Energy Harvesting using Piezoelectric Materials

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ABSTRACT

With the decrease in energy consumption of portable electronic devices, the concept of harvesting renewable energy in human surrounding arouses a renewed interest. This technical paper focusses on one such advanced method of energy harvesting using piezoelectric material.

Piezoelectric materials can be used as mechanisms to transfer mechanical energy, usually ambient vibration, into electrical energy that can be stored and used to power other devices. A piezoelectric substance is one that produces an electric charge when a mechanical stress is applied. Conversely, a mechanical deformation is produced when an electric field is applied. Piezo-film can generate enough electrical density that can be stored in a rechargeable battery for later use. Piezoelectric materials have a vast application in real fields. Some of the latest applications are mentioned below.

Currently, there is a need to utilize alternative forms of energy at passenger terminals like airports and railways across the world. Cleaner, more sustainable forms of electrical power are needed in order to keep costs lower, to maintain positive and productive relationships with neighbours and to insure a healthier environment for future generations. The use of piezoelectric devices installed in terminals will enable the capturing of kinetic energy from foot traffic. This energy can then be used to offset some of the power coming from the main grid. Such a source of power can then be used to operate lighting systems.

The increasing prevalence and portability of compact, low power electronics requires reliable power sources. Compared to batteries, ambient energy harvesting devices show much potential as power sources.A piezoelectric generator can be developed that harvests mechanical vibrations energy available on a bicycle. The electrical energy thus produced can be used to power devices aboard the bike, or other portable devices that the cyclist uses. Electrical energy can also be generated from traffic vibrations (vibrations in the road surface) using piezoelectric material.

Keywords

Piezoelectric material, foot traffic, mechanical energy ,electrical energy, piezoelectricity, energy harvesting, piezo harvester.

1. INTRODUCTION

In the current era, which is witnessing a skyrocketing of energy costs and an exponential decrease in the supplies of fossil fuels, there arises a need to develop methods for judicious use of energy which lay emphasis on protecting the environment as well. One of the novel ways to accomplish this is through energy harvesting. Energy harvesting, or energy scavenging, is a process that captures small amounts of energy that would otherwise be lost as heat, light, sound, vibration or movement. It uses this captured energy to improve efficiency and to enable new technology, like wireless sensor networks. Energy harvesting also has the potential to replace batteries for small, low power electronic devices.

Piezoelectric materials can be used as a means of transforming ambient vibrations into electrical energy that can then be stored and used to power other devices. With the recent surge of microscale devices, piezoelectric power generation can provide a convenient alternative to traditional power sources used to operate certain types of sensors/actuators, telemetry, and MEMS devices. The advances have allowed numerous doors to open for power harvesting systems in practical real-world applications. Much of the research into power harvesting has focused on methods of accumulating the energy until a sufficient amount is present, allowing the intended electronics to be powered.

In this paper we review and detail some of the topics in power harvesting using piezoelectricity stating its fundamental working. We have cited implementation of piezoelectric materials in transportation hubs like airports, bus terminals, railway stations etc. as well as extracting energy from shoes. They also find their application in lighting systems which are powered by electricity generated through foot traffic. We propose to implement the same concept of energy harvesting in our university from the kinetic energy of feet and vehicles for the lighting of streetlamps within the campus.

2. FUNDAMENTALS OF PIEZOELECTRICITY

A piezoelectric substance is one that produces an electric charge when a mechanical stress is applied (the substance is squeezed or stretched).Conversely, a mechanical deformation (the substance shrinks or expands) is produced when an electric field is applied. This effect is formed in crystals that have no centre of symmetry. In order to produce the piezoelectric effect, the polycrystal is heated under the application of a strong electric field. The heat allows the molecules to move more freely and the electric field forces all of the dipoles in the crystal to line up and face in nearly the same direction (Figure 1).

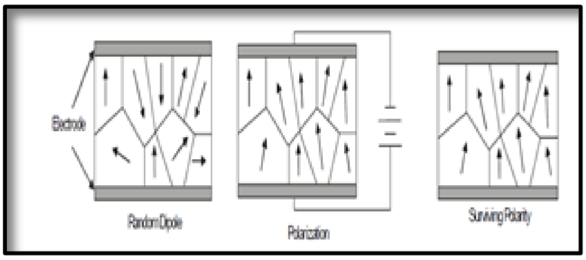

Fig 1: Polarization of ceramic material to generate piezoelectric effect.

