cause deformation. Other than receiving kinetic energy, thermoelectricity effect generates voltage from temperature gradient. As same as piezoelectricity, thermoelectricity is also reversible. Photovoltaic energy harvesting has the most abundant energy source. Solar radiation can be converted into electric power using semiconductor material with photovoltaic effect. Solar cell panels are commonly used to capture the sunlight and generate direct current. The productivity of photovoltaic energy harvesting depends on the number of junctions the semiconductor material has. Other factors such as surface texture, antireflection coating and doping elements will slightly affect the productivity. Electromagnetic energy harvesting employs an electric conductor moving in a magnetic field to generate electricity in an electric field following Faraday's law.

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Smart Transportation Infrastructure Application

Nowadays, to improve the sustainability of the transportation infrastructure, a variety of sensors are installed in the transportation infrastructure to achieve various applications such as evaluating the structural health [1, 2], transportation data collection [3], and ambient condition monitoring [4]. Many researchers and engineers show great interest in powering these sensors or other micro-scale electronics [5]. Besides, powering lighting electronics like LED bulb has also been achieved [6]. Little application has been documented about powering ancillary facilities such as traffic light, signal board and etc. duToit et al. has performed a comparison between the energy outputs of solar, thermoelectric, and piezoelectric energy harvesting technology [7]. In Fig. 1, the power outputs of four energy harvesting methods are illustrated and compared based on the work of Voigt et al. [8]. Obviously, solar energy has the largest energy density. But it only can be reached under direct sunlight. The power density will be limited at low illumination conditions of a cloudy day or tunnel area, which is more valuable to the sensors and micro-scale electronics. Compared to the other three, piezoelectric energy harvesting can continuously provide power supply to the micro-scale electronics and transportation facilities under any condition. Therefore to power such devices, piezoelectric energy harvesting is more promising.

State of the Art of Piezoelectric Energy Harvesting

Recently, a considerable number of research has been done to improve the productivity of the piezoelectric energy harvesting system with different configurations. As a brittle material, the strain level of PZT should be limited. To withstand a higher degree of strain, Lee et al. has developed a Poly Vinylidene Fluoride (PVDF) film coated with poly (3,4-ethylenedioxy-thiophene) / poly (4-styrenesulfonate) [PEDOT/PSS] electrodes [9]. In 2002, Roundy et al. has proposed the use of vibration as an important power source

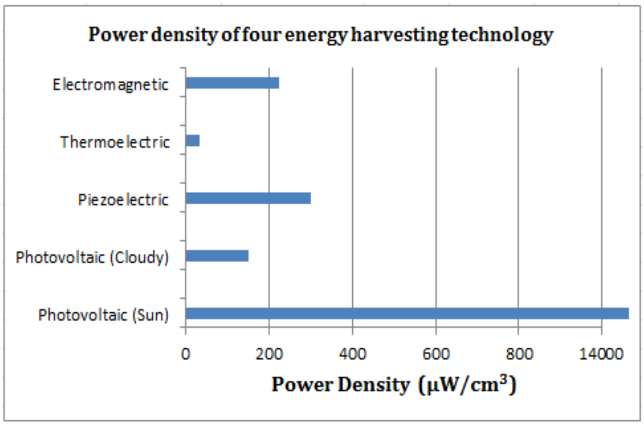

Fig. 1. The Comparison of the Output Power of Four Energy Harvesting Technology (Voigt et al, 8).

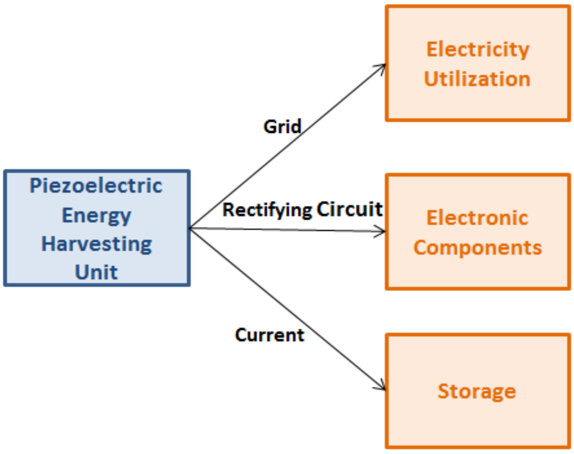

Fig. 2. The Potential Utilization of the Piezoelectric Energy Harvesting Power Output.

