

# **Study of different Energy Scavenging Techniques through Vibration and its Micro Power Applications**

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## **ABSTRACT**

Sensor's networks and information technology known at present an intensive development due to their numerous applications in car industry, aeronautics, telephony, computing and so on. To embark these systems in a large scale it is necessary for them, to be completely autonomous from an energy point of view. Vibration Energy Harvesting is a key point for powering sensor nodes, towards the development of autonomous sensor systems. To generate electrical energy three transduction mechanisms piezoelectric, electrostatic and electromagnetic are used. A comprehensive review of existing piezoelectric generators is presented including resonant, impact coupled and human based devices for micro power utilization. Electromagnetic generators employ electromagnetic induction arising from the relative motion between a conductor and a magnetic flux gradient. Electromagnetic generators presented in the literature are reviewed including wafer-scale integrated versions and large scale discrete devices. Electrostatic generators utilize the relative movement between electrically isolated charged capacitor plates to generate the energy. The work done against the electrostatic force between the plates gives the harvested energy. Electrostatic based generators have been reviewed under the classifications of electrets based and electrets free electrostatic devices. This paper reviewed the existing all three types of transduction mechanism for energy harvesting and their application

Keywords— Energy Harvesting, Electromagnetic, piezoelectric, Electrostatic, Converter

## **1. INTRODUCTION**

Traditional wireless sensors are deployed on conventional battery sources for their functions. These batteries have limited life span, they have to be recharged or replaced when depleted. Replacement of battery is one of the major limitation for far located sensor nodes. Energy harvesting is a solution to eliminate this limitation. Energy harvesting is available all around us in the various forms such as solar, thermal, wind, mechanical and acoustic. According to law of conservation of energy; the energy can neither be created nor be destroyed, it changes one form to another. Energy harvesting follows the same principle as converting ambient energy surrounding a system into useful electrical energy, accumulating and storing for later use. However, most of these energy sources are only available in ambient quantities. It will not be able to supply enough energy to power a useful system without some form of voltage conditioning.

Even those available in large useful quantities would still require conversion to a useful electrical form. Energy harvesting devices or modules is effectively and efficiently used to trap or capture these ambient energies which are then accumulated and stored for immediate or later use.

To develop a totally autonomous device however, traditional batteries with limited life span have to be replaced with energy harvesters. These devices can provide clean and renewable electrical energy sources. Vibration based energy harvesting is one of the attractive solutions for powering autonomous micro systems, due to the fact that, vibration sources are ubiquitous in the ambient environment.

Vibration based energy harvesting is one of the promising solutions for powering autonomous micro systems, due to the fact that, vibration sources are ubiquitous in the ambient environment. The electrical energy is converted from vibrational energy via electrostatic, electro-mechanic or piezoelectric transduction method.

As vibration energy harvesting is promising, but having challenges that taken into consideration for effective energy harvesting. For effective energy harvesting, the harvester must be in resonance with the source frequency. Gieras et al suggested that resonance frequency can be adjusted via altering the length of the cantilever [1], while Wu et al have used a similar technique for tuning purposes via moving a tip mass [2]. Roundy et al describes other methods for tuning the resonance by applying an electrical potential to alter the beam stiffness through thermal, electrostatic, and piezoelectric methods [3][4]. Prasad et al have proposed a magnetic force resonance frequency tuning technique which allows one to tune the natural frequency of the energy harvesting beam to match both lower and higher source frequencies [5]. MEMS energy harvesting devices can be passively tuned due the non linearity of piezoelectric materials [6]. Adapting these techniques to a self-tunable energy harvesting device would enable the device to tune its natural frequency by itself without user intervention.

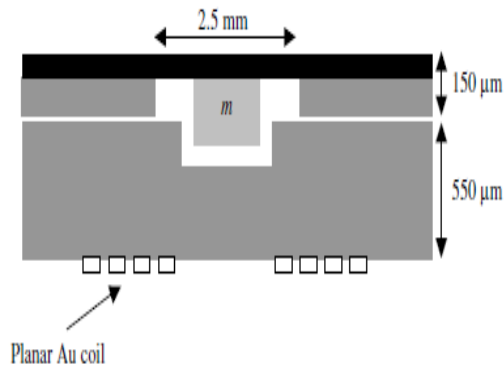
## **2. ELECTROMAGNETIC**

In 1831, Faraday discovered the concept of Electromagnetic induction. It is the generation of electric current in a conductor located within a magnetic field. The conductor typically takes the form of a coil and the electricity is generated by either the relative movement of the magnet and coil, or because of changes in the magnetic field. One of the most effective methods for energy harvesting is to produce electromagnetic induction by means of permanent magnets, a coil and a resonating cantilever beam. In principle, either the magnets or the coil can be chosen to be mounted on the beam while the other remains fixed.