The piezoelectric effect can now be observed in the crystal. Figure 2 illustrates the piezoelectric effect. Figure 2a shows the piezoelectric material without a stress or charge. If the material is compressed, then a voltage of the same polarity as the poling voltage will appear between the electrodes (b). If stretched, a voltage of opposite polarity will appear (c). Conversely, if a voltage is applied the material will deform. A voltage with the opposite polarity as the poling voltage will cause the material to expand, (d), and a voltage with the same polarity will cause the material to compress (e). If an AC signal is applied then the material will vibrate at the same frequency as the signal (f).

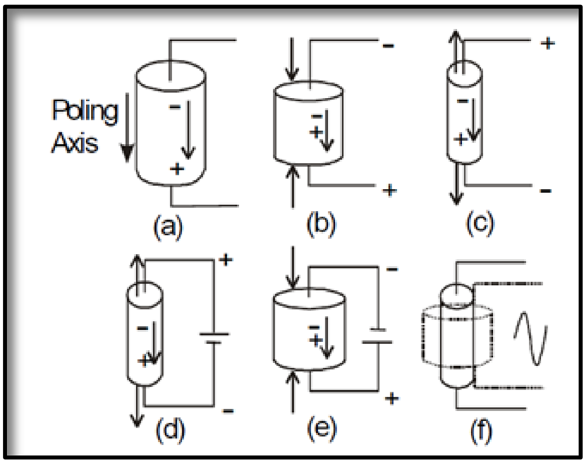

Fig 2: Example of piezoelectric effect

3. EQUIVALENT CIRCUIT OF A PIEZOELECTRIC HARVESTER

An input vibration applied on to a piezoelectric material as shown in Figure 3 causes mechanical strain to develop in the device which is converted to electrical charge.[8] Lead-zirconate-titanate (PZT) is a commonly used piezoelectric material for power generation. The equivalent circuit of the piezoelectric harvester can be represented as a mechanical spring mass system coupled to an electrical domain as shown in Figure 3. Here, L_M represents the mechanical mass, C_M the mechanical stiffness and R_M takes into account the mechanical losses. The mechanical domain is coupled to the electrical domain through a transformer that converts strain to current. On the electrical side, Cp represents the plate capacitance of the piezoelectric material. At or close to resonance, the whole circuit can be transformed to the electrical domain, where the piezoelectric element when excited by sinusoidal vibrations can be modelled as a sinusoidal current source in parallel with a capacitance Cp and resistance Rp. One of the challenges in a power generator of this type is the design and construction of an efficient power conversion circuit to harvest the energy from the PZT membrane. Another unique characteristic of this power source is that it outputs relatively low output voltages for the low levels of input vibration typically encountered in ambient conditions. This low output voltage makes it challenging to develop rectifier circuits that are efficient since many diode rectifiers require nonzero turn-on voltages to operate.

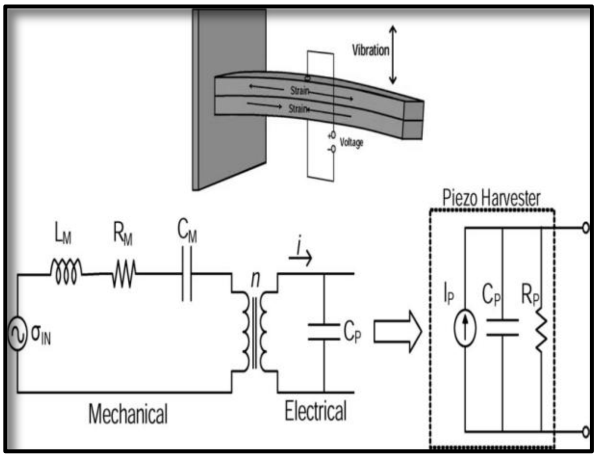

Fig 3: Equivalent circuit of piezoelectric harvester.