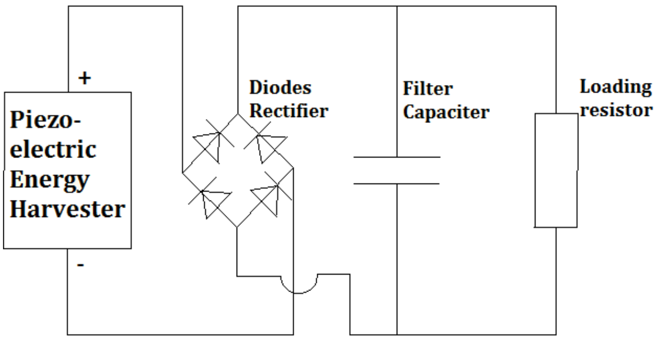

Fig. 3. The Layout of the Classic Power Output Optimizing Interfacial Circuit.

of piezoelectric energy harvesting [10]. Jeon et al. have designed a cantilever-type energy harvester using thin film PZT and 1μW has been generated from a 170μm × 260μm beam [11]. The power generating method was named as 31-mode by the author. A potential design utilizing 33-mode (pure compressing) has been introduced by duToit et al [12]. A review article with a wide coverage of energy harvesting using piezoelectric materials was published at 2007 [13]. The power output of 31-mode is maximized when the cantilever beam vibrates with a specific frequency or the resonant frequency. However, the output drops dramatically when the vibrating frequency deviates from the resonant frequency [14].

Power Output Rectifying

The extracted energy from piezoelectric energy harvesting can be utilized through various ways. It can be connected to the electric grid, to power small electronics or transportation facilities after being rectified, or be stored in a capacitor or a battery. Fig. 2 is a scheme of the potential utilization of the power output from energy harvesting.

The ultimate purpose of energy harvesting is to offer a usable power source from converting the ambient energy. Since the external excitation source is random mechanical vibration or deflection process, it has varying power output amplitudes and frequencies [14]. Such varying power output is not compatible with needs of micro-scale electronics. The varying voltage induced from the piezoelectric material requires rectification before being stored or used. The common solution to provide usable power from energy harvesting is adding interfacial circuits. Recently, many researchers have moved their focus to designing optimized circuit for energy harvesting systems. Ottman et al. have developed the classic optimizing interfacial circuit as shown in Fig. 3 [15]. It consists of a diode rectifier and a filter capacitor. They have proposed another energy harvesting interfacial circuit includes a step-down dc-to-dc converter [16]. The converter would regulate the electric energy flow to the target stable level. Guyomar et al have brought up the concept of interfacial circuit in their study with a switch connected to an inductor [17]. It was named as "Synchronized switch harvesting on inductor (SSHI)". It can significantly improve the conversion efficiency. This type of circuit requires an input signal to control the switch. Badel et al. have proposed two variations of the SSHI, Parallel SSHI (PSSHI) and Series SSHI (SSSHI) [18]. The voltage processing device is connected in parallel and series with the piezoelectric harvester respectively in PSSHI and SSSHI as shown in Fig. 4. The combination of the diode capacitor and loading resistor can be replaced by rechargeable battery. Roundy et al. has proposed a simple charge pump circuit which can also estimate the energy output per cycle [10]. In the work presented by Jeon et al., rectifier consisting of four diodes and a capacitor were used to rectify the power output [11]. It has been mentioned that the forward voltage drop of the diodes should be as small as possible to develop the largest possible dc current. Selecting the rectifier with low leakage current is important. Lefeuvre et al have brought up a concept that the interfacial circuit should have different modules with different functions [19]. Module 1 rectifies the varying voltage into usable energy source. Module 2 optimizes the power flow from the rectified power output from Module 1. An optional module 3 may increase the power output from the energy harvesting system under certain circumstances. Fig. 5 is a scheme of all three modules.

In-progress Project

In the United States, there are approximately 250 million registered vehicles. Significant energy of the traveling vehicles is wasted in deforming pavements. The deflection of the pavement enables

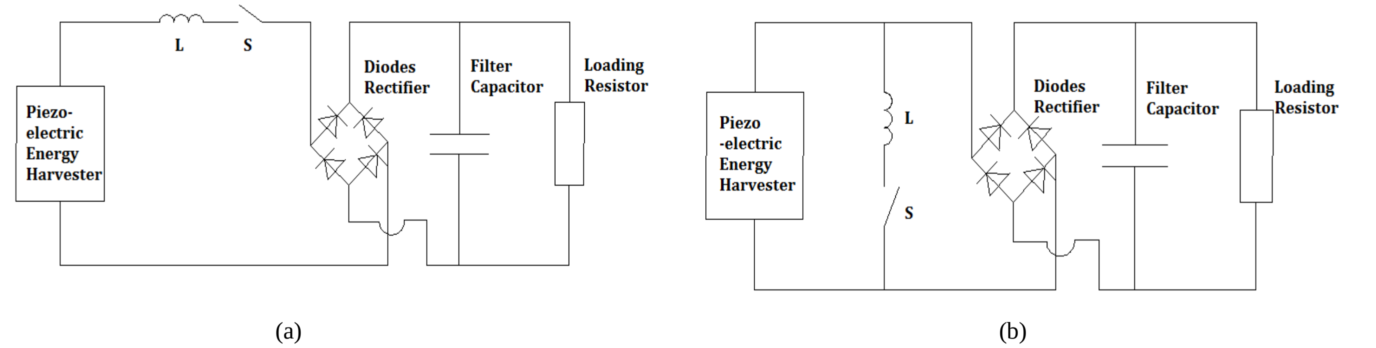

Fig. 4. The Layout of the SSSHI (a) and PSSHI (b) Interfacial Circuits.