### **2.1 Wafer Scale implementation**

Williams et al [7] described an electromagnetic approach as shown in figure 1. The size of the electromagnetic transducer is  $5\text{mm} \times 5\text{mm} \times 1\text{mm}$ . The electromagnetic generator consists of a seismic mass  $m$ , and spring  $k$ . When the generator starts vibrated, the mass moves out of the phase with the generator, therefore there is a net movement between the mass and the housing. This relative displacement is assumed to be

sinusoidal in nature and can drive a suitable electromagnetic transducer to generate electrical energy. The transducer is interpreted as a dashpot,  $d$ , as the conversion of mechanical energy into electrical energy damps the vibrations.



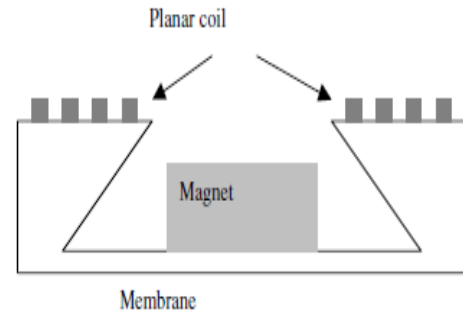
**Figure 1: Cross-section of the electromagnetic generator proposed by Williams *et al* [ 8].**

Shearwood *et al* from the University of Sheffield, UK [9] fabricated a generator which comprises of a flexible circular membrane. It was bulk micro machined on a GaAs substrate coated with a 7 μm layer of polyimide. Inside the membrane a SmCo magnet, of mass of  $2.4 \times 10^{-3}$  kg, was attached. On a separate wafer the planar Au coil of 13 turns was patterned. The device was tested and generated 0.3 μW at excitation frequency of 4.4 kHz. The measured electrical power output was lower than the expected value and this was thought to be due to the nonlinear effects of spring stiffening, which occurred as the excitation amplitude was increased.

Mizuno *et al* designed resonant micro generator [10] having a beam with an integrated coil and a fixed external magnet. The dimensions of the cantilever beam were  $500 \times 100 \times 20$  μm and the size of the NdFeB magnet was  $30 \times 10 \times 6$  in mm. The resonant frequency of the structure was 58 kHz. A power output of only 6 nW was predicted for a typical single-element electro-magnetic micro-generator. The estimated magnitude of the output voltage was being only 1.4mV. The authors fabricated a larger version of their proposed device for evaluation purposes.

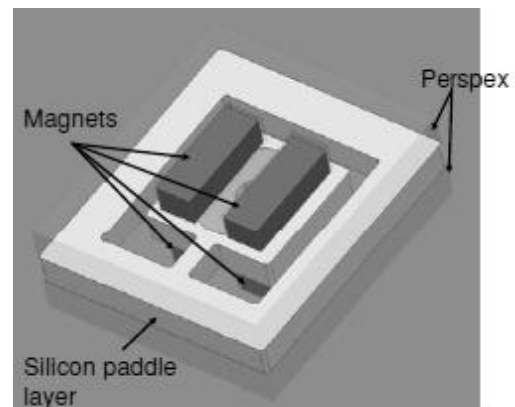
Huang *et al* have raised the issue of human-powered electrical generation [11] and suggest a method of using an electromagnetic harvester comprising a planar copper coil, a nickel-iron spring element and a magnet. The resonant frequency of the device is 100 Hz and generating is reported to be ability of producing 0.16 μW for an excitation level provided by a finger tap.

A similar structure has been investigated by Serre *C et al* [12], who have used the spring of a polyimide film, NdFeB magnet and a 1.5 μm thick aluminium layer made planar coil as shown in figure 2. The power output is 1.44 μW for a displacement of 10 μm and a resonant frequency of 400 Hz.



