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A STUDY OF VIBRATION ENERGY HARVESTER

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ABSTRACT

This paper is a comparative study of energy harvesting technology based on mechanical vibration. Recently, the study of the conversion of vibrational energy into electrical power has become a major field of research. Recent advances on ultra-low power portable electronic devices for low cost power supply are using conventional battery. However problems can occur when batteries die off because of their finite lifespan. In portable electronics, battery needs to be replaced when it dies replacement of the battery can become a tedious task because we do not know when the battery dies. People searched for more efficient portable power sources for advanced electronic devices. The critical long-term solution should therefore be independently of the limited energy available during the functioning or operation of such devices. Mechanical Energy Harvesting Systems may enable wireless and portable electronic devices to operate because they carry their own power supply that completely self-powered. Various types of vibration devices, piezoelectric materials and mathematical modeling of vibrational energy harvestings are summarized. This paper will investigates some of the research that has been performed in the area of vibration energy harvesting.

Keywords: energy harvesting, vibration, mechanical energy, electrical energy, PZT, frequency.

INTRODUCTION

Nowadays, the field of vibration energy harvesting has fascinated significant attention for low power and portable energy sources due to the development and mass consumption of portable electronic device. This energy harvesting has experienced significant growth over the past few years due to the ever-increasing desire to produce portable and wireless electronic with extended lifetime (Antaki *et al.* 1995). The use of batteries not only leads to their costly replacement, especially for sensors (Mirzaeitar *et al.* 2008) at inaccessible locations, but also causes pollution to the environment. Besides, the batteries also place limitation on the miniaturization of micro or nano-electromechanical systems. With the improvements in integrated circuits, the size and power consumption of current electronics has dramatically decreased.

Therefore, the technology of energy harvesting from ambient natural environmental has received a great interests and has been investigated by many research, especially when vibration energy harvesting has been a topic of discussion and research since three decades. With the ever increasing and demanding energy needs, unearthing and exploiting more and more energy sources has become a need of the day. Energy harvesting (Arms *et al.* 2005; Dwari *et al.* 2010; Fang *et al.* 2009) is the process by which energy is derived from external sources and utilized to drive the machines directly, or the energy is captured and stored for future use.

Different energy sources existing in the environment around a system, such as solar, wind, tidal energy utilizing geothermal energy and other mechanical vibration, can be the options for energy harvesting (Dhukara *et al.* 2013; Guigon *et al.* 2008a). Among them, pervasive vibration sources are suitable for small-scale power generation of low-power electronics and thus have attracted more research attention. The energy harvesting by converting waste vibration energy into useful electrical energy has become a promising solution to replace or to charge the batteries which are commonly used in these applications such as monitoring sensors or wireless communication devices (Beeby *et al.* 2006; Barrero *et al.* 2010; Penamalli *et al.* 2011). The advantages of energy harvesting to these devices is not only limited to reducing the cost of batteries and maintenance, but is it also useful to reduce the energy consumption and its impact on the environment (Stanto *et al.* 2010).

Vibration energy harvesting (Tang *et al.* 2011; Burrow *et al.* 2008) studies have activated adopting the perspective that linear assumptions and stationary excitation characteristics used in earlier analyses and designs are insufficient for the application of harvesters in many realistic environments. The principal challenge is that linear oscillators, well suited for stationary and narrow band excitation near their natural frequencies, are less efficient when the ambient vibration energy is distributed over a wide spectrum, may change in spectral density over time, and is dominant at very low frequencies.

The need for power harvesting devices (Chalasani *et al.* 2008; Donelan *et al.* 2008) is caused by the use of batteries as power supplies for these wireless electronics. As the battery has a finite lifespan, recharging needs to be done once discharged. Extended life of electronic devices is required; it also has more benefits in systems with limited availability, such as those used in monitoring a machine or an instrument in a manufacturing plant used to organize a chemical process in a harmful environment. Charging of batteries (Phipps *et al.* 2011; Hann *et al.* 1999) in order to provide energy to the electronic devices in the applications such as borders or hilly regions is a tedious job to do. So, the objective of this paper present a review of vibration energy harvesting mechanism integrating effects of piezoelectric (Gonzalez *et al.* 2002), electromagnetic, or electrostatic and investigated its characteristics as well.

OVERVIEW OF ENERGY SOURCES

The growth of advances technologies of low power electronics such vibration energy harvesting (VEH) (Wickenheiser *et al.* 2010), a kind of clean, saving and protecting the natural environment and renewable energy scavenging has gradually gained massive attention from worldwide researchers in the past decade for its essential potential applications in areas of self-powered wireless sensor networks (Paradiso *et al.* 2005; Meninger *et al.* 2001), autonomous lower power microsystems, distributed computing and portable power sources, etc., to replace or replenish traditional power sources, such as battery, etc. Even, high energy density batteries have been design but the amount of energy accessible in the batteries is not only limited but also low, which limits the lifespan of the systems.

There are many vibration energy harvesters that have been demonstrated in the literature (Choi *et al.* 2009), such as, Beeby *et al.* (2007) developed a miniscale electromagnetic energy harvester prototype that consists of a coil and a silicon wafer cantilever beam, with four pole magnets as its proof mass. The harvester was able to produce considerably high power over its size. Meanwhile, earlier Roundy (Roundy *et al.* 2003; Roundy *et al.* 2004) developed a miniscale piezoelectric energy harvester (Han *et al.* 2004) that have a similar structure to what have been demonstrated by S. Beeby. The harvester is used piezoelectric instead of silicon wafer as the cantilever beam, and tungsten alloy as the proof mass instead of the magnets. If the harvesting process of energy (Collins *et al.* 2006; Eichhorn *et al.* 2010), such as solar or wind is well done, it can be said that the harvesting energy from vibration is still in the beginning. Such as, taking into concern that the vibrations and movements which create vibrations are always present in the environment, this dimension of the renewable energy can be a main factor of interest for the future. So, this main propose of this research is studied in the harvest of the energy from vibrations (Elfrink *et al.* 2009; Erturk *et al.* 2010).

Sodano, Inman, & Park, (2004), suggested method alters mechanical energy into electrical energy by spraining a piezoelectric material. Strain or deformation of a piezoelectric material causes charge separation across the device, producing an electric field and consequently a voltage drop proportional to the stress applied. The piezoelectric materials (Hollkamp *et al.* 1994) that exist naturally as quartz were not interesting properties for the production of electricity (Rome *et al.* 2005), however artificial piezoelectric materials such as PZT (Lead Zirconate Titanate) present advantageous characteristics (Shen *et al.* 2008). Piezoelectric materials belong to a larger class of called ferroelectrics. The oscillating system is typically a cantilever beam structure with a mass at the unattached end of the lever, which provides higher strain for a given input force (Roundy & Wright, 2004).

One of the defining traits of a ferroelectric material is that the molecular structure is oriented such that the material exhibits a local charge separation, known as an electric dipole. Throughout the artificial piezoelectric material composition the electric dipoles are orientated randomly, but when a very strong electric field is applied, the electric dipoles reorient themselves relative to the electric field; this process is termed as poling. Once the electric field is extinguished, the dipoles maintain their orientation and the material is then said to be poled. After the poling process is completed, the material will exhibit the piezoelectric effect. The voltage designed form varies with time and strain, successfully producing an irregular AC signal on the average. Piezoelectric energy transformation harvests relatively higher voltage and power density levels than the electromagnetic system (Huang *et al.* 2011; Wang *et al.* 2013). Furthermore, piezoelectricity has the capability of some elements, such as crystals and some types of ceramics, to produce an electric prospective from a mechanical stress.

Carlos *et al.* (2013) stated that energy harvesting generate from the sea motion, which by using low cost disk piezoelectric element. These piezoelectric components together with a horizontal balance like physical pendulum, create an electrical power generator that harvests the mechanical energy bought by the sea movements preferably from the heave and pitch motion that the sea waves (Cargo *et al.* 2011; Drew *et al.* 2009; Xu *et al.* 2011) induce in a moored –floating body as might be a buoy. The physical design of the mechanical to electrical energy converter is the main point of this system operated, and many ideas listed to create a free ball movement which impacts the disk piezoelectric. The stator is fixed in a cage with two PZT-4 piezoelectric disks, which received impacts from the lead balls every time the cage is destabilized. The higher level of sea motion can produce great amounts of electrical energy if the system is designed with the suitable materials purpose to function well under non-sunny condition, to complement a solar panel based system application, to provide energy during the night and cloudy days, where the sea motion is increased. The system can be applied in mediums other that the sea, where energy from kinetic movements can be harvested or other moving electronics devices.