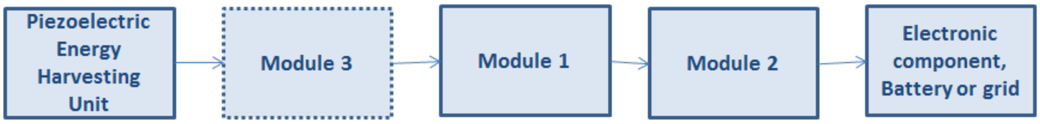

Fig. 5. The Scheme of the Interfacial Circuit for Energy Harvesting System.

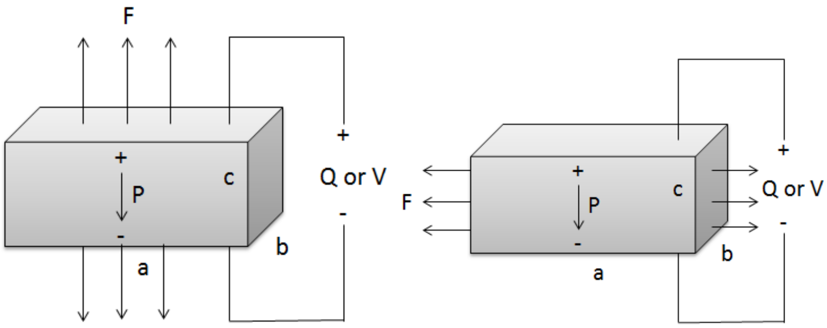

Fig.6. The Illustration of 33- (Left) and 31- (Right) Coupling Mode of Piezoelectric Energy Harvesting.

piezoelectric material to generate electricity. Thus it is possible to harvest wasted energy from deforming pavements.

Objectives

This research focuses on developing a piezoelectric-based energy harvesting system to collect wasted energy in deforming pavements. Considering the large number of vehicles, this technology will provide a new type of clean energy to supply powers for various applications. The objectives of the research include designing the energy harvesters for high energy productivity, packaging and installation methods for durability, and cost-benefit assessments to evaluate implementation potentials.

Coupling Modes of Piezoelectric Energy Harvesting

Two commonly known coupling modes of piezoelectricity are the 31-mode and the 33-mode. With 31-mode the piezoelectric material generates piezoelectric energy from transverse displacement. The piezoelectric material will be excited by the vertical deflection of the pavement and start vibration. During vibration, the excitation amplitude and the transverse displacement of the material will be maximized when the vibrating frequency equals its resonant frequency. The power output is maximized at the mean time. Different from the 31-mode, the power output of the system linearly increases with the deflection of the pavement with the 33-mode, or the stress along the poling direction of the material. These two coupling modes are illustrated in Fig. 6 based on the information provided in a review performed by Anton and Sodano [13]. Baker et al. [20] has concluded that with small level of force, energy harvesting system configured with 31-mode is more efficient. However, with a great level of force such as the stress induced by a vehicle on the pavement, 33-mode configuration is more efficient and durable. From Inman's work [21], the deflection that the passenger cars bring to the pavement can be expressed as:

$$y(t) = (0.01)sin\omega_b t \tag{1}$$

where

$$\omega_b = \mathrm{v}\left(\frac{\mathrm{km}}{\mathrm{h}}\right)\left(\frac{1}{0.006km}\right)\left(\frac{hour}{3600s}\right)\left(\frac{2\pi\, rad}{cycle}\right) = 0.2909\mathrm{v\ rad/s} \tag{2}$$

v represents the vehicle's velocity in km/h. From these two equations it can be seen that with 31-mode the vehicle's speed determines the excitation frequency and the power output. Since the power output is much lower at off-resonance condition and the vehicles' velocity is relatively random, the 33-mode is more suitable than 31-mode to this application.

Material Selection

Three widely-used piezoelectric materials are crystalline materials, piezoceramics and polymers. Piezoceramic has become a popular selection of many researchers and engineers due to its high performance. However, it is relatively more brittle than other piezoelectric materials. Lead-zirconate-titanate piezoceramic occupied most of the commercial market due to its high cost-effectiveness. It has many variations with different percentages of chemical compositions.