**Figure 2. Inertial generator described by Serre *C et al* [12].**

Beeby *et al* have designed a silicon-based generator having micro machined paddle, four NeFeB magnets and a wire-wound coil [13] as shown in figure 3. Two of the magnets are located within etched recesses in the two Pyrex wafers. These are bonded to each face of the silicon wafer. The coil is placed on a silicon cantilevered paddle, which is designed to vibrate laterally in the plane of the wafer. The device has a resonant frequency of 9.5 kHz and has been shown to generate 21 nW of electrical power from 1.92 m s<sup>-2</sup> rms.



**Figure 3. A silicon electromagnetic generator (after Beeby *et al* [13]).**

El-Hami *et al* in their paper [14] presents the simulation, fabrication, modeling and characterization of a vibration-based electromechanical power generator. The device made of a cantilever beam (spring), fixed at one end and supporting a pair of magnets (NdFeB) on a c-shaped core at the free end as shown in figure 4. The coil is made up of many turns of copper wire and is fixed in position between the poles of the magnets. It was found that power generation in excess of 1 mW for a volume of 240 mm<sup>3</sup> at a vibration frequency of 320 Hz was obtained. Several companies are emerging now days in field of energy harvesting. Kinetron, a electromagnetic product patent by a Dutch manufacturer is capable of harnessing the kinetic energy produced by the movement of the human wrist [15]. UK based company Perpetuum Ltd [16] has developed a series of vibration powered electromagnetic generators which cover a broad range of vibration frequencies.

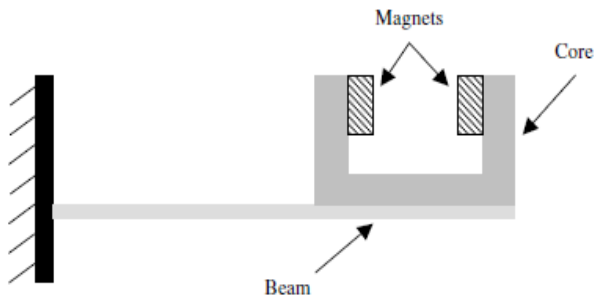


Figure 4. The electromagnetic generator proposed by El-Hami et al [14].

### 3. PIEZOELECTRIC

In 1880 Pierre and Jacques Curie found that certain crystals, most notably quartz and Rochelle salt, produced a surface charge under a compressive load. This generation of electric charge under mechanical pressure is known as the direct piezoelectric effect. One year later, Gabriel Lippman mathematically proved the converse piezoelectric effect, where an induced voltage will cause mechanical deformation. And later experimentally observed by the Curie brothers. The natural crystals that were initially discovered exhibited weak coupling between the mechanical and electrical domains. More recently however, synthetic piezoelectric materials have been created with increased coupling that enable the use of piezoelectricity in real world applications. The piezoelectric effect exists in several crystalline materials due to the polarity of the unit cells within the material. This polarity leads to the production of electric dipoles in the material which give rise to the piezoelectric properties.

The application of mechanical strain causes rotation of the dipoles, leading to an apparent charge flow that can be measured as current by placing electrodes on opposite faces of a piezoelectric material (direct piezoelectric effect). Similarly, the application of a voltage across the material will cause rotation of the dipoles which results in an induced strain in the material (converse piezoelectric effect).

The piezoelectric constitutive equation is described mathematically

$$\{S\} = [s^E]\{T\} + [d^t]\{E\}$$

$$\{D\} = [d]\{T\} + [\epsilon^T]\{E\}$$

Where S is the mechanical strain, D is the displacement, E is the applied electric field and T is stress.

The piezoelectric materials have vast applications as electromechanical coupling of piezo materials make them act as a sensors while operating in direct effect and as an actuator while operating in converse effect.

Commercially a large range of piezoelectric devices are available. The most common piezoelectric material is lead zirconate titanate (PZT), a piezoelectric ceramic. Piezoelectric ceramics are often used however, they are extremely brittle. In an effort to create flexible piezoelectric material, several piezoelectric fiber-based materials have been developed.

These materials contain thin extruded strands of piezoceramic fiber embedded in an epoxy matrix with flexible surface electrodes. Piezoelectric fiber-based materials have the advantage of being flexible and can be mounted on curved

surfaces, however, their coupling is typically weaker than that of monolithic ceramics. Additionally, piezoelectric polymer material, most notably polyvinylidene fluoride or PVDF, provides the highest degree of compliance but the weakest coupling. The wide range of piezoelectric materials allows for their use in a variety of diverse applications.

