Recent Developments in the Field of Piezoelectric Energy Harvesting & Advanced MEMS: An Overview

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Abstract— The study of power harvesting has had substantial increase over the past few years due to the ever-increasing desire to develop portable and wireless electronic with extended life. Current portable and wireless devices must be planned to include electrochemical batteries as the power source. The usage of batteries can be troublesome due to their limited lifespan, thus calling for their periodic replacement. Energy scavenging devices are planned to capture the ambient energy surrounding the electronics and convert it into useable electrical energy. The concept of power harvesting works towards developing self-powered devices that do not require replaceable power supplies. A number of sources of harvestable ambient energy exist, including waste heat, vibration, electromagnetic waves, wind, running water, and solar energy. While each of these origins of vitality can be effectively applied to power remote sensors, the structural and biological communities have put an emphasis on scavenging vibration energy with piezoelectric materials. Piezoelectric energy harvesters generate electricity depending on the quantity of power used in compressing or deforming the fabric, the quantity and character of distortion of the material's crystal structure and the speed or frequency of compressions or vibrations to the fabric. There are more than 200 appropriate materials which need careful selection for the special application. This article will survey recent literature in the area of piezoelectric power harvesting and present the current country of power harvesting in its campaign to create completely self-powered devices and micro electro mechanical systems.

Key words: Piezoelectric Energy Harvesting, MEMS

I. Energy Harvesting from Wearable Transducers

In the era of comfortable science and technology, we all are surrounded by a number of devices without which we can't survive like mobile phones, iPhones, digital cameras, voice recorders, musical instruments and even biomedical devices such as pacemakers. Due to decrement in size and power requirements of such daily use devices, researchers are focusing on developing such circuits which can generate electric energy from our body movements and hence can supply power to our portable electronic devices. Energy harvesting technology using piezoelectric materials is a significant step in this direction because of their ability to directly convert the mechanical strain into an electric charge. In this section we have reviewed some papers which are related to wearable piezoelectric transducers.

Starner (1996) worked on finding various locations on the human body on which energy harvesting devices can be placed and can be actuated from body vibrations.

Post and Orth (1997) worked on developing the wearable circuits from commercially available fibers like silk, ganza etc. in order to transmit the energy generated around the body to the storage medium.

Kymissis (1998) worked on harvesting the energy from the shoes (Fig:1) of a walker by using three different kinds of devices (a "thunder" actuator, a rotary magnetic generator, multilayer PVDF foil) and checked their abilities to power a battery less radio frequency tag and developed the desired circuit using a capacitor in order to accumulate the charge. He concluded that the use of the rotary generator was unrealistic for the desired purpose.

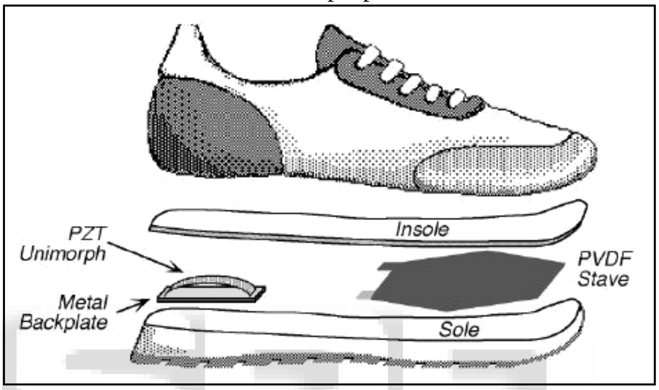

Fig. 1: Piezoelectric shoe harvester. Kymissis et al. (1998)

Shank (1999) worked on conditioning the electrical energy extracted from a stronger and less intrusive bimorph piezoceramic embedded into the sole of a shoe.

Ramsey and Clark (2001) analyzed the ability of piezoelectric transducer to power an in-vivo-MEMS, by actuating a square thin plate from blood pressure and concluded that intermittent power supply is feasible rather than continuous power supply.

Gonzalez et al. (2002) divided the human activities into two categories which represents the continuous and discontinuous mechanical energy sources available in the human body and also calculated the amount of power generated from various activities.