Minazara *et al.* (2014) developed the vibrations energy harvesting principle using piezoelectric materials into designing piezoelectric generator and installed it on a bicycle handlebar to supply portable electrical energy. The advanced a piezoelectric generator that harvests mechanical vibrations energy available on a bicycle. Based on the observations, this experiments that have conducted have shown that the few mW that produced by the piezoelectric generator is able to power bike LED-lamp. A static converter transforms the electrical energy in a suitable form to the targeted portable application. Values of generating electrical power are reported and commented. The conversion chain starts with a mechanical energy source: bike. Bike vibrations are converted into electricity via piezoelectric element. Embarked piezoelectric transducer, which is an electromechanical converter, undergoes mechanical vibrations therefore produce electricity. The electricity produced is thereafter formatted by a static converter before supplying a storage system or the load (electrical device). The advantages of this vibration energy harvesting principle into the piezoelectric generator adapted to the identified natural mode of vibration of the bicycle (Zhou *et al.* 2011; Zuo *et al.* 2011; Grouthier *et al.* 2013).

Soon (2010), described the electromagnetic generator with repulsively stacked magnets for harvesting energy from traffic induced low frequency bridge vibrations. The electromechanical coupling model is validated from magnet falling tests and shown to be an effective model for evaluating the power performance of electromagnetic energy harvesters. Numerical simulations have been conducted to show the feasibility of the prototype energy harvesting device and its ability to improve the multilayer repulsively stacked magnetic (Ebrahimi *et al.* 2008) of the energy harvesting device into power production applications. Further fine frequency tuning to the dominant frequency of the target bridge and lowering the structural damping (Grouthier *et al.* 2013; Mathers *et al.* 2015). In order to produce more advance an electromagnetic coupling in limited space, array is a special design with the arrangement of permanent magnets that doubles the magnetic field on one side of the array while purpose cancelling the field to near zero on the other side. The electromagnetic vibration energy harvester reported here is only, with resonant frequency of 44.9Hz and ability to generate an average power of over 120 μW and 4mm thick, which makes it one of the thinnest electromagnetic energy harvesters among existing non-MEMS devices (Saadon *et al*. 2011).

Robert & Radu (2011) proposed that some aspects about the operation and design of a harvesting generator of electricity from ambient vibration by electromagnetic induction method. Harvesting generator is developed to work at high value of frequency or low frequencies, especially close to ambient vibration (Scruggs *et al.* 2007; Scruggs *et al.* 2012). The effective principle consists to move a magnetic component inside a coil. Mobile magnetic component has in its structure rare earth permanent magnets, NdFeB. Currently they are the best performing, due to high energy density which retains the properties for a long period. At the outside of the enclosure which houses the magnets, it is a coil with two windings connected in phase opposition. These magnetic fluids also play role act as the common materials due to have collective performances of liquids. The magnetic fluids also perform as a ring around the mobile magnets with existed of metal particle in its composition and as their friction with the housing of the generator is reduced.

Barker *et al.* (2010), described that the high temperature energy harvester, incorporating silicon carbide electronics and a PZT energy harvester can operate at 300 Celsius. The system comprises of a PZT piezoelectric energy harvester with silicon carbide Schottky diode full wave rectifier, which can rectify the AC supplier by the piezoelectric harvester at higher temperatures than conventional silicon components. In the case of vibration energy harvesting, this can be dramatically increased output voltage from the device. At resonance, the peak tip displacement of the bi-morph will be much greater and so will significantly increase the stress in the piezoelectric layers (Anton *et al.* 2007). The resonance frequency of the device decreases with temperature. The experiment result shows that although the peak output voltage from the piezoelectric energy harvester decreases at elevated temperature, it is still capable of producing a usable voltage. However, as the temperature increases the voltage drop of the SiC schottky diode decreases, same as 300 Celsius voltage drop of a single diode of 0.1V. This decreasing in voltage drop means the system operates at elevated temperatures and produce rectified output. This output can be used to power a high temperature communications or sensor system to replace batteries, in order to extend periods of time when coupled with high temperature capacitive storage element, as such this is a first step to developing a high temperature vibration based energy harvesting system (Barker *et al.* 2010).

The potential of harvesting energy from human activity has been reviewed by some researchers (Starner and Paradiso 2004; Mathers *et al.* 2015), there are many parts of the human body contains a huge amount of energy. Such as, walking, breathing, blood pressure, finger motion and so on. It should be noted that most of them are on the small scale of power output, except for energy harvester from walking. The kinetic energy from human movement can be harvested and converted into electrical energy. The electrical energy produced can be used to power other wearable electronics. Energy harvester in shoes based on either pressure of human body on the shoe sole or kicking force during walking (Shenck *et al.* 2001; Nathan *et al.* 2001).

Kymissis *et al.* (1998) studied energy harvester mounted on sneakers that generated electrical energy from pressure on the shoe sole. The output power of their type of energy harvester was reported. The first energy harvesters had multilayer laminates of PVDF, the second one contained a PZT unimorph and the third one was a rotary electromagnetic generator. The PVDF and PZT element mounted between the removable insole and rubble sole. The PVDF stack was in the front of the shoe while the PZT unimorph was at the heel.

Given that a human body is considered to be a source of several vibrations, various approaches for harvesting the vibration energy that involves the transform of the vibration energy produced by the human body to electrical energy have been established. An electromagnetic energy harvester for vibrations generated by the human body is proposed. The suggested device was fabricated without any winding wires by using planar

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coils. The recommended energy harvester comprises a magnetic spring and inductive components. It is preferred to use the magnetic spring for human body vibrations, which are aperiodic in a very low frequency domain. The inductive components are composed of planar coil layers.

Carrol & Duffy (2005) reported a sliding electromagnetic generator placed inside the shoes sole or energy harvesting. This device extracted electrical energy from the kicking force during walking. The generator consists of a set of three coils with magnets moving inside the coils. Paradiso et al. have investigated power-harvesting from running shoes as a method of generating power for wearable electronics. The authors describe three types of generators: a piezoelectric bender placed in the sole, which flexes during the human gait; a unimorph attached to a curved steel plate, which flexes under the pressure of a heel strike. The harvested power is used to supply an RFID tag transmitting an identification string every few steps. Although the electromagnetic generator was capable of harvesting one to two orders of magnitude more power than the piezoelectric ones, it was reported to have a noticeable effect on the user's gait. The authors suggest that the piezoelectric solutions are neater, and with the ever reducing power consumption of wearable devices, their power output will be sufficient (Sodano *et al.* 2004a; Sodano *et al.* 2004b).

(Kim *et al.* (2007) described the use of a piezoelectric cymbal transducer to generate electricity from the vibration of a car engine. A cymbal-shaped device was chosen because the authors state that this structure is efficient at transferring stress through the material. The transducer would be placed between the engine and engine mounting, so that force is directly applied to it. The available power is calculated from the effective capacitance and open circuit voltage of the piezoelectric element. The device was then connected to a full wave rectifier, smoothing capacitor, and buck converter, giving a maximum processed output power. The target application is charging of the car's battery, for which the device size and power levels will need to be much higher.

Clark and Ramsay (2001) considered force driven piezoelectric generators (Li *et al.* 2008) for medical applications. The input energy for the generator is intended to be in the form of fluctuating pressure in a blood vessel. The authors study a square sheet of piezoelectric material held in a rigid frame, with pressure applied normal to the sheet surface. Besides that, the efficiency of the fabricated vibration energy harvester was evaluated at low frequency excitation. The results also confirm that the proposed energy harvester successfully produced an output power of several hundred microwatts from human body vibrations. Summary of these energy sources is tabulated in Table-1.

Table-1. The energy sources used by energy harvesting devices.

Mechanic	Deriving from vibrations, sounds, deformations and elastic stresses
Thermal	Waste heat from furnaces, heaters, motors, and different kinds of attrition
Light	Sunlight and artificial light, with photodiodes or solar panels
Electromagnetic	Inductors, coils and transformers
Natural	Wind, tides, waves, ocean currents, solar energy
Human body	Both thermal and mechanical, generated by the normal functioning of a living organism, such as walking
Others	Chemical energy or biological sources

MECHANICAL VIBRATIONAL ENERGY HARVESTING

The growth of advances technologies of low power electronics such vibration energy harvesting (VEH), a kind of clean, saving and protecting the natural environment and renewable energy scavenging has gradually gained massive attention from worldwide researchers in the past decade for its essential potential applications in areas of self-powered wireless sensor networks, autonomous lower power microsystems, distributed computing and portable power sources, etc., to replace or replenish traditional power sources, such as battery. Figure-1 is a block diagram of vibration energy harvesting system.