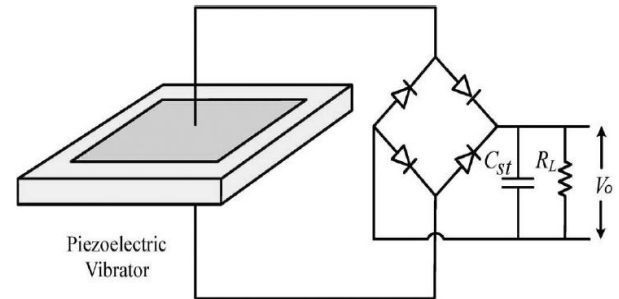


Figure 5. Vibration energy harvester through piezo material

A.Vasquez Quintero et al [17] in their paper “Vibration Energy Harvesters on Plastic foil by lamination of PZT thick sheets” presents a low complexity and low temperature fabrication process for vibration energy harvesters. They presented a process flow used to transfer thinned PZT thick sheets onto flexible polymeric substrates (PET) using lamination techniques. The transfer was achieved using a dry film photoresist laminated at relatively low temperatures (85°C). The geometrical influence on resonance frequencies were investigated by FEM simulations. Optimization of the output power was performed by modifying the neutral plane within the device and by using a localized seismic mass at tip; which has resulted in an output power of 30  $\mu$ W at 52 Hz and an acceleration of 1g.

Ahmed Telba et al [18] present modeling and simulation of piezoelectric energy harvesting. The research motivation is to reduced power requirement of small electronic components, like the wireless sensor networks used in structural health monitoring applications. They describes a dynamic model to simulate piezoelectric harvester and to identify model parameter with real time measurements. The main core of the setup includes National Instruments simulation and real time measurements tool Labview which is used to simulate and measure the real data from the piezoelectric energy harvesting system through a compact data acquisition system (cDAQ-NI 9188).

Gaudara Ravi Prakash et al [19] designed and modeled a MEMS based energy harvesting device to convert beta particle energy to electrical energy via piezoelectric effect. This Cantilever beam resonates at a frequency of 110 KHz and an output voltage obtained is 0.0956 V. They proposed device which is found to be suitable for beta particle energy harvesting and can be used as potential micro-generator. An electrostatic cantilever actuated by radioisotope emitted electrons has been modeled and simulated. The long half life of the source enables the cantilever to be used as an electromechanical transducer for long run applications. Furthermore, the temperature insensitivity of the radioisotope charge particle emission might enable extreme high or low temperature operation, not possible with chemical batteries. The developed and simulated model is capable of generating 0.0956 V and occupying volume of  $0.3 \times 10^{-12}$  m<sup>3</sup>, 38 such

cantilevers occupying a volume of  $11.1 \times 10^{-12} \text{ m}^3$  to generate 3.7V (mobile phone batteries).

Suyog N Jagtap et al [20] optimize the geometry of the MEMS based energy harvesting device. Performance comparison is done between various devices and they proposed the device which is suitable for energy harvesting and can be used as potential micro generator.

Chengliang Sun et al [21] established a general theoretical framework for estimating the piezoelectric potential. The energy conversion efficiency and output power of a series of nanostructures with different morphologies and made from different materials. Static analysis studies the maximum piezoelectric potential that can be produced by a ZnO NW, BaTiO<sub>3</sub> NW, ZnO nanofin when they are subjected to a constant external force. The dynamic analysis is performed to study the power generation ability via the vibration of these nanostructures agitated by ambient vibration energy. Systematic comparisons were established between NW and NF morphologies and among ZnO, BaTiO<sub>3</sub>, and PMN-PN materials by revealing their output voltages, powers, and conversion efficiencies. The size dependency analysis suggested the optimal size choices for NW and NF structures. The highest voltage output was found from ZnO NWs, whereas BaTiO<sub>3</sub> and PMN-PT could generate larger output power.

