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A Review of Vibration Energy Harvesting, Techniques and Applications

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Abstract: Energy harvesting is the process of drawing out a small amount of energy from the ambient environment. The ambient environment is characterized by various available sources of energy such as solar, wind, vibration, gas, liquid flows, etc., which can be converted to usable energy. Vibration energy harvesting is a mechanical process of gathering ambient energy from vibrating sources that can be converted into electrical energy using different techniques of conversion. Vibration energy is available in the urban and industrial environment, but it is often overlooked as a source of power to be scavenged for electricity. The main harvesting techniques are electromagnetic conversion, electrostatic conversion and piezoelectric conversion. This paper will review the work carried out by researchers during the last few years in this field and will compare the different conversion techniques.
Keywords: Energy harvesting, Energy conversion, Electromagnetic, Electrostatic, Piezoelectric

1. Introduction

For decades, the concept of energy harvesting has been implemented in energy systems powered by the ambient environment of the real world, but its concretization is heavy, complex and expensive. However, examples of markets in which such an energy harvesting approach has been used with success include wireless medical devices, detection of tire pressure, transport infrastructure and building automation [1].

Energy harvesting is a technology that permits the capture of otherwise unused ambient energy such as wind, vibration, temperature gradients, energy of gas and liquid flows and converts it into usable electrical energy. Energy harvesting is a perfect match for wireless devices and wireless sensor networks that rely on rechargeable batteries [2]. This form of energy generation is also called energy scavenging or power harvesting [3].

Several attempts are being made for energy harvesting from the ambient environment in different conversion technologies and their applications. Many environments are subject to ambient vibration energy that commonly goes unused. A variety of conversion technologies exist for converting ambient vibration energy as it exists to a form of mechanical movement that can be harnessed then into electrical energy. The main conversion technologies are electromagnetic conversion, electrostatic conversion, and piezoelectric conversion. Ambient vibrations can be found in many applications including natural, commercial, industrial and transport environments. Examples are vehicle engine compartments, ships, bicycles, trains, helicopters, washing machines, fridges, microwave ovens, pumps and machinery, floors (train stations, offices, nightclubs), bridges, walls, windowpanes, speakers, and humans (human heartbeat) [4].

The amount of energy generated by this approach depends fundamentally upon the quantity and form of the vibration energy available in the application environment and the efficiency of the generation and the electronic power conversion [5].

This paper reviews the field of vibration energy harvesting, describing the different techniques of conversion that may be employed and their applications, compares them, and summarizes all this information in table form.

2. Various techniques of vibration energy harvesting

Vibration energy represents the most abundant energy source after solar. Vibration energy harvesting is a mechanical process of gathering ambient energy from a vibration source and converting it into electrical energy using various technologies. The techniques used to recover the energy produced in the environment by vibrations are arousing more and more interest and these can be converted into energy production tools. The exploitation of ambient vibration energy appears to be an excellent way of converting vibration energy into electricity. Vibration energy harvesting is converted into electrical energy through various techniques, including electromagnetic conversion which implements the inductive effect, electrostatic conversion based on the electrical force generated between two plates of a charged capacitor and piezoelectric conversion which converts a mechanical stress into electrical charges directly [5]. In the following sections, these different types of conversion techniques are described and examined.

2.1 Electromagnetic conversion

Faraday was the first to discover the electromagnetic phenomenon. Electromagnetic induction is the production of electrical current into a conductor that is found in a magnetic field. This is why it is characterized by a law that called the Faraday law. Several systems of vibration energy harvesting are based upon the movement of a permanent magnet inside a coil. This movement creates a current in the coil and on the surface of the coils proportional to the variation of the magnetic flux in the coil, therefore proportional to the velocity of the magnet. Figure 1 shows two frequently observed examples of electromagnetic conversion [6]. In electromagnetic conversion, permanent magnets are used to produce a strong magnetic field and a coil is used as the conductor. Either the permanent magnet or the coil is fixed to the frame while the other is attached to the inertial mass. The relative displacement caused by the vibration makes the transduction mechanism work and generate electrical energy.