4. ENERGY HARVESTING PIEZOELECTRIC CIRCUIT

A piezoelectric harvester is usually represented electrically as a current source in parallel with a capacitor and resistor. The current source provides current proportional to the input vibration amplitude. For the sake of the following analysis, the input vibrations are assumed to be sinusoidal in nature and hence the current is represented as $i_p=I_p\sin w_pt$, where $w_p=2\pi f_p$ and f_p is the frequency with which the piezoelectric harvester is excited. The power output by the piezoelectric harvester is not in a form which is directly usable by load circuits such as micro-controllers, radios etc. which the harvester powers. The voltage and current output by the harvester needs to be conditioned and converted to a form usable by the loadcircuits. The power conditioning and converting circuits should also be able to extract the maximum power available out of the piezoelectric energy harvester. Commonly used analog and digital circuits require a regulated supply voltage to operate from. Since the piezoelectric harvester outputs a sinusoidal current, it first needs to be rectified before it can be used to power circuits.

We use a circuit using full wave bridge rectifier. The capacitor $_{Cr}$ at the output of the rectifier is assumed to be large comparedto C_p and hence holds the voltage at the output of the rectifier $V_r$essentially constant on a cycle-to-cycle basis. The non-idealities of the diodes V_d is represented using a single parameter which is the voltage drop across the diode when current from the piezoelectric harvester flows through it. Everyhalf-cycle of the input current waveform can be split into 2 regions. For the full-bridge rectifier, in the interval between $t=t_{on}$ to $t=_{toff}$and , the piezoelectric current $i_p$flows into C_p to charge or discharge it. In this interval, all the diodes are reverse biased and no current flows into the output capacitor C_r.

This condition continues till the voltage across the capacitor C_p is equal to V_r+ $2V_d$ in magnitude. When this happens, one set of diodes turn ON and the current starts flowing into the output. This interval lasts till the current i_p changes direction. At low values of V_r, most of the charge available from the harvester flows into the output but the output voltage is low.