M. Guizzetti, [22] designed a geometry to improve the performance of the converter. In this context FEM simulations have been used in order to optimize the piezoelectric layer thickness. By using the application moving mesh mode the parametrized geometry was created. Under an applied acceleration, the electrical energy generated by the converter was calculated, finding the optimal thickness for the piezoelectric layer. The different geometries were considered verifying that they do not affect the optimal thickness. They verified that the optimal thickness ratio  $t_{\text{PZT}}/t_{\text{substrate}}$  is independent from the converter dimensions, and it is influenced only by the mechanical properties of the piezoelectric layer and the substrate.

Sebastain Pobering, [23] in their research paper “Power Supply for Wireless Sensor System” presents an energy harvesting system which generates electrical energy from flowing media without any rotating parts. They developed a generator which converts Kinetic energy of flowing media into electricity without any rotating part. Piezoelectric bimorph cantilevers is used in generator with very low maintenance requirement. Maximum Voltage of .8 V have been achieved at air flow velocity of 35 m/s. Investigations on a macroscopic model of the generator have proven the functionality of the principle. Output voltages of 0.8 V and power ratings up to 0.1 mW have been achieved by one cantilever. Because the used cantilevers are not optimized these values can be strongly increased. Adjacent cantilevers have shown a strong influence on each other which can increase the deflection and amplification can increase the power output.

Sodano *et al.* (2004) [24] use a PSI-5h4e piezo bonded onto a plate ( $80\text{mm} \times 40\text{mm} \times 0.095\text{in.}$ ) to collect a charge in first, a capacitor, and second in a NiMH cell. For the capacitor, they use an adaptation of a circuit designed for a self-powered RF tag.

Gao *et al* perform a three dimensional analysis for free vibration on composite laminate plates with piezoelectric

layers. Power series are used as solutions to displacement and electric potential.

Different mode shapes and analytical natural frequencies are calculated and compared to measured values. The power series expansion method is proven to be simple and convenient.

Wang *et al* develops sets of equations for determining the deformation compatibility between piezoelectric patches and beams or plates. The interaction forces between the piezoelectric patches and substrates are caused by structural deformation and an electric field imposed upon the piezoelectric patch. The static capacitance is found to vary according to deformations caused by the imposing electric field.

The piezoelectric patches could be used as sensors to monitor the change in static capacitance with the same piezoelectric patches used as actuators.

#### 4. ELECTROSTATIC

A capacitor having two plates which are electrically isolated from each other by vacuum, air or an insulator. Battery of voltage  $V$  creates opposite charges  $Q$  on the plates of the capacitor, leading to storage of the charge when the voltage source is disconnected. In Micro-electro mechanical system the separation between the two plates is typically very small (nm to  $\mu\text{m}$ ).

Capacitance of the capacitor:

$$C = Q/V$$

Where  $C$  = capacitance in farads,  $Q$  = charge on the plate in coulombs and  $V$  = the voltage on the plates in volts.

For a parallel plate capacitor,  $C$  is given by:

$$C = \epsilon (A/d)$$

Where  $\epsilon$  = the permittivity of the material between the plates in  $\text{F m}^{-1}$ ,  $A$  = the area of the plates in  $\text{m}^2$  and  $d$  is the separation between the plates in m.

If  $\epsilon_0$  = the permittivity of free space, the above equation can be expressed in terms of the dielectric constant  $\kappa = \epsilon/\epsilon_0$  of the insulator material:

$$C = \kappa\epsilon_0 (A/d)$$

The voltage across a parallel plate capacitor is calculated as:

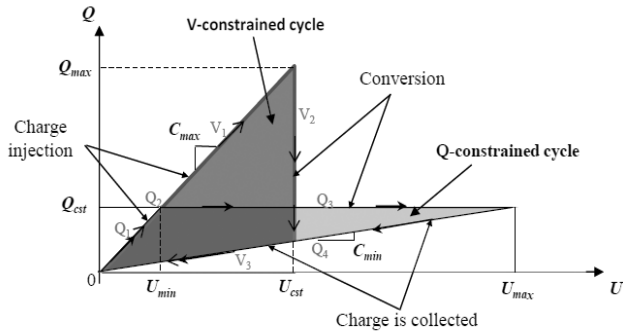
$$V = Q/d/\epsilon_0 A$$

The work done against the electrostatic force between the Plates provides the harvested energy. Electrostatic converters broadly divided into two parts:

1. Electret-free electrostatic converter
2. Electret based electrostatic converter

##### 4.1 Electret free electrostatic converters

These types of converters use conversion cycles which is made up of a charges & discharges of a capacitor. These energy cycles are commonly charge constrained and voltage constrained cycles.