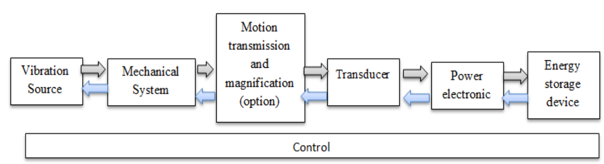

Figure-1. Block diagram of vibration energy harvesting system (Wang *et al.* 2013).

Generally, energy harvesting, or energy scavenging as the process is sometimes referred to a device associated with capturing residual energy as a by product of a natural environment phenomenon or industrial process and is therefore considered free-energy. The development of advanced techniques allowed to capture, to store and to manage amounts of natural energy, transforming them into electrical energy to supply low power devices or store it for later use. There are categories into difference type of energy harvesting sources, e.g. solar, vibration, temperature and electromagnetic waves as shown in Table-1. More often than not, these residual energies are released into the environment as wasted potential energy sources. Of these sources,

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electromagnetic wave provides by far the least power density. Because of this, the capturing and conversion of the energy has to be done very efficiently. Moreover, advancements in microprocessor technology have increased power efficiency, effectively reducing power consumption requirements.

Motion energy or vibrations are an attractive source for powering miniature energy harvesting generators. Vibration energy harvesting (Cao *et al.* 2006a; Dallago *et al.* 2008; Ferrari *et al.* 2009) is converted mechanical vibration energy into useful electrical energy by utilizing piezoelectric, electromagnetic, or electrostatic transducers. In order to convert mechanical energy into electrical energy, one should be able to realize a movement between the mechanical parts of the generator. Vibration consist however, of a travelling wave (Fairbanks *et al.* 2011) in or on a solid material, and it is often not possible to find a relative movement within the reach of a small generator, therefore, one has to couple the vibration movement to the generator by means of the inertia of a seismic mass.

Vibration energy harvesting involves the conversion of ambient mechanical energy present in the environment into electrical energy by employing certain transduction mechanisms. The three main types of converters used in vibration energy harvesting are piezoelectric devices (Elfrink *et al.* 2009), electrostatic devices and electromagnetic devices (Gieras *et al.* 2007).

[1] Piezoelectric devices: they use piezoelectric materials that present the ability to generate charges when they are under stress/strain.
[2] Electromagnetic devices: they are based on electromagnetic induction and ruled by Lenz's law. An electromotive force is generated from a relative motion between a coil and a magnet.
[3] Electrostatic devices: they use a variable capacitor structure to generate charges from a relative motion between two plates.

Table-2. Vibration energy harvester for small –scale devices from mechanical to electrical converters (Park *et al.* 2008).

Piezoelectric converters	Electromagnetic converters	Electrostatic converters
Use of piezoelectric materials	Use of Lenz's law	Use of a variable capacitor structure

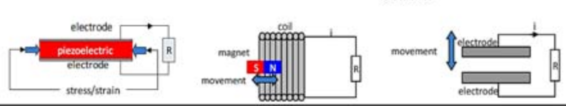

Table-2 shows vibration energy harvester for small-scale devices from mechanical to electrical converters. In addition, the vibration energy harvesting is able to deliver sustainable power and could be an alternative power source for applications that are either in harsh or contaminated conditions, or difficult to access such as safety monitoring devices (Park *et al.* 2008), structure embedded micro-sensors, or biomedical implants (Donelan *et al.* 2008). Along with these benefits, there are many other motivations including but not limited to active vibration control (Liu *et al.* 2009) and so on, which are paving the way to the future of energy harvesting, including no wire cost, not maintain cost, high reliability and practically infinite operating lifespan.

a) Piezoelectric vibration energy harvesters

Piezoelectricity (Dallago *et al.* 2008; Ferrari *et al.* 2006) was first discovered by the brothers Pierre Curie and Jacques Curie in 1880. They predicted and demonstrated that crystalline materials like tourmaline, quartz, topaz, cane sugar, and Rochelle salt (sodium potassium tartrate tetrahydrate) can generate electrical polarization from mechanical stress. Piezoelectric effect has been separated into two types, which are direct piezoelectric effect and converse piezoelectric effect. The piezoelectric effect is a material property where an applied mechanical strain introduces an electric field across the material (direct effect) and conversely applied electric fields introduce deformations in the material (converse effect). But, converse piezoelectricity was mathematically (after the discovery of the direct piezoelectric effect) assumed from fundamental thermodynamic principles by Lippmann in 1881 and then Curies has emphasized the reality of the converse piezoelectric effect (Kim *et al.* 2007; Ottman *et al.* 2002; Ottman *et al.* 2003).

If the same material is subjected to a voltage drop (i.e. an electrical potential difference applied across its electrodes), it deforms mechanically. This is called the converse piezoelectric effect. The direct piezoelectric effect is responsible for the material's ability to function as a sensor, whereas, the converse piezoelectric effect is accountable for its ability to function as an actuator (Nakano *et al.* 2003). It is important to note that these two effects usually coexist in a piezoelectric material. Hence, the piezoelectric properties are necessary to comprise a sign convention to simplify this ability to improve electric potential. The piezoelectric effect is the process of internal generation of electrical charge resulting from an applied mechanical force. The origin of the piezoelectric effect was, in general, clear from the very beginning.

In the piezoelectric of energy harvesting based on vibration (Galhardi *et al.* 2008; Granstrom *et al.* 2007), the materials need to be further developed to endure a large stress and to enhance durability. Piezoelectric materials are generated electric charge when a mechanical load is applied and therefore are in advance used to convert mechanical energy in form of pressure or force into electric energy. When a vibration source (Jolly *et al.* 1997) is applied to the energy harvesting system, the piezoelectric beam and the magnets would oscillate as one unit, produces a stress or strain in the piezoelectric and a change of magnetic flux in the coil, which result in generation of useful electrical power from both transducers.

Energy harvesting device commissioning piezoelectric conversion mechanism characteristically consists of cantilever beam (Johnson *et al.* 2006, Zhu *et al.*

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2010) covered with piezoelectric material and a mass employed on the tip of a beam. The small scale piezoelectric converter devices of based on vibration energy harvesting common materials have been used are PZT-5A, PZT-5H, MFC and PVDF, but only PZT-5A have potential to generate high amounts of output power (Zhu *et al.* 201; Beeby *et al.* 2007), and their compact dimension suitable for MEMS incorporation. The PZT piezoelectric materials are often brittle, tend to change their properties through operational life, and it's even able to function without existing of external voltage source and coefficient of electromechanical coupling is high (Wu *et al.* 2008; Mateu *et al.* 2004).

Piezoelectric is one of the four general types of mechanical-to-electrical energy conversion mechanisms for harvesting vibration energy (Wang *et al.* 2010; Wang *et al.* 2011). Once the consistent mechanical stress is applied with piezoelectricity, the ability of its certain crystals will produce a voltage. But, the shape of the piezoelectric crystal will bend comparatively to an externally applied voltage when occurs of piezoelectric effects is reversible. The strain is proportional to electric potential.

The electric potential is proportional to the strain. Piezoelectric energy harvesters can work in either d33 mode or d31 mode as shown in Figure-2. In d31 mode, a lateral force is applied in the direction perpendicular to the polarization direction, an example of which is a bending beam (Goldschmidtboeing *et al.* 2008) that has electrodes on its top and bottom surfaces as in Figure- 2(a). In d33 mode, the force applied is in the same direction as the polarization direction, an example of which is a bending beam that has all electrodes on its top surfaces as in Figure-2(b). Although piezoelectric materials in d31 mode normally have a lower coupling coefficient than in d33 mode, d31 mode is usually be used (Anton and Sodano, 2007; Kok *et al.* 2009). This is because when a cantilever or a double-clamped beam (two typical structures in vibration energy harvesters) bends, more lateral stress is formed than vertical stress, which makes it easier to couple in d31 mode.