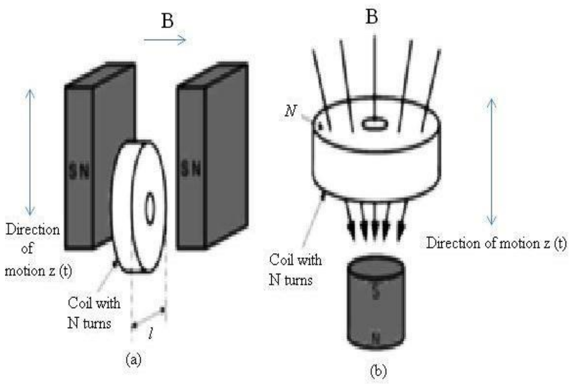

Figure 1: Electromagnetic conversion [6]

In Figure 1(a), the cutting of the magnetic field of the coil varies as a function of the relative movement among the coils and magnets. In Figure 1(b), there is a distance between the magnets of the magnetic field. In the two events, the induced voltage is function of the relative moving velocity and it is determined by following equation as:

$$e_m = k \times \frac{dz}{dt} \qquad (1)$$

Where k is Electromagnetic coupling factor which corresponds to $-N \times l \times B$ and $-N \times S \times \frac{dB}{dz}$ representing the variation in coupled flux per unit displacement, N is the number of turns in the coil, l is the effective length of the coil [m], B is the flux density across the coil [T], $\frac{dz}{dt}$ is the relative motion among the magnet and coil by time. S is the effective area of the coil [m^2], $\frac{dB}{dz}$ is the gradient of the magnetic flux density between the coil and magnet by velocity.

Usually, the simplest structure used is a mobile magnet and a fixed coils, or vice versa. The damping coefficient of induced electromagnetic conversion b_e , for calculating the power harvesting output, is given by:

$$b_e = \frac{k^2}{R_C + R_L + j\omega L_C} \qquad (2)$$

Where R_C is the resistance of the coil [Ω], R_L is the resistance of the load [Ω], L_C is the inductance of the coil [H], ω is the angular frequency of vibration [rad.s^{-1}].

When the electromagnetic conversion operates at frequencies of low resonance, the impedance of the coil is much smaller than its resistive impedance. Therefore, the inductive impedance is negligible and the damping coefficient of induced electromagnetic transduction b_e becomes:

$$b_e = \frac{k^2}{R_C+R_L} \quad (3)$$

The damping factor electrically induced ζ_e is given by:

$$\zeta_e = \frac{k^2}{2m\omega(R_C+R_L)} \quad (4)$$

In the equation 4, R_L can vary adjusted from b_e to b_m and thus the power output can be maximized. The load resistance optimum and the maximum power load are given by the following expressions:

$$R_L = R_C + \frac{k^2}{b_m} \quad (5)$$

$$P_e = \frac{ma^2}{16m\omega_r\left(1-\frac{R_C}{R_L}\right)} \quad (6)$$

Where b_m is the parasitic damping coefficient, a is the acceleration of the vibration [ms^{-2}], m is the seismic mass [g], ω_r is the resonant frequency [Hz].

Several studies on conversion of ambient vibration to electrical energy via electromagnetic conversion have been carried out. The main problem (3) concerning this conversion technique is that the output voltage level is too low.

Beeby et al. [7] studied a harvester of energy placing a coil at the end of a cantilever overhang excited by the base and oscillating between two magnets. They presented a small components volume, practical volume 0.15cm^3, electromagnetic vibration energy harvesting device optimized for a low level of ambient vibration based upon real application data. The generator produced useful power of 46μW to a resistive load of 4kΩ from a vibration level of 60mg, when the device was shaken at its resonant frequency of 52Hz. The generator delivered 30% of the total power dissipated in the generator to electrical power in the load. From the basic equations governing electromagnetic generators, they concluded that the energy decreases with device volume, and reducing input vibration acceleration.

Li et al. [8] developed a vibration-induced power generator with total volume of 1 cm^3 using a lasermicro machined copper resonating spring based on Faraday's Law of induction according to which a spring can convert mechanical energy into useful electrical power. By innovative spring designs, the mass can be made to vibrate horizontally while the input vibration is applied vertically. The horizontal vibration provides significantly higher output voltage for the generator. Li et al. have developed a generator capable of producing 2V DC with 64Hz to 120Hz input frequency at 250 to 1000μm input.

Williams et al. [9] developed a design methodology for linear micro-generators, applied to the design of a millimeter scale electromagnetic micro-generator. The fabrication of a prototype device is described using generally available micro fabrication techniques. The results of testing the device on a variable amplitude vibration source, in vacuum and air, are presented. With the prototype device, the generation of electrical energy from mechanical vibrations was a power of 0.3μW at an excitation frequency of 4MHz. The power produced by such devices is proportional to the cube of the frequency of vibration. In order to maximise the power that can be produced in any particular application, the resonant frequency of the generator should be designed to match the frequency spectrum of the source vibration, and the maximum possible deflection of the device should be made as large as possible. They concluded that mechanical damping is a dominant limiting factor in these devices and significant improvements in power output may be obtained through better spring linearity and vacuum operation. The electromagnetic coupling should also be optimized to ensure a good impedance match between the device and the electrical load.