**Figure 6: Standard energy conversion cycles for electret-free electrostatic devices**

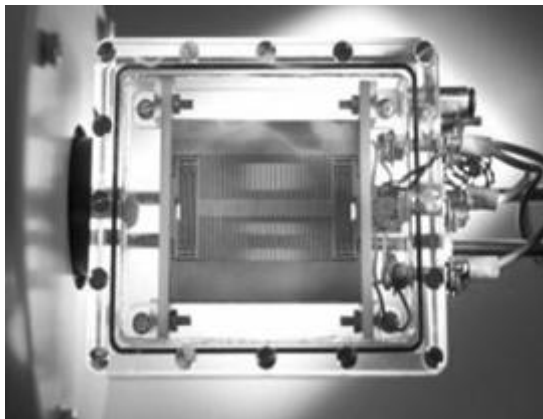
## 4.2 Electret based electrostatic converters

These types of converters having the capability to direct convert the mechanical power into electricity by using electrets. Electrets are dielectric materials, basically they are electrostatic dipoles equivalent to permanent magnets (but in electrostatic) that keep charges for the years. As we know that energy harvesting vibrations requires two conversion steps i.e., mechanical to mechanical converter as in mass spring resonator which turns ambient vibrations into a relative movement between two elements and mechanical to electrical converters that convert relative movement into electricity.

Meninger et al at the MIT in 2001, developed MEMS electrostatic comb based VEH [25]. This energy harvesting device used in plane overlap electrostatic converter. They proven that if power management electronics is limited in voltage, the voltage constrained cycle enables to maximize output power. So far, for this prototype charge constrained cycle was adopted to simplify the power management circuits. Tashiro et al, [26] in 2002 designed a pacemaker which is capable of harvesting power from heartbeats. This prototype was installed on the heart of a goat & it was 58  $\mu\text{W}$ .

In 2003, [27] the best structure for the electrostatic devices was in plane gap closing proved by Roundy. He would be able to harvest up to 100  $\mu\text{W}/\text{cm}^2$ .

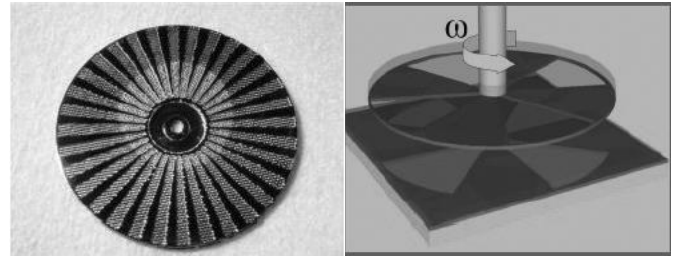
The highest power density of a eVEH ever reached was developed by a Despesse in 2005[28]. They are able to work on a low vibrations frequencies and able to harvest 1mW for a vibration of 0.2 G@ 50 Hz



**Figure 7: Electrostatic VEH [28].**

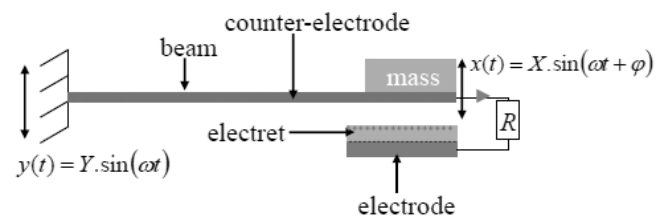
From a long time various electrets based generator exploiting a mechanical energy of rotation were developed. One of them

was developed in 2003, able to turn a relative rotation of upper plate compared to the lower plate into electricity by Boland [29].



**Figure 8: Boland's electrets based generator prototype**

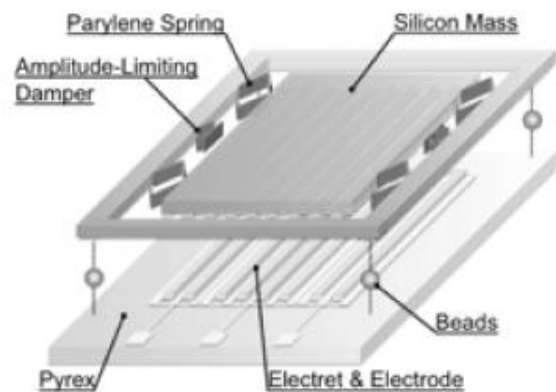
Mizuno et al in 2003 [30], designed an out of plane gap closing structure using a clamp free beam moving above an electret. The same structure was also studied by Boisseau et al [31] in 2011.