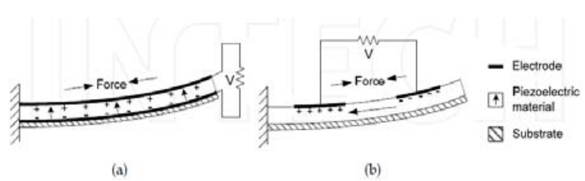

Figure-2. Two types of piezoelectric energy harvesters (a) d31 mode (b) d33 mode (Wahied *et al.* 2012).

b) Electromagnetic vibration energy harvesters

Besides piezoelectric materials, electromagnetic motors are also often used in vibration energy harvesting, especially when the vibration magnitude is large. Electromagnetic motor can act as an actuator and a harvester at the same time, capable of bi-directional power flow. The electromagnetic motor can be modeled as a voltage source in series with the inherent inductance and a resistor of the motor. And in this case, the electric energy is dissipated by the resistor into heat waste (Bell *et al.* 2008; Palomera Arias, 2005). Pure resistance load also provides a method to measure and approximation the potential amount of energy in the energy harvesting system (Gupta *et al.* 2006), although the practical loads are not always pure resistive.

On the other hand, when the electromagnetic transducer is used as passive vibration damper (Suda *et al.* 2003), the vibration performance can be further improved by shunting the damper with a resistor, capacitor, and inductor network (Fleming, 2002; Hagood and Flotow, 1991; Hollkamp, 1994) rather than dissipating the electric energy into heat waste (Starner *et al.* 1998), and must replace the resistor with a charging circuit and an energy storage device to store the electric energy. The above stated investigated analysis and modeling are for linear electromagnetic motors. Similar relations can be obtained for the rotational electromagnetic motors with permanent magnets. Energy recovery from vehicle suspension is such an example. Instead of dissipating the vibration energy into heat waste using shock absorbers, the energy can be harvested, meanwhile reducing the vibration (Gupta *et al.* 2006; Nakano *et al.* 2003; Zuo *et al.* 2011b; Zuo *et al.* 2011c).

Electromagnetic vibration energy harvesting devices (Cao *et al.* 2007; Koukarenko *et al.* 2006) introduces an optimization approach which is applied to determine optimal dimensions of the components (magnet, coil and back iron). Electromagnetic mechanism of vibration energy harvesting is based on Faraday's law of electromagnetic induction stating that "an electrical current will be induced in any closed circuit when the magnetic flux through a surface bounded by the conductor changes". One of the most effective ways of achieving this for energy harvesting is by applying of permanent magnet and coil. Electromagnetic harvesters transform kinetic energy (Li *et al.* 2011; Li *et al.* 2013) into electricity by moving a coil across the magnetic field (Mann *et al.* 2008) of a stationary magnet, thereby inducing a voltage across the coil. Electromagnetic harvesters are simple and rugged, do not require any smart materials (Guyomar *et al.* 2005; Glynner *et al.* 2004) or source of voltage, but are difficult to manufacture in micro scale. Output voltage is low (0,1 V). Macro-scale devices are fabricated using high-performance bulk magnets and multi-turn coils. Electromagnetic harvesters are heavy and bulky due to their large magnetic components.

Electromagnetic induction occurs during magnetic field applies changes in strength or the conductor is moved through it. It was designed and constructed a generator that is based on relative movement of a permanent magnet in relation to a coil. The advantage of this device based on principal electromagnetic induction (Kawamoto *et al.* 2008) to harvest energy is that has a low cost of production, no maintenance required and is able to harvest energy in a wide range of frequencies. The theory behind electromagnetic vibration harvesting has been detailed earlier (Saha *et al.* 2006; Saha *et al.* 2008). The

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permanent magnet and coils are common used into electromagnetic energy harvesters to generate a strong magnetic field. The coils normally perform as a conductor or composed with permanent magnet act to fix to the frame, though the other attaches to the inertial mass. Generally, the static coil can grow lifespan of the device when the magnet is in mobile as the coils is fragile associated to the magnet, while the coil is in a static condition. In generating electrical energy, the consequences of ambient vibration are due to the relative displacement between magnet and coil as shown in Figure-3.

Based on Fawaday Law, electromotive force (e.m.f) which states that the strength of the magnetic field is directly proportional to induced voltage, which interconnected with velocity of relative motive and the number of turns of coil. At the expense of low voltage, the electromagnetic energy harvester, the external voltage source and mechanical constraints are removed but probably have a great output current level. Beeby *et al.* (2007a), mentioned that performance of electromagnetic energy harvesters condense to become in micro-scale. So, due to the use of discrete permanent magnets, it is challenging to incorporate electromagnetic energy harvesters with the MEMS fabrication process.

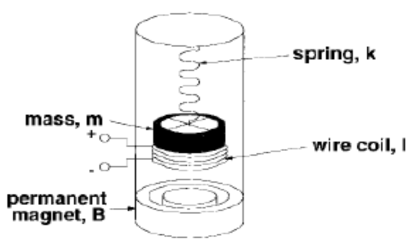

Figure-3. Electromagnetic conversion device, which vibrations will make the spring attached mass move inducing a magnetic field with the magnet thus creating energy (Williams *et al.* 2001; Carrol & Duffy 2005).

Electromagnetic vibration harvesters can be fabricated in the standard or inverse configuration. In the inverse configuration, the coil moves while the permanent magnet is immovable. In the standard configuration, the permanent magnet whose function is to generate the magnetic flux is movable while the coil is fixed. Figure-4 presents the configurations of electromagnetic vibration harvesters.

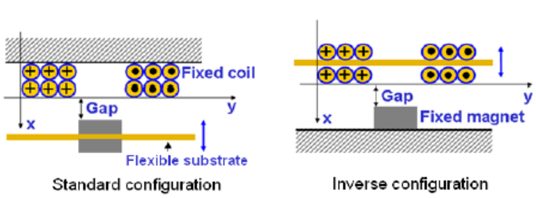

Figure-4. Configurations of electromagnetic vibration harvesters (Lumentut *et al.* 2011).

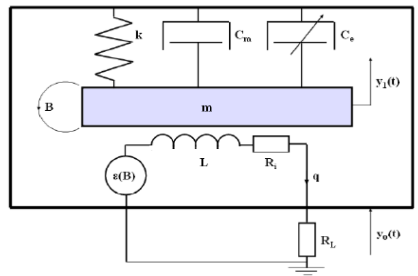

Figure-5. Lumped parameter model of electromagnetic vibration harvesters (Wang *et al.* 2010).

The size of rotational electromagnetic generators is commonly smaller compared to linear motors in vibration energy harvesting principal. But, it is a necessary process involve of conversion linear motion of vibration into rotational motion. According to with rotational electromagnetic motors, including links, screws, rack and pinions, and fluids, there are some mechanisms have been suggested with prototypes have been built to obtain its harvesters as shown in Figure-5. Recently, Gupta *et al.* (2006 recommended to use level mechanism in a regenerative shock absorber, which contains of a geared rotational motor and a level, resulting in six resolutions of the motor to one of the level. This arrangement can not only change the relative linear motion into rotational motion, but also can magnify the motion resulting in a higher efficiency.

Usually, ball screw mechanism is used to convert the rotational motion of the electromagnetic motor into linear motion, resulting in linear actuator. In energy harvesting from vibration, researchers use it inversely. Kawamoto *et al.* (2008) presented an electromechanical actuator consisting of rotational electromagnetic motor and ball–screw mechanism. A prototype is also built. The ball– screw transfers the linear motion into rotational motion and then drives the electromagnetic motor. And also using ball–screw mechanism, Zhang *et al.* (2007) showed a full-vehicle experiment to test the vibration performance and possibility for energy harvesting. Camila *et al.* (2010) designed an electromagnetic transducer with ball–screw mechanism for energy harvesting from large-scale civil structures, for which the power levels can be above 100 W for excitation frequencies below 1 Hz. The phenomena of system applying ball-screw mechanism will also introduce extra dynamics are fully required to be examined.

c) Electrostatics vibration energy harvesters

Electrostatic harvesting (Basset *et al.* 2009; Genda *et al.* 2003) of mechanical energy is based on varying vibration-dependent capacitance of variable capacitors (varactors). Ambient vibrations induced displacement of charger plates of fructose and mechanical energy is converted into electrical energy. In the variable capacitor also name as varactor consists of two sets of electrodes, which is one set is fixed on the housing while

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and another set of electrodes is attached to the inertial mass. The changed of the capacitance depended on mechanism to make the movable of fixed electrodes.