Niu et al. (2004) calculated the power generated from different body motions like the ankle, knee, joint, center of mass, walking, heel strike and concluded that heel strike can be best way to generate power because of the ease of introducing a piezoelectric transducer into the shoe.

Renaud et al. (2005) purposed the analytical model of a non-resonant system in order to analyze the possibilities of energy harvesting from wrist and arm motion during walking and found that proper positioning can produce maximum of 40μW of power.

Sohn et al. (2005) modeled a PVDF film based piezoelectric power harvester using finite element modeling in order to harvest energy from a fluctuating vibrational source like blood pressure of body and obtained a maximum power output of 0.61μW. There was an error of 8% in between theoretical results and FEM analysis, then he performed the experimental work and generated 0.33µW power.

Platt et al. (2005a) prepared an experimental model of energy harvesting and sensing unit that can be fitted into total knee replacement units, which was capable of harvesting the energy from knee movements as well as providing the necessary power to sensing circuitry which can sense abnormal knee conditions like over stressing, misalignment, degradation etc.

Mateu et al. (2003) connected two piezoelectric films in parallel arrangement and inserted them into sole of shoe and obtained 18µW power under the walking load of 68kg.

Mateu and Moll (2005) worked to optimize the overall configuration and shape of a shoe energy harvester using different combinations of materials (homogeneous bimorph, heterogeneous bimorph, heterogeneous unimorph PVDF films) in -31 and -33 modes and found that greatest power can be obtained from a simply supported triangular heterogeneous unimorph beam subjected to distributed load.

II. Energy Harvesting and Vibrational Damping

We can see counting less vibrating bodies in our surrounding environment, some at very low frequency and some at very high. Even we move with, a phone in our pocket and time watch on our wrist, are also vibrating bodies. Vibrations are responsible for the instability of a body/structure/component, and should be controlled and minimized for the proper functioning. Vibrations can be reduced by applying mass damping and stiffness on suitable locations on a structure that is known as Passive vibration reduction. These techniques include traditional vibration dampers, shock absorbers, and base isolation. But these techniques results in increased weight and low response. So, the mechanical vibrations induced in light weight aerospace and large-scale flexible structures have attracted engineers to investigate and develop materials to suppress these vibrations. Piezoelectric materials can be used as sensors and actuators for vibration control because of low mass, high actuating force and fast response.

When we convert the vibrations of a system into electrical energy using piezoelectric materials somewhere we are minimizing the level of vibrations in that system because of energy scavenging. Piezoelectric energy harvester takes its energy from the vibrations of the medium and thus damps the level of disturbance. Even sometime its applications can be seen in active vibration control where the electrical energy obtained from the piezoelectric sensor can be used to actuate the piezoelectric actuator which damps the vibrations of the system. In this section we have reviewed some of the papers which have focused on vibration damping applications of piezoelectric energy harvesters.

Chhabra et al. (2010) worked at suppressing the active vibrations of a cantilever & simply supported thin plate through optimally placing the piezoelectric actuators, using integer coded Modified Genetic Algorithm (MGA). In this work they used concept of maximization of controllability index (which is a function of size & position of piezoelectric actuators) using integer coded MGA to optimally place the actuators on the plate. In order to analyze the control effectiveness, schemes like LQR (Linear Quadratic Regulator) optimal control scheme and classical control strategy like constant gain velocity feedback control scheme, were used.

JM Hale, AH Daraji (2012) investigated the optimal placement of ten piezoelectric sensors/actuator pairs on a square isotropic cantilever plate, using genetic algorithm and an objective function based on modified H∞, in order to suppress the first six modes of vibrations within reduced computational cost, than other published results. For modeling the entire structure, including the plate, with piezoelectric sensor/actuator pairs, the finite element method and Hamilton's principle were used. The minimization of an absolute average open loop dB gain for all sensors/actuator pairs and modes was taken as the objective function and the symmetrical distribution of ten sensor/actuator pairs, about the plate axes of symmetry, was found as optimal configuration.

Fujun et al. (2005) found that by taking the maximization of controllability grammian, as the objective function, optimization of piezoelectric patch actuators can be achieved and also the requirement of energy for vibration control can be minimized. ANSYS Finite Element Analysis Package was used for structural analysis and optimization was implemented using genetic algorithm.