Qian Zhang and Eun Sok Kim [10] described a new idea to increase the energy conversion efficiency of electromagnetic transduction by orders of magnitude. They used an array of alternating north- and south-orientation magnets to enhance magnetic flux change by more than an order of magnitude. Magnetic flux changes for a magnet array and a single magnet are simulated and compared. A micro fabricated energy harvester of 20mm×5mm×0.9mm weighing 0.5g generates an induced electromotive force of V_{p-p}=30mV with 2.6µW power output into 10.8Ω load when it is vibrated at 290Hz with a vibration amplitude of 11µm. The macro scale version, scaled up to 51mm×51mm×10mm weighing 90g, generates an induced electromotive force of V_{p-p}=22V with 158mW power output (into 96Ω load) when it is vibrated at 82Hz with a vibration amplitude of 414µm, and lights an incandescent light bulb.

Zorlu and Külah [11] presented a non-resonant environmental vibration based electromagnetic MEMS energy harvester, which generates energy from low frequency vibrations with low displacement amplitude. They used a prototype electromagnetic transduction technique to produce electrical energy. This type of technique can be adapted also for electrostatic and piezoelectric conversion. The prototype has a size of 4mm×8.5mm, and the peak to peak of the movement of the magnet is between 3 to 5mm. It generates a rms voltage of 2.1mV and rms power of 18.5µW at a frequency of 10Hz, with external vibration 5mm peak to peak (1g) and an energy of 1.1µj which is transferred to equivalent resistive loads from each coil for each occurrence of the mFupC. This prototype is a good candidate for energy harvesting applications with non-resonant vibration characteristics including the motions of a vehicle, the movement of the branches of trees and human motions.

Wang et al. [12] designed, simulated, fabricated and characterized a micro electromagnetic vibration energy harvester with sandwiched structure and air channel. The harvester consists of an upper coil, lower coil, a nickel planar spring integrated with silicon frame and a NdFeB permanent magnet. The tested natural frequency of the magnet-spring system is to 228.2Hz. Comparison of the simulation and the tested natural results shows that the Young's modulus of micro electroplated Ni film is about as 163GPa rather than 210GPa of bulk Ni material. These experimental results show that the sandwiched structure and the air channel in the silicone frame of the prototype can make the induced voltage to 42%. The resonant frequency of the prototype is 280.1Hz at an acceleration of 8 m/s^2 which results from the nonlinear magnet spring system. The prototype generates a charging voltage of 162.5mV when it is at resonance and the input vibration acceleration is 8m/s^2 and maximum charging power obtained is about 21.2µW when the load resistance is 81Ω.

2.2 Electrostatic conversion

Energy harvesting by electrostatic conversion can be accomplished by two conductors separated by a capacitor which vibrates relative to each other. By varying the distance between the conductors, the stored energy in the condenser changes thereby becoming a device converting mechanical energy into electrical. Unlike electromagnetic and piezoelectric conversion systems, electrostatic conversion systems need to be preloaded before producing electricity (power) and they are mechanically limited to prevent contact between the conductors causing a short circuit.

Electrostatic conversions are classified into three categories:

- Electrostatic conversion *in plane overlaps* in which the overlap area varies between the electrode fingers as shown in Figure 2 (a).
- Electrostatic conversion *in plane gap closing* where the gap varies among electrode fingers as shown in Figure 2 (b).
- Electrostatic conversion *out of plane gap closing* where the gap varies among the two main electrode plates as shown in Figure 2 (c) [6].

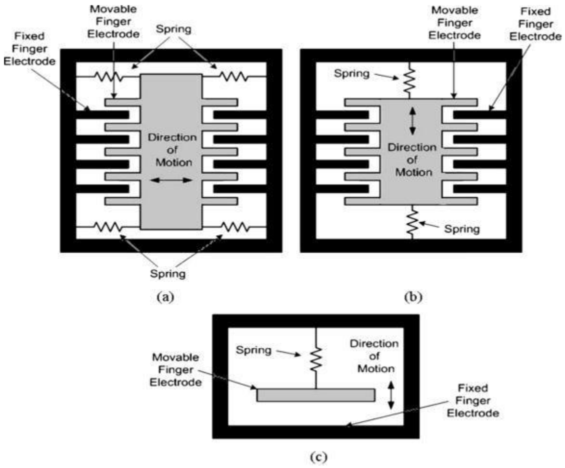

Figure 2: Electrostatic conversion