The variable capacitance (Chih *et al.* 2006; Sterken *et al.* 2007) value is visible to adjust to either maximum or minimum. The charge of variable capacitor will move from capacitor to the storage device or to the load as the capacitance value when the charge of capacitor is embarrassed. When the capacitance are firstly has been charged, will separate its plates by vibrations, and mechanical energy is transformed into electrical energy. The advantage of this principle of harvesting is ease of integration of such devices into printed circuit boards of MEMS, no need for smart materials and high output voltage (2~10 V) . Disadvantages of electrostatic devices are their dependence on external voltage source.

The concept of construction variable capacitors is according to the principal of electrostatic energy harvesters. This technique is determined by on the variable capacitance of vibration-dependent varactors especially in MEMS fabrication (Meninger, Mur-Miranda, Amirtharajah, Chandrakasan, & Lang, 2001). Constant voltage or constant current are accomplishing the transformation when through two mechanisms. For example, the charges of variable capacitor will drive out of the device when the plates split and capacitance is reduced, when the voltage across a variable capacitor is kept in static condition as its capacitance alter after a primary charge. The complete drive energy of variable capacitor can be used into charging battery or stored in an energy pool, to produce the necessary voltage source within the respective time windows.

The most prominent feature of this method is eligible for IC-compatible nature, given that MEMS (Micro-electromechanical system) variable capacitors are fabricated through relatively well-known silicon micro-machining techniques. The moderate power density inside electromagnetic method has potential to generate higher and more practical output level. In a study conducted to test the possibility and consistency of the different ambient vibration energy sources by Marzencki (2005), three different vibration energy sources (electrostatic (Kloub *et al.* 2009; Suzuki *et al.* 2010), electromagnetic, and piezoelectric) were considered and related according to their complexity, energy density, size, and encountered problems.

Electrostatic converters (Honzumi *et al.* 2010) are capacitive structures made of two plates separated by air, vacuum or any dielectric materials. A relative movement between the two plates generates a capacitance variation and then electric charges. These devices can be divided into two categories, that is electret-free electrostatic converters (Boisseau *et al.* 2010; Despesse *et al.* 2005) that use conversion cycles made of charges and discharges of the capacitor (an active electronic circuit is then required to apply the charge cycle on the structure and must be synchronized with the capacitance variation) and electret-based electrostatic converters that use electrets, giving them the ability to directly convert mechanical power into electricity .

Electrostatic energy harvesters (Naruse *et al.* 2009; Halvorsen *et al.* 2009) can be categorized into three types as shown in Figure-6, i.e. In-Plane Overlap which able be adjusted at overlap area between electrodes, In-Plane Gap. Closing which varies the gap between electrodes and Out-of-Plane Gap which varies the gap between two large electrode plates. Electrostatic energy harvesters have high output voltage level and low output current. But, mechanical constraints are desired in electrostatic energy harvesting. External voltage source or pre-charged electrolytes is also needed. Besides, electrostatic energy harvesters also have the ability to produce high output impedance. In addition, a majority of existing vibration energy harvesters are out-of plane, i.e. the vibration direction is parallel with the thickness of the energy harvester. This kind of devices requires space out of the plane to allow the inertial mass to oscillate freely, which makes them thick. In comparison, the inertial mass of an in-plane energy harvester oscillates perpendicular to the thickness of the harvester, which makes the harvester planar.

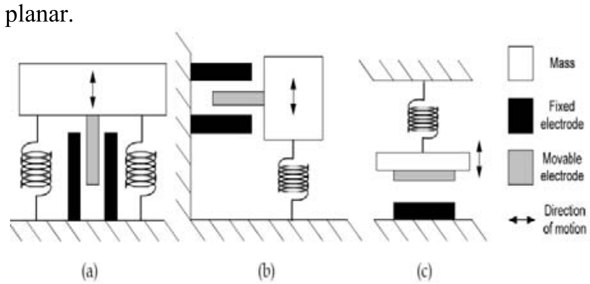

Figure-6. Three types of electrostatic energy harvesters (a) In-Plane Overlap (b)In-Plane Gap (Halvorsen *et al.* 2009).

Closing (c) Out-of-Plane Gap Closing (Naruse *et al.* 2009; Halvorsen *et al.* 2009).

Table-3 is present the overall advantages and disadvantages of three types of vibration energy converter type.

Table-3. Advantages and disadvantages of vibration energy converter type.

	Piezoelectric devices	Electromagnetic devices	Electrostatic devices
Advantages	-high output voltages -high capacitances -no need to control any gap	-high output currents -long lifetime proven -robustness	-high output voltages -possibility to build low-cost systems -coupling coefficient easy to adjust -high coupling coefficients reachable -size reduction increases capacitances
Disadvantages	-expensive (material) -coupling coefficient linked to material properties	low output voltages -hard to develop MEMS devices -may be expensive (material) -low efficiency in low frequencies and small sizes	-low capacitances -high impact of parasitic capacitances -need to control µm dimensions -no direct mechanical-to-electrical conversion for electret-free converters

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CONCLUSIONS

In this paper summarizes studied of environmental friendly vibration energy harvesting of the conversion of vibrational energy into electrical power has become a major field of research. It illustrated various designs of vibration energy harvesting from ambient vibrations using electrostatics, piezoelectric and electromagnetic. Most of the harvesting circuits were developed based on the periodic or harmonic excitations. It may not be applicable to the piezoelectric vibration energy harvester designed to operate in random or broadband excitation circumstances. When compared with energy stored in common storage device, it has more improvement in term of sustainability, maintenance free and environmentally friendly. Efficient ways to convert environmental noise into electrical energy. Compared with the all about stating energy resources, less effort has been dedicated to developing sound energy harvesting methods. Since vibration energy harvesting is a clean, ubiquitous, sustainable energy source, it is great interest to study the mechanism generated by energy harvesting.

In future work research efforts have also concentrated on harvesting energy such as airborne vibration and flow induced vibration or even from sources surrounding like acoustic, airdrop and heat into energy harvesting, which play a major role in greening world's energy supply. The future challenges to be addressed in the research field include improving the conversion efficiency and energy harvesting and storing circuits. Actually, one of the possibilities to recharge such batteries is to use energy harvested from the surrounding. The advantages of energy harvesting is not trying to replace batteries, but instead alleviating some of their drawbacks, especially in relation to the maintenance issue. This is a new alternative, efficiency, and renewable energy with lots of potential applications.

REFERENCES

[1] Antaki, J. F., Bertocc, G.E., and Green E.C. (1995). A gait powered autologous battery charging system for artificial organs. ASAIO Journal, 41(3), pp. 588-595.

[2] Anton, S. R. and Sodano, H. A. (2007). A review of power harvesting using piezoelectric materials (2003-2006), In: Smart Materials and Structures, 16, pp.1-21.

[3] Arms, S.W., Townsend, C.P, and Churchill, D.L. (2005). Power management for energy harvesting wireless sensors. Proceedings of SPIE, Int'l Symposium on Smart Structures & Smart Materials, pp.1-9.

[4] Barker, S., Vassilevski, K. V., Wright, N. G. and Horsfall, A. B. (2010). High temperature vibration energy harvester system. Conference, IEEE sensor, Kona, HI, pp. 300-303.

[5] Barrero, G, A., Alonso, G. and Sanz-Andres, A. (2010). Energy harvesting from transverse galloping, In: Journal of Sound and Vibration, 329, pp. 2873-2883.

[6] Basset, P., Galayko, D., Paracha, A., Marty, F., Dudka, A. and Bourouina, T. (2009). A batch-fabricated and electret-free silicon electrostatic vibration energy harvester. IOP Journal of Micromechanics and Microengineering, 19(11), pp.1-10.

[7] Beeby, S. P., Tudor, M. J. and White, N. M. (2006). Energy harvesting vibration sources for microsystems applications, In: Measurement Science and Technology, 17, pp. 175-195.

[8] Beeby, S. P., Torah, R. N., Tudor, M. J. Glynne-Jones, P. O., Donnell, T., Saha, C. R., and Roy, S.(2007). A micro electromagnetic generator for vibration energy harvesting, In: Journal of Micromechanics and Microengineering, 17, pp. 1257-1265.

[9] Behrens, S. (2011). Design of electromagnetic energy harvesters for large-scale structural vibration applications. Proceedings of the SPIE International Symposium on Smart Materials and Structures/ NDE, San Diego, CA, 7977, pp.1-11.