Bruant, L. Proslier (2005) performed their research to found the optimization criteria for placing the piezoelectric sensors/actuators independently on a structure, through considering residual modes, in order to ensure good observability or good controllability of each mode of structure and to limit spill-over effects.

I.Bruant, L.Gallimard, Nikoukar (2006) used a modified criteria, for optimization of number of sensors and their locations on a simply supported thin plate in order to achieve control over structural vibrations and to ensure good observability of the system. A semi genetic algorithm was developed which minimizes the number of sensors needed (from 8 to 3 in the experimental study over the plate) and optimizes their locations.

Bruant, L.Gallimard, Nikoukar (2010) investigated the optimal location and orientation of piezoelectric sensors/actuators for active vibration control. GA (genetic algorithm) technique was adopted to solve this bi-objective optimization which ensures the good observability and controllability of each mode of the structure, by taking into account the residual modes which are less observable and controllable.

K.D Dhuri, P. Seshu (2009) considered the maximization of controllability and minimization of change in natural frequency, as objective functions, for locating and sizing the piezoelectric sensors/actuators, on stationary & rotating cantilever beam cases. Multi objective genetic algorithm, MOGA (non dominated sorting GA based on simulated binary crossover and polynomial mutation) technique was used for optimizing the location and sizing of piezo patches. The Pareto optimal solutions were discussed and concluded that: least NF change is occurred using multiple and short piezos.

Kim-Ho Ip, Ping-Cheung Tse (2001) studied the steady state responses of four rectangular aluminum plates (of different aspect-ratio and of either simply supported or cantilevered boundary conditions) through a formula incorporating results from FEA, with a focus on controlling the first five modes of vibrations (individually or simultaneously) in order to optimally locate a properly oriented piezoelectric patch actuator, to improve the controllability of isotropic plate against vibrations.

Yang Y. et al. (2006) optimized the active vibration controls' parameters and feedback control gains of the control system of smart beams for vibration suppression. This process includes the placement and actuators bonded on smart beam's surface. The use of genetic algorithm has been developed. The maximization of energy dissipation criterion was introduced for the optimization of the control system. Also the distributions of the piezoelectric patches have been developed. Neeraj et. al. (2014) reviewed various optimization techniques: Meta-heuristic approaches such as evolutionary approach (genetic algorithms), simulated annealing, tabu search, swarm intelligence for the optimal placement of piezoelectric sensors/actuators on a smart structure for the purpose of active vibration control.

Varun et al. (2013) worked on the fuzzy logic controller for active vibration control of cantilever plate (figure:2). The tip displacement and tip velocity is taken as the input to the controller and control force is taken as the output. Rule base consists of nine rules. The controller found suitable for first three modes of vibration of the beam.

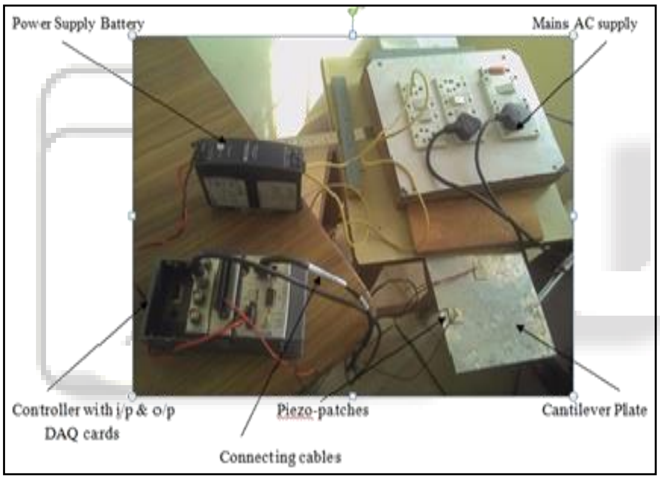

Fig. 2: Equipments used for active vibrations control, Varun et al.(2013)