**Figure 9: Cantilever based electrets energy harvester [31]**

In 2007, Sterken et al [32] first designed an integrated structure using full sheet electrets. A full sheet is used as the polarization source. The main drawback of this prototype is to add a parasitic capacitance in series with the energy harvester which limiting the capacitance's variation and the converter's efficiency.

In 2006, the first structure using patterned electrets was developed by the University of Tokyo [33]. Miki et al [34] improved the first architecture devices by developing a multiphase system and using non-linear effects.



**Figure 10: Multiphase electret energy harvester exploiting non-linear springs**

Developing low-resonant frequency energy harvesters is a big challenge for small scale devices. In most of the cases ambient vibrations' frequencies are below 100 Hz. It brings to

long and thin springs difficult to obtain by using silicon technologies. Therefore to reduce resonant frequency of VEH keeping small dimension solutions as parylene spring [35] were developed. Nourse has already using microballs that such a system could operate at very low frequencies (<2 Hz) and could produce up to 40  $\mu$ W [36].

**Table 1: An overview of electrostatic VEH for electret free**

Author	Tashiro	Roundy	Despesse
Ref	[26]	[27]	[28]
O/P power	36 $\mu$ W	11 $\mu$ W	1050 $\mu$ W
Surface	-	100 mm <sup>2</sup>	1800 mm <sup>2</sup>
Volume	15000 mm <sup>3</sup>	100 mm <sup>3</sup>	1800 mm <sup>3</sup>
Vibration	1.2G@6 Hz	0.23G@100Hz	0.3G@50hz
Polarization Voltage	45V	-	3 V

**Table 2: An overview of electrostatic VEH for electret based**

Author	Ref	Vibration /Rotation	Active surface	O/P power	Electr ic potent ial
Boland	[29]	4170 rpm	0.8 cm <sup>2</sup>	25 $\mu$ W	150 V
Sterken	[32]	1G@500 Hz	0.09 cm <sup>2</sup>	2 nW	10 V
Boisseau	[31]	0.1G@50 Hz	4.16 cm <sup>2</sup>	50 $\mu$ W	1400 V
Miki	[34]	1.57G@6 3Hz	3 cm <sup>2</sup>	1 $\mu$ W	180 V
Nourse	[36]	0.4G@2Hz	9 cm <sup>2</sup>	40 $\mu$ W	-
Suzuki	[35]	5.4G@37 Hz	2.33cm <sup>2</sup>	0.28 $\mu$ W	450 V

## 5. CONCLUSION

There are three main approaches that can be used to implement a vibration to energy generator. All of the three technologies described in this review has their own pros and cons and these are now summarized. Piezoelectric offer the

simplest approach. The structural vibrations are directly converted into a voltage output by using an electrode piezoelectric material. These types of generators are the simplest type to fabricate and can be used in force and impact coupled harvesting applications. One of the major advantages is that piezoelectric transduction principle is particularly well suited to micro engineering. This method is capable of producing relatively high output voltages but only at low electrical currents. Electromagnetic generators are well-established technique of electrical power generation and the effect has been used for many years in a variety of electrical generators. The spring/mass configurations that can be used with various types of material those are well suited and proven in cyclically stressed applications. The electrostatic generator concept is easily realizable as a micro electro mechanical system and much processing know-how exists on the realization of in plane and out of plane capacitors. The electrostatic generators require an initial polarizing voltage or charge. Electrostatic generators can utilize electrets to provide the initial charge and these are capable of storing charge for many years. The output impedance of the devices is often very high and this makes them less suitable as a power supply. The three main techniques of harvesting energy from ambient vibrations have been shown to be capable of generating output power levels in the range of  $\mu$ W to mW.

Vibration-powered wireless sensor systems can be used in numerous scenarios and several research groups across the world are addressing possible uses in ambient intelligence, medical implants and smart clothing. Wireless, battery-less industrial condition monitoring systems are already close to commercialization.

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