[10] Bell, L.E. (2008). Cooling, heating, generating power, and recovering waste heat with thermoelectric systems. Science 321(5895), pp.1457–1461.

[11] Boisseau, S., Despesse, G. and Sylvestre, A. (2010). Optimization of an electret-based energy harvester. Smart Materials and Structures, 19(7), pp.1-10.

[12] Burrow, S. G., Clare, L. R., Carrella, A. and Barton, D. (2008). Vibration energy harvesters with non-linear compliance, In: Active and Passive Smart Structures and Integrated Systems 2008, Proceedings of the SPIE, 6928, pp. 1110-1117.

[13] Cao, X. and Lee, Y. (2006). Design and fabrication of mini vibration power generator system for micro sensor networks. In: Proceedings of 2006 IEEE international conference on information acquisition, Shanghai, China, pp. 91–95.

[14] Cao, X., Chiang, W. and King, Y. (2007). Electromagnetic energy harvesting circuit with feedforward and feedback DC-DC PWM boost converter for vibration power generator system. IEEE Transactions on Power Electronics, 22(2), pp. 679–685.

[15] Cargo, C. J., Plummer, A. and Hillis, R. (2011). Determination of optimal parameters for a hydraulic power take-off unit of a wave energy converter in

regular waves. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 226(1), pp. 98–111.

[16] Carlos, V., Daniel, T., Antoni M. and Joaquin. R. (2013). Sea motion electrical energy generator for low power applications. IEEE conference proceeding Standard on Piezoelectricity, pp.1-7.

[17] Carroll, D. and Duffy, M. (2005). Demonstration of wearable power generator, Proceedings of the 11th European Conference on Power Electronics and Applications, Dresden, Germany, pp.1-10.

[18] Camila, G. G., Vitor, R. F., Michael, J. B., Samuel, D. S. and Vicente, L. J. (2010). Energy Harvesting Using Piezoeletric and Electromagnetic Transducers. Proceedings of the 9th Brazilian Conference on Dynamics Control and their Applications, pp. 1166-1171.

[19] Chih, H., Yen B. and Lang, J. (2006). A variable capacitance vibration-to-electric energy harvester. IEEE Transactions Circuits System, 53(2), pp. 288-295.

[20] Clark, W. W. and Ramsay, M. J. (2001). Piezoelectric energy harvesting for bio MEMS applications. Proc. SPIE 4332, Smart Structures and Materials 2001: Industrial and Commercial Applications of Smart Structures Technologies, 4332, pp. 429–438.

[21] Chalasani, S. and Conrad, J.M. (2008). A survey of energy harvesting sources for embedded systems. In: Proceedings of IEEE Southeastcon, Huntsville, Alabama, pp. 442–447.

[22] Choi, S., Seong, M. and Kim, K. (2009). Vibration control of an electrorheological fluid-based suspension system with an energy regenerative mechanism. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 223(4), pp.459–469.

[23] Collins, L. (2006). Harvesting for the world: energy harvesting techniques. IEEE Power Engineer, 20(1), pp. 34–37.

[24] Dallago, E., Miatton, D. and Venchi, G. (2008). Active self supplied AC-DC converter for piezoelectric energy scavenging systems with supply independent bias. In: IEEE international symposium on circuits and systems, ISCAS Seattle, Washington, pp. 1448-1451.

[25] Despesse, G., Chaillout, J. J., Jager, T., Leger, J. M,, Vassilev, A., Basrour, S.and Charlot, B. (2005). High damping electrostatic system for vibration energy scavenging. Proceeding sOc-EUSAI, pp. 1-4

[26] Dhakara, L., Huicong, L., Tay, H. and Chengkuo, L. (2013). A new energy harvester design for high power output at low frequencies, Technical Proceedings of the 2005 NSTI Nanotechnology Conference and Trade Show, Anaheim, California, USA,199, pp. 344-352.

[27] Donelan, J. M., Li, Q. and Naing, V. (2008) Biomechanical energy harvesting: generating electricity during walking with minimal user effort. Science, 319(5864), pp.807–810.

[28] Drew, B., Plummer, A. and Sahinkaya, M. (2009) A review of wave energy converter technology. Proc. IMechE Vol. 223 Part A: Journal Power and Energy, 223(8), pp. 887–902.

[29] Dwari, S. and Parsa, L. (2010). An efficient AC–DC step-up converter for low-voltage energy harvesting. IEEE Transactions on Power Electronics, 25(8), pp. 2188–2199.

[30] Ebrahimi, B., Khamesee, M. B. and Golnaraghi, M. F. (2008). Design and modeling of a magnetic shock absorber based on eddy current damping effect. Journal of Sound and Vibration, 315(4–5): pp.875–889. .

[31] Erturk, A., Vieira, W. G. R., De Marqui, C. Jr. and Inman, D. J. (2010). On the energy harvesting potential of piezoelectric systems, In: Journal of Applied Physics, 96(18), pp. 1-3.

[32] Eichhorn, C., Tchagsim, R., Wilhelm, N., Goldschmidtboeing, F. and Woias, P. (2010). A compact piezoelectric energy harvester with a large resonance frequency tuning range, Proceedings PowerMEMS 2010, pp. 207-211.

[33] Elfrink, R., Kamel, T., Goedbloed, M., Matova, S., Hohlfeld, D., van Andel,Y., and Van Schaijk, R. (2009). Vibration energy harvesting with aluminum nitride-based piezoelectric devices, In: Journal of Micromechanics and Microengineering, 19(9), pp. 1-10.

[34] Fairbanks, J. (2011). Vehicular thermoelectrics: a new green technology. In: Thermoelectric applications workshop, Coronado, CA, Wave energy utilization: A review of the technologies. Renewable and Sustainable Energy Reviews, 14(3), pp. 899–918.

[35] Fang, H. B., Liu, J. Q., Xu, Z. Y., Dong, L., Wang, L., Chen, D., Cai, B. C. and Liu, Y. (2006). Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting, In: Microelectronics Journal, 37(11), pp. 1280- 1284.

[36] Ferrari, M., Ferrari, V. and Guizzetti, M. (2006). Piezoelectric multi-frequency energy converter for power harvesting in autonomous Microsystems. In Eurosensors The 20th European conference on Solid-State Transducers Eurosensors 2006, Sweden, 142(1), pp.329-335.

[37] Ferrari, M., Ferrari, V., Guizzetti, M., Andò, B., Baglio, S. and Trigona, C. (2009). Improved Energy Harvesting from Wideband Vibrations by Nonlinear Piezoelectric Converters, Proceedings of Eurosensors XXIII, Lausanne, Switzerland, 162(2), pp. 425-431.

[38] Galhardi, M. A., Guilherme, T. H. and Junior, V. L. (2008). A review of power harvesting from vibration using piezoelectric materials and applications. In: The 7th Brazilian conference on dynamics, control and applications. Presidente Prudente, Brazil, 36(3), pp. 197-205.

[39] Genda, T., Tanaka, S. and Esashi, M. (2003). High power electrostatic motor and generator using electrets. Solid-State Sensors Actuators and Microsystems Conference, 2007, 12th International Conference on, 2003, Proc. Transducers, 1, pp. 492-495.

[40] Gieras, J. F., Oh, J.H.., Huzmezan, M. and Sane, H. S. (2007). Electromechanical energy harvesting system. In: Journal of Micromachining and Microengineering , pp. 1-13.

[41] Glynne, J. P., Tudor, M. J., Beeby, S. P. and White, N. M. (2004). An electromagnetic, vibration-powered generator for intelligent sensor systems, In: Sensors and Actuators A: Physical, 110(1-3), pp. 344-349.

[42] Goldschmidtboeing, F., and Woias, P. (2008). Characterization of different beam shapes for piezoelectric energy harvesting, In: Journal of Micromachining and Microengineering, 18(10), pp.1-10.

[43] Gonzalez, J. L. Rubio, A. and Moll, F. (2002). Human powered piezoelectric batteries to supply power of wereables electronic devices, Int. J. Soc. Mater. Engineering Resource, 10(1), pp. 34–40.

[44] Granstrom, J., Feenstra, J. and Sodano H. A. (2007). Energy harvesting from a backpack instrumented with piezoelectric shoulder straps. Smart Materials and Structures, 16, pp. 1810–1820.