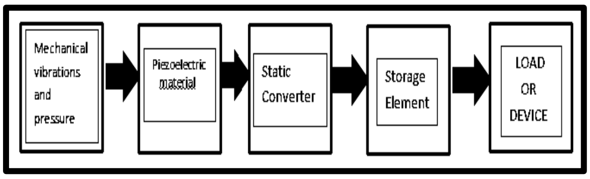

Fig 4: General block diagram

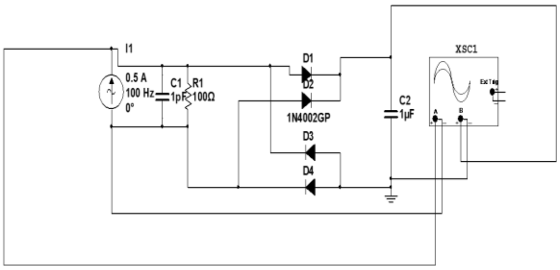

Fig 5: Energy harvesting circuit

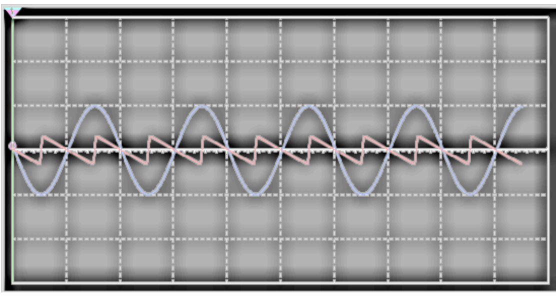

Fig 6: Simulation result

5. APPLICATION IN THE PRESENT SCENARIO :-

5.1. Energy harvesting in Transport Terminals:

Airportsand railways are vital transportation hubs that will greatly benefit from new energy technologies. Lower costs along with cleaner day-to-day operations from green forms of energy will allow airports to operate more efficiently and effectively. One such idea that will fit well in such setting is the capturing of kinetic energy from passenger foot traffic. This novel idea is not only clean but it is also renewable.
Using the floor space in airport terminals[6] allows for a large source of otherwise wasted energy to be captured and utilized as an alternative form of energy for the lighting systems within airports. Placing piezoelectric devices that are used to capture energy from foot traffic underneath airport terminals can effectively capture electrical energy and send it back to the power grid through inverters, which are needed in order to convert the DC power, from the piezoelectric, into AC power used by terminal lighting systems.
Other onboard example is the East Japan Railway Company (JR East).It conducted a demonstration experiment from January 19 to March 7, 2008, at Yaesu North Gate, Tokyo Station, on a new power-generating floor. Installed at the ticket gate area, it generates electricity from the vibrations created by passengers walking through the ticket gates.
The power-generating floor is embedded with piezoelectric elements, which are 35 millimeters in diameter, and disc-shaped components used for loudspeakers. It uses 600 of these elements per square meter. While the loudspeaker creates sound by converting electric signals to vibrations, the floor adopts the reverse mechanism that produces electricity by harnessing the vibrational power generated from passengers' steps. It is being developed by JR East with the aim of making stations more environmentally friendly and energy efficient (Japan for Sustainability, 2008).
The piezo devices, due to their small thin shape, could be placed underneath floor tiles or carpet with few complications. In order to harness the power a capacitor could be used to store the electricity like in the train stations or inverters. The power could then be routed directly to specific electrical devices such as lights or billboards or it could be sent to the main power grid in order to supplement the main power supply. There are many installation options and applications of these devices; the specific type of installation will depend upon the intended use of the piezo devices within the terminals. Experimentation with different areas and by observing locations of high foot traffic in such terminals are important in determining the optimal locations for capturing kinetic energy from walking.

5.2. Energy harvesters in shoes (Moonie Harvesters)

The pressure exerted by a person while walking can converted into electrical energy to power portable devices. This is done by embedding a moonieharvester[12]into a shoe. The "Moonie,' is a metal ceramic composite transducer that has been developed by sandwiching a poled lead zirconatetitanate (PZT) ceramic between two specially designed metal end caps.The operating principle of the moonie harvester is also shown in Figure 3. The structure serves as an amplifier for the input force which, in this case, is the weight of the person wearing the shoe. The force on the heel presses the curved plates which in turn expand the piezoelectric disk sandwiched in between the steel plates. The stress is evenly distributed on the disk as opposed to beam structures where the majority of the stress is located at the fixed end of the beam.

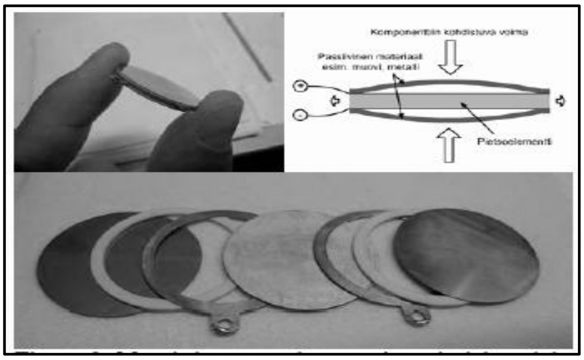

Fig 7:Moonie harvester

The energy output of one step was recorded as 81 µJwhich translates to 162 µWfor two shoes when walking 2 steps per second. The power density at 1 step / s frequency was measured as 56 µW/cm3. The size of the piezo element was 17.5 mm in diameter and the thickness was 500 µm. The material used was PZT-5H.

5.3. Established Projects

The energy harvested by the **Pavegen**[10]tile can immediately power off-grid applications such as pedestrian lighting, way-finding solutions and advertising signage or be stored in an on-board battery in the unit.The top surface of the flooring unit is made from 100% recycled rubber and the base of the slab is constructed from over 80% recycled materials. The system is designed can be simply retrofitted in place of existing flooring systems as well specified for new developments.

Innowattech[9]has developed a new alternative energy system that harvests mechanical energy imparted to roadways, railways and runways from passing vehicles, trains and pedestrian traffic and converts it into green electricity. The system, based on a new breed of piezoelectric generators, harvests energy that ordinarily goes to waste and can be installed without changing the habitat.

6. PROPOSALS FOR ADOPTING E.H. SYSTEMS WITHIN M.T.T. CAMPUS

1. Harnessing energy from the foot traffic in the M.I.T. Food Court: Thin, piezoelectric pads can be installed underneath the floor material. The pressure placed upon the pads as people walk will generate the needed force to create an electrical charge, which can then be used for the lighting system.High levels of foot traffic inside food court would allow for the potential of high energy acquisition from a renewable, clean resource. This adopted idea will provide for a safe, clean and renewable supplemental source of power.