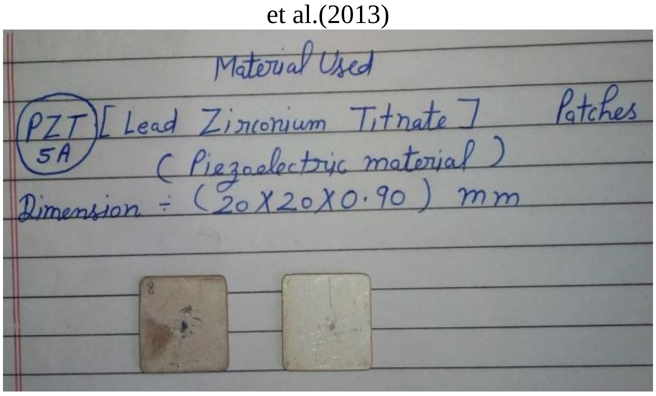

Fig. 3: Piezoelectric material used in the analysis, Varun et al.(2013)

Chhabra et. al. (2013) worked to control the active vibrations of beam like structures with distributed piezoelectric actuator and sensor layers bonded on top and bottom surfaces of the beam. Better control effect can be obtained by locating the patches at the different positions. The piezoelectric patches are placed on the free end, middle end and fixed end. The study is done through simulation in MATLAB for various controllers like POF, PID and Pole Placement technique.

Ashwani et al. (2014) performed the modal analysis of of a smart cantilever beam structure through making FEM model in ANSYS and using Block Lanczos solver to find out the optimal placement of different shapes actuator patches in the region of maximum strain and found that rhombus patch provided better effect to control the active vibrations. Table (1) shows the control effects of different shape patches and it is clear from the table that a patch with rhombus shape has minimum settling time and provides better control effect.

S.No	Shape of Piezoelectric Patch	Contact Area Sq.mm	Settling Time without control	Settling Time with control
1	Rectangular	500	8.4 sec	6.5 sec
2	Triangular	100	7.2 sec	6 sec
3	Rhombus	200	6.6 sec	5.5 sec

Table 1: Comparison of shapes of piezoelectric actuators, Ashwani et al.(2014)

Piezoelectricity v/s Other Techniques: A Comparison Piezoelectricity is not the only way to convert ambient vibrations into electrical energy, but there are some other techniques also by which this conversion can be done. There are generally three techniques by which pressure electricity can be harvested: electrostatic generators, electromagnetic generators and piezoelectric energy harvesters. Electromagnetic energy harvester contains an oscillating magnet with in a coil producing the current in the coil. In electrostatic energy harvester two conductors are separated by a dielectric, that vibrate relative to each other, behaving like a capacitor. In this section we have reviewed some papers in order to compare the advantages and disadvantages of each method of energy harvesting.

Roundy et al. (2003) performed a qualitative comparison analysis of all three methods of vibrational energy harvesting and found that electrostatic harvester require a separate voltage source to function and have an ease to get integrated into a microsystem, electromagnetic harvester don't require any separate voltage source to operate but produce low voltage output and piezoelectric harvester don't require any voltage source to harvest energy and produce a considerable amount of power output but it is more difficult to integrate them into a microsystem. They experimentally concluded that piezoelectric harvester are capable of producing more power per unit volume than electrostatic harvester.

Roundy (2005) continued his study of comparison of three methods of vibrational energy harvesting and made some more useful conclusions for practical applications. He explained that selection of a technique depends upon level of vibrations in the environment and the size of harvester and found that electromagnetic harvester produces low voltages which further get reduced if the size of harvester increases, piezoelectric harvester produces high voltage output, low current and level of current decreases both in electrostatic as well as in piezoelectric harvester as the size of device increases.

Sterken et al. (2004) compared all three techniques by their mathematical modeling and concluded that electromagnetic harvesters are best suited for large systems, electrostatic harvesters are best suited for small systems and piezoelectric harvester can be used for any size systems however its capability of producing maximum power is less than other two systems. Poulin et al. (2004) performed the analytical comparison of piezoelectric and electromagnetic methods for harvesting energy from human movement in order to power portable electronic devices and concluded that piezoelectric systems produces high power density and best suited for micro-scale applications while electromagnetic systems are best suited for macro-scale applications.

Niu et al. (2004) compared the energy harvesting abilities of all three methods, from heel strike during walking. They found that electrostatic harvester would not be useful due to requirement of separate voltage source to operate, piezoelectric harvester don't produce significant amount of power during the compression mode under heel strike, however the electromagnetic harvester are inefficient under low excitations but can be efficient if the heel strike excitations can be translated into rotational excitations.