Besides the configuration, the material property is another important factor to conversion efficiency. Many works have pointed out that the piezoelectric charge constant (effective piezoelectric strain constant), d, and the piezoelectric voltage constant, g, are governing the magnitude of transduction [13, 22]. In 33-mode, they are expressed as d_{33} and g_{33}. From the testing results of Erturk's work [23], it can be concluded that with higher piezoelectric coefficient (d and g) the harvesting system has better power output. It's also proved that smaller elastic compliance also contributes to good performance. C.D. Richards found that the quality factor, Q, is important for optimizing the energy harvesting system [24]. With lower quality factor, the piezoelectric material has less damping leading to the heat transfer energy loss. By using a high-Q material, the system loses less energy and has more available energy to capture. Thus great quality factors are necessary for building an efficient energy harvesting system.

Evaluation of the System

Both laboratory experiments and field tests are performed to evaluate the productivity of the proposed energy harvesting system. The testing results will help to optimize the design of the harvesting system. The fatigue resistance and durability of the harvesting systems are also evaluated. Model Mobile Load Simulator (MMLS) is used to perform the laboratory experiments. MMLS is a pavement testing frame with multiple tires imitating the tire motion of motor vehicles. It could apply cyclic loading on the energy harvesting system. The velocity and the applied load of the tires are adjustable from 0-24 km/h (0-15 MPH) and 0-295kg (0-650 lb) for each tire. Fig. 7 illustrated the MMLS frame. The field test is performed at a weigh station with real and controlled traffic. There are about 3300 trucks passing the scale system every day. As known, the energy loss on flexible (asphalt) and rigid (cement concrete) pavement are different. The productivity of the proposed system will be tested with both types of pavement. The field testing on national highways will be eventually performed. In both laboratory experiments and field tests the power output with different loading resistance, capacitor charging time and power density will be collected and analyzed. Material Testing System (MTS) frame will be used to measure the mechanical properties as fatigue resistance and compressive strength of the candidate piezoelectric material. Stochastic finite element modeling will be conducted to determine the overall cost-effectiveness with the field testing results.

Power Rectifying and Storage

Fig. 7. Model Mobile Lading Simulator laboratory testing frame.

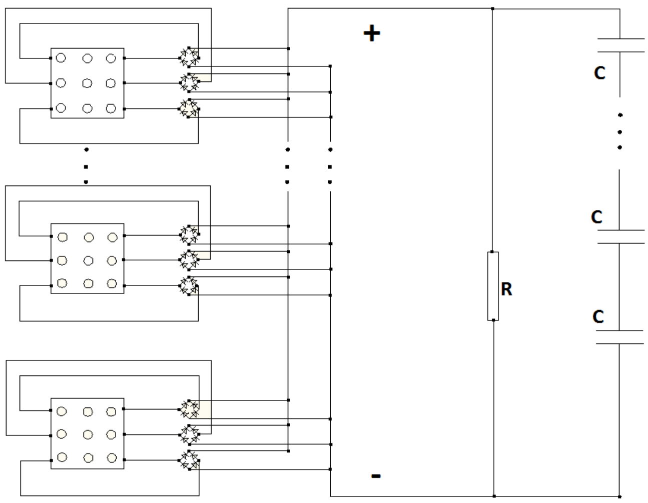

Fig. 8. The Layout of the Candidate Interfacial Circuit.

Since the excitation from the travelling vehicle is quite random, the power output from the harvester will be random as well. A rectifying interfacial circuit is required to convert the power output into usable energy. For such random excitation, the synchronized switch is not compatible with the energy harvesting system. Bridge rectifier will be used as the module 1 of the circuit to convert all the negative voltage into positive. The combination of the loading resistor and super capacitor will serve as the module 2. Adding a certain loading resistor will maximize the voltage on the charging capacitor or battery to optimize the power from the energy harvester. Another critical issue that has rarely been noticed of the piezoelectric energy harvesting is the voltage phase interference. Since the external excitation from the vehicle's tire on each piezoelectric material is not synchronized, the materials may produce opposite voltage. The extracted energy might be weakened when the opposite voltage interfere with (or even cancel out) each other. To optimize the power output under this condition, diode rectifier will be added on each part of the piezoelectric material along the vehicle's traveling direction. The layout is shown in Fig. 8. Another difficulty may be encountered is determining the loading resistance of the circuit which depends on the equivalent resistance of the entire energy harvesting system. The resistance of the piezoelectric material varies with the frequency of the external excitation. The resistance decreases as the frequency increases. Thus the equivalent resistance will be different when different loadings are applied. The resistor and number of the capacitor will be adjusted for the specific loading condition.

Summary

This paper presents the general philosophy of designing and evaluating energy harvesting systems using piezoelectric materials from deforming pavements. Piezoelectric energy harvesting provides stable and long lasting clean power output. The energy density is only lower than photovoltaic energy harvesting. According to the investigated energy need, it's suitable for powering transportation infrastructural facilities like sensors, small- and micro- scale health monitoring electronics.

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