[45] Grouthier, C., Michelin, S., Modarres S. Y., and Langre, E. (2013). Self-similar vortex-induced vibrations of a hanging string, Journal Fluid Mechanics, 724, pp. 1-11.

[46] Guigon, R., Chaillout, J.J., Jager, T. and Despesse, G., (2008a). Harvesting raindrop energy: experimental study. Smart Materials and Structures, 17(1), pp.1-10.

[47] Gupta, A., Jendrzejczyk, J.A. and Mulcahy, T. M. (2006). Design of electromagnetic shock absorbers. International Journal of Mechanics and Materials in Design, 3(3), pp. 285–291.

[48] Guyomar, D., Badel, A. and Lefeuvre, E. (2005). Toward energy harvesting using active materials and conversion improvement by nonlinear processing. IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control, 52(4), pp. 584–595.

[49] Halvorsen, E., Westby, E. R., Husa, S., Vogla, N. P., Leonov, V., Sterken, T. and Kvisteroy, T. (2009). An electrostatic Energy harvester with electret bias Solid-State Sensors Actuators and Microsystems Conference, 2009, Proceeding Transducers, pp. 1381-1384.

[50] Hahn, R. and Reichl, H. Batteries and power supplies for wearable and ubiquitous computing. In Third Intl Symp. on Wearable Computers, pp. 168-169.

[51] Han, J., Jouanne, A. and Le, T. (2004). Novel power conditioning circuits for piezoelectric micro power generators. In: Proceedings of the 19th annual IEEE applied power electronics conference and exposition, Anaheim, California, pp. 1541–1546.

[52] Hollkamp, J. J. (1994). Multimodal passive vibration suppression with piezoelectric materials and resonant shunt. Journal of Intelligent Material Systems and Structures, 5, pp.49–57.

[53] Honzumi, M., Ueno, A., Hagiwara, K., Suzuki, Y., Tajima, T. and Kasagi, N. (2010). Soft-X-Ray-charged vertical electrets and its application to electrostatic transducers. IEEE 23rd International Conference on, Micro Electro Mechanical Systems (MEMS), Proc. MEMS, pp. 635-638.

[54] Huang, K., Yu, F. and Zhang, Y. (2011). Active controller design for an electromagnetic energy-regenerative suspension. International Journal of Automotive Technology, 12(6), pp. 877–885.

[55] Jansen, A., Fridstedt, S. and Weernink, A. (2000). A battery less remote control for Volvo, results of a feasibility study. In ISATA 2000 Conference on Automotive and Transportation Technology, pp. 1-9.

[56] Johnson, T. J., Charnegie, D. and Clark, W. W. (2006). Energy harvesting from mechanical vibrations using piezoelectric cantilever beams. In: Proceedings of SPIE, structure sand materials: damping and isolation, San Diego, CA, 6169, pp. 81–92.

[57] Jolly, M. R. and Margolis, D. L. (1997). Regenerative systems for vibration control. Journal of Vibration and Acoustics, 119, pp. 208–215.

[58] Kawamoto, Y., Suda, Y. and Inoue H. (2007). Modeling of electromagnetic damper for automobile suspension. Journal of System Design and Dynamics, 1(3), pp. 524–535.

[59] Kawamoto, Y., Suda Y, Inoue H. (2008). Electro-mechanical suspension system considering energy consumption and vehicle maneuver. Vehicle System Dynamics, 46, pp. 1053–1063.

[60] Kim, H., Priya, S. and Stephanous, H. (2007). Consideration of impedance matching techniques for efficient piezoelectric energy harvesting. IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control, 54(9), pp. 1851–1859.

[61] Kloub, H., Hoffmann, D., Folkmer, B. and Manoli, Y. (2009). A micro capacitive vibration Energy harvester for low power electronics. Proceeding Power MEMS, Washington DC, USA Power MEMS, pp.165-168.

[62] Kok, S. L., White, N. M. and Harris, N.R. (2009). Fabrication and characterization of freestanding thick-film piezoelectric cantilevers for energy harvesting, In: Measurement Science and Technology, 20(12), pp.1-10.

[63] Koukarenko, E., Beeby, S. P., Tudor, M. J., White, N. M., Donnell, T., Saha, T., Kulkani, S. and Roy, S. (2006). Micro-electromechanical systems vibration powered electromagnetic generator for wireless sensor applications, In: Microsystem Technologies, 12(11), pp. 1071-1077.

[64] Kymissis, J., Kendall, C., Paradiso, J. and Gershenfeld, N. (1998). Parasitic power harvesting in shoe, Digest of Papers. Second International Symposium on Wearable Computers, Pittsburgh, Pennsylvania, USA, pp. 132-139.

[65] Li, Q., Naing, V and Hoffer, J.A. (2008). Biomechanical energy harvesting: apparatus and method. In: 2008 IEEE international conference on robotics and automation, Pasadena, California, pp. 3672–3677.

[66] Li, P., Zhang, C. and Zuo, L. (2013). Review of power electronics for kinetic energy harvesting systems. In proceedings of SPIE Conferences on Smart Structures and Materials, 27(2), pp. 803 – 815.

[67] Li, Z., Brindak, Z. and Zuo, L. (2011). Modeling of an electromagnetic vibration energy harvester with motion magnification. In: 2011 ASME international mechanical engineering congress and exposition (IMECE), CO. Denver, Colorado, pp. 285-293.

[68] Liu, Y., Tian, G. and Wang, Y. (2009). Active piezoelectric energy harvesting: general principle and experimental demonstration. Journal of Intelligent Material Systems and Structures, 20, pp. 575–585.

[69] Lumentut, M.F. and Howard I.M. (2013). Analytical and experimental comparisons of electromechanical vibration response of a piezoelectric bimorph beam for power harvesting. Piezoelectric Technology, 36(1), pp. 66–86

[70] Mann, B. P. and Sims, N.D. (2009). Energy harvesting from the nonlinear oscillations of magnetic levitation. Journal of Sound and Vibration, 319(1–2), pp. 515–530.

[71] Mateu L. and Moll, F. (2005). Optimum piezoelectric bending beam structures for energy harvesting using shoe inserts. Journal of Intelligent Material Systems and Structures, pp.1771-1785.

[72] Mathers, A. Moon, K. S. and Yi, J. Y. J. (2009). A Vibration-Based PMN-PT Energy Harvester. IEEE Sensors Journal, 9(7), pp. 731–739.

[73] Meninger, S., Mur-Miranda, J., Amirtharajah, R., Chandrasakan, A. P. and Lang, J. H. (2001). Vibration to electric energy conversion, IEEE Trans. on VLSI 9, 9(1), pp.64 – 76.

[74] Minazara, E,. Vasic, D. and Costa, F. (2014). Piezoelectric Generator Harvesting Bike Vibrations Energy to Supply Portable Devices, Australian Mining Technology Conference, pp.1-6.

[75] Mirzaeifar, R., Bahai, H. and Shahab, S. (2008). Active control of natural frequencies of FGM plates by piezoelectric sensor/ actuator pairs. Smart Materials and Structures, 17(4), pp.1-10.

[76] Nakano., K, Suda, Y. and Nakadai, S. (2003). Self-powered active vibration control using a single electric actuator. Journal of Sound and Vibration, 260, pp. 213–235.

[77] Nathan, S. Shenck and Joseph P. A. (2001). Energy scavenging with shoe-mounted piezoelectric. IEEE Micro, 21(3), pp. 30–42.

[78] Naruse, Y., Matsubara, N., Mabuchi, K., Izumi, M. and Suzuki, S. (2009). Electrostatic micro power generation from low-frequency vibration such as human motion. IOP Journal of Micromechanics and Micro engineering, pp. 1-5

[79] Ottman, G., Bhatt, A.C. and Hofmann, H. F. (2002). Adaptive piezoelectric energy harvesting circuit for wireless remote power supply. IEEE Transactions on Power Electronics, 17, pp. 669–676.

[80] Ottman, G., Hofmann, H. F. and Lesieutre, G. A. (2003). Optimized piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode. IEEE Transactions on Power Electronics, 18(2), pp. 696–703.

[81] Paradiso, J. and Starner, T. (2005). Energy scavenging for mobile and wireless electronics. IEEE Pervasive Computing, 4(1), pp. 18–27.

[82] Park, G., Rosing, T. and Todd, M. D. (2008). Energy harvesting for structural health monitoring sensor networks. Journal of Infrastructure Systems, 14, pp. 64–79.

[83] Penamalli, G. R. (2011). Structural health monitoring and energy harvesting for railroad. Master Thesis, State University of New York at Stony Brook, Stony Brook, NY.

[84] Phipps, A., Dung, P., Kerber, M. and Dick, B. (2011). Development of kinetic energy harvesting systems for vehicle applications. IEEE Sensor, pp. 24-27.

[85] Robert, G. and Radu, O. (2011). Harvesting Vibration Energy by Electromagnetic Induction, Annals of the University of Craiova, Electrical Engineering series, (35) pp. 7-13.

[86] Roundy, S. and Wright, P. K. (2004). A piezoelectric vibration based generator for wireless electronics, In: Smart Materials and Structures, 13, pp. 1131-1142.

[87] Roundy, S., Wright, P. K. and Rabaey, J. (2003). A study of low level vibrations as a power source for wireless sensor nodes, In: Computer Communications, 26(11), pp. 1131- 1144.

[88] Rome, L.C., Flynn, L. and Goldman, E. M. (2005). Generating electricity while walking with loads. Science, 309, pp. 1725– 1728.

[89] Saadon, S. and Sidek, O. (2011). A review of vibration-based MEMS piezoelectric energy harvesters. Energy Conversion and Management, 52(1), pp. 500–504.

[90] Saha, C. R., O'Donnell, T., Loder, H., Beeby, S. P. and Tudor, M. J. (2006). Optimization of an electromagnetic energy harvesting device, In: IEEE Transactions on Magnetics, 42(10), pp. 3509-3511.

[91] Saha, C. R., O'Donnell, T. Wang, N. and McCloskey P. (2008). Electromagnetic generator for harvesting energy from human motion, In: Sensors and Actuators A: Physical, 147, pp. 248–253.

[92] Scruggs, J. T. (2007). Multi-objective optimization of regenerative damping in vibrating structures. In: Proceedings of the 27th American control conference, New York, pp. 2672 – 2677.

[93] Scruggs, J. T., Cassidy, I. L. and Behrens, S. (2012). Multi-objective optimal control of vibratory energy harvesting systems. Journal of Intelligent Material Systems and Structures, pp. 1-9.

[94] Shen, D., Park, J., Ajitsaria, J., Choe, S., Wikle, H. C. and Kim, D. (2008). The design, fabrication and evaluation of a MEMS PZT cantilever with an integrated Si proof mass for vibration energy harvesting, In: Journal of Micromechanics and Micro engineering, 18(5),pp. 1-10.

[95] Shenck, N. and Paradiso, J. (2001). Energy scavenging with shoe-mounted piezoelectric. IEEE Micro, 21(3), pp. 30–42.

[96] Sodano, H. A. and Inman, D. J. (2004). A review of power harvesting from vibration using piezoelectric materials. The Shock and Vibration Digest, 36, pp. 197–205.

[97] Sodano, H. A., Park, G. and Inman, D. J. (2004). Estimation of electric charge output for piezoelectric energy harvesting. Strain, 40, pp. 49–58.

[98] Soon-Duck Kwon. (2010). A t-shaped piezoelectric cantilever for fluid energy harvesting. Applied Physics Letter, 97, pp. 1-10.

[99] Stanton, S. C., McGehee, C. C. and Mann, B. P. (2010). Nonlinear dynamics for broadband energy harvesting: investigation of a bistable piezoelectric inertial generator. Physica D: Nonlinear Phenomena, 239 (10), pp. 640–653.

[100] Starner, T. E. (2003). Powerful change part 1: Batteries and possible alternatives for the mobile market, IEEE Pervasive computing, 2(4), pp. 86–88.

[101] Starner, T. and Paradiso, J. (2004). Human generated power for mobile electronics. In: Low Power Electronics Design, C. Piguet, ed., CRC Press, 45, pp. 1–35.

[102] Sterken, T., Fiorini, P., Altena, G., Van Hoof, C. and Puers, R. (2007).Harvesting Energy from Vibrations by a Micromachined Electret Generator. Solid-State Sensors

ARPN Journal of Engineering and Applied Sciences

[103] Actuators and Microsystems Conference, 2007, Proc. Transducers, pp.129-132.

[104] Suda, Y., Shiiba, T. and Hio, K. (2003). Study on electromagnetic damper for automobiles with nonlinear damping force characteristics road test and theoretical analysis. In: Proceedings of the 18th IAVSD symposium, vehicle system dynamics supplement, Kanagawa, Japan, 41, pp. 637–646.

[105] Suzuki, Y., Miki, D., Edamoto, M. and Honzumi, M. (2010). A MEMS Electret Generator With Electrostatic Levitation For Vibration-Driven Energy Harvesting Applications. IOP J. Micromech. Microeng. pp.1-11

[106] Tang, X. and Zuo, L. (2011a). Enhanced vibration energy harvesting using dual-mass systems. Journal of Sound and Vibration, 330(21), pp. 5199–5209.

[107] Wahied, G., Ali, Sutrisno, W., Ibrahim. (2012). Power Analysis for Piezoelectric Energy Harvester. Energy and Power Engineering, 4(6), pp.496-505.

[108] Wang, D. A. and Chang, K.-H. (2010). Electromagnetic energy harvesting from flow induced vibration, In: Microelectronics Journal, 41, pp. 356–364.

[109] Wang, D. A. and Ko, D.-A. (2010). Piezoelectric energy harvesting from flow-induced vibration, In: Journal of Micromechanics and Microengineering, 20(2), pp. 1-10.

[110] Wang, D.A., Pham, H.-T., Chao, C.-W. and Chen, J. M. (2011). A piezoelectric energy harvester based on pressure fluctuations in Kármán Vortex Street, Proceedings World Renewable Energy Congress 2011, Linköping, Sweden, pp.

[111] Wang, J., Lin, T. and Zuo, L. (2013). High efficiency electromagnetic energy harvester for railroad application. ASME Design Engineering Technical Conference (IDETC 2013), pp.1-10.

[112] Williams, C., Shearwood, C., Harradine, M., Mellor, P., Birch, T. and Yates R. (2001). Development of an electromagnetic micro-generator. IEEE Proc. G-Circuits, Devices and Systems, 148, pp. 337–342,

[113] Wu, X., Lin, J., Kato, S., Zhang, K., Ren, T. and Liu, L. (2008). A frequency adjustable vibration energy harvester, Proceedings of Power MEMS 2008 μEMS 2008, Sendai, Japan, pp. 245-248.

[114] Wickenheiser, A. and Garcia, E. (2010). Power optimization of vibration energy harvesters utilizing passive and active circuits. Journal of Intelligent Material Systems and Structures, 21, pp. 1343–1361.

[115] Xu, T., Siochi, E. J and Jiang, X. (2011). A ultra-high efficiency hybrid piezoelectric harvester capturing orders more energy. Award-winning energy harvester brings practical applications closer, pp. 20-30.

[116] Zhou, W., Penamalli, G. R. and Zuo, L. (2011). Efficient and broadband vibration energy harvester with multi-mode dynamic magnifier. Smart Materials and Structures, 21(1), pp. 24-35.

[117] Zhu, D., Almusallam, A., Beeby, S., Tudor, J. and Harris, N. (2010). A Bimorph Multi-layer Piezoelectric Vibration

[118] Energy Harvester, Proceedings of Power MEMS 2010, Leuven, Belgium, pp.1-4.

[119] Zhu, D. and Beeby, S. (2011). Kinetic energy harvesting, In: Energy Harvesting Systems: Principles, Modeling and Applications, New York Dordrecht Heidelberg London, pp. 1-78,

[120] Zhu, D., Tudor, M. J. and Beeby, S. P. (2010). Strategies for increasing the operating frequency range of vibration energy harvesters: a review, In: Measurement Science and Technology, 21(2), pp. 1-10.

[121] Zuo, L. and Zhang, P. (2011). Energy, ride comfort, and road handling of regenerative vehicle suspensions. In: 2011 ASME dynamic systems and control conference, Arlington, Virginia, 135(8) pp.1-8.

[122] Zuo, L., Penamalli, G.P and Wang, J. (2011b). High-efficiency energy generator for harvesting ocean wave and mechanical vibration power, 24(7), pp. 1405-1430.

[123] Zuo, L. Scully, B. and Shestani, J. (2011c). Design and characterization of an electromagnetic energy harvester for vehicle suspensions. Smart Materials and Structures, 19(4), pp. 4-10.