III. Recent Developments in the Area of Vibration Energy Harvesting

Shen et al. (2015) improved the technique of enhanced synchronized switch harvesting (ESSH) and developed a new energy harvesting technique called adaptive synchronized switch harvesting (ASSH) in order to optimize the energy conversion from broadband vibrations and found that the extracted power was three times more than the previous ESSH technique. In 2014 workers of SAMLAB at the Ecole Polytechniqye Federale de Lausanne EPFL, worked to produce high performance piezoelectric unimorph MEMS energy harvester at the wafer level based on thinned sheets of the bulk form of the piezoelectric ceramic lead zirconate titanate (PZT) using microfabrication process. Researchers at Chalmers University of Technology in Sweden have developed accumulating motion pulses generator AMPG(a novel electrodynamic harvester), to harvest vibrations over a wider and lover(sub-kHz) range of frequencies, based on electromechanical technology and the products will be available in the market till the end of this year(2015). A group of researchers from Northwestern University have fabricated low stiffness polymer based springs using digital masks and UV-curable resins directly from computer aided designs and the technique of micro-stereolithography in order to develop miniaturise MEMS and other harvesting devices with lower resonant frequencies.

A group from Technical University of Denmark have tried to develop MEMS comprising four-wafer stack structure and fluoropolymer as an electret material, with low resonant frequency, from electrostatic technique. A similar technology has been used by Electret Alliance and developed a "micro electret" energy harvester at the University of Tokyo using low stiffness parylene springs which allows it to operate over broader range of frequencies and the technology has been used in a wireless RF sensor module. A group of Wake Forest University worked to generate a voltage due to a difference between body's temperature and ambient temperature, from thermoelectric effect of multi-walled carbon nanotube/polyvinylidene difluoride PVDF. Professor Wang's group at Georgia Institute of Technology used triboelectric effect which utilizes the action of contact/separation between an area of human skin and PDMS films, in order to power a tactile sensor system for tracking the location. Pavegen system, a Loughborough University spin-off, developed a energy harvesting system from human footfalls ,to store the charge in batteries and first installation the system was seen in March 2014 at train station in Saint Omer France. Georgia Tech Group developed a hybrid cell in 2009, comprising light sensitive dye-sensitised solar cell DSSC and motion responsive gallium nitride substrate with dense vertical arrays of ZnO nanowires, which was capable of harvesting energy from both solar energy as well as vibrational/motional energy.

IV. Conclusions

Most of the researchers have worked on harvesting the vibration energy from piezoelectric materials through the principal of electrostatic, electromagnetic and piezoelectricity. One of the most common conclusion all they have made is that the piezoelectricity is the best way to harvest the power because it doesn't need any separate voltage source to operate, it is easy to integrate it into a microsystem as well as capable of producing more power per unit volume than electrostatic harvester.

Many of the researchers have utilized the piezoceramics for the purpose of vibrational damping rather than for energy harvesting by using the converse piezoelectric effect and stated that piezoelectric materials can be a better option for active vibration control of the structures.

Many of the researchers have focused on improving the energy harvesting efficiency using better circuitry and improved configurations. Some of them have used the hybrid piezoelectric material for the purpose.

Piezoelectric harvester can directly convert the strain into electrical energy without any demand of external voltage source and also suited for any size device configuration. In malice of these attributes, output voltage produced by these harvesters is quite less and even during cyclic loading conditions with chances of equipment failure are more.

We can make the technology of piezoelectric energy harvesting more reliable and trustful by using more flexible piezoelectric materials with high coupling coefficients and integrating them into efficient rectifiers and storage circuits.

As we have observed that a lot of researches have done concerned to the use of piezoceramics in various areas however the topic of applications of piezoelectric polymers yet not deeply touched.

Many researchers have worked on harvesting the energy from wearable transducers like shoe transducers, wearable fabrics etc. using thin and long films of piezo-polymers.

As we know that if the thickness of piezo-film is increased the amount of power generated can be improved. But still much of work has not done on the utility of thick films of piezo-polymers for the purpose of energy harvesting.

So there is a great need of doing experimental and analysis work on thicker piezo-polymers.

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