2. Use of piezoelectric materials on roads near the entrances: Energy can be harnessed from the road traffic at the entrances of the campus. This can be implemented by installing piezoelectric pads below the speed breakers which will generate electrical energy as vehicles apply pressure on them while moving over them. Power could then be routed directly to specific electrical devices such as lights, or inverters could be installed to convert the DC power from the piezo devices into AC power used in the street lighting system.

3. Energy harnessing from foot traffic on footpaths (crowd farming): The footpath can be reconstructed in such a way that piezoelectric pads can be installed so as to capture energy from the foot traffic. The energy obtained can be send to the main power grid of the campus from where it can be redirected to satisfy power needs elsewhere in the campus such as light for street lights, etc. The data collected from electricity maintenance department of MIT campus, showed that the power consumed by a street light of 70 watt is 25.2kwh per month and that by one of 250 watt is 90kwh per month approximately when it is operated for 12 hours. Hence we can make use of this technology to generate the green electricity.

6.1. Technology to generate piezoelectricityusing vehicular pressure:

The energy consumed by the vehicle (sourced in the fuel combustion) utilized for a variety of applications; one of them is to overcome rolling resistance. A typical asphalt road can be described as a visco-elastro-plastic material, with elasticity being its dominant material characteristic. When a vehicle passes over a road, the road deflects vertically. This deflection is released as thermal energy. For a road with embedded piezoelectric generators, part of the energy the vehicle expands on roads deformation is transformed into electric energy (via direct piezoelectric effect) instead of being wasted as thermal energy.

The mechanical energy is derived from the compression stress created during the vehicles' travel on road. Only part of the energy from the fuel combustion of the vehicle is used for moving the car along the road or run useful accessories, such as air conditioning. The rest of the energy is lost to engine inefficiencies.

The energy expended on the vehicle's movement is mainly used to overcome rolling resistance, resistance occurring when the wheel is moving forward on the road surface. In addition to the energy used to move the wheel forward (in the horizontal direction), part of the fuel combustion is wasted on creating a deformation in the asphalt, which is basically the product of the loaded wheel's influence on the road surface.

A typical asphalt road can be described as a visco-elasto-plastic material, with elasticity being its dominant material characteristic. When a vehicle passes over a road, the road deflects vertically. The deflection is proportional to thevehicle weight.The only source for harvesting electric energy is this part of mechanical energy related to the asphalt vertical deformation, which is a percentage from the total energy of the vehicle.

It is known that the vertical load of the vehicle's wheels yields compression stress, diminishing with depth. The generators are embedded at a depth of about 5 cm; the area where thecompression stress is maximal and hence the piezo effect can be maximised.

The external load results in the deformation in both the asphalt layer covering the generators and the generators, similar to the typical deformation in a piezoelectric column loaded underaxialload.

The deformation of the generator and the shortening of the piezoelectric columns embedded in the generators, generate charges on the piezoelectric columns that are the source for the electricity.

The energy needed to deform the road is a function of various parameters such as: the surface quality of the road, asphalt type,temperature.

Moreover, the stiffness of the piezoelectric generators is function of the piezoelectric material; thus, the weighted Young modulus of the generator is higher than that of the asphalt. When piezoelectric generators are embedded under the asphalt, the total vertical deflection of the road is decreased due to the higher Young’s modulus of the generator. It does not change the MPG of the vehicle.

7. CONCLUSION

In this paper a theoretical model for energy harvesting system using piezoelectric materials have been presented. It is evident that harnessing energy through piezoelectric materials provider a cleaner way of powering lighting systems and other equipment. It is a new approach to lead the world into implementing greener technologies that are aimed at protecting the environment. Piezoelectric energy harvesting systems are a onetime instalment and they require very less maintenance, making them cost efficient. One of the limitations of this technology is that its implementation is not feasible in sparsely populated areas as the foot traffic is very low in such areas.

Further experimentation has to be carried out for its implementation on a larger scale, with an efficient interface circuit at a low cost in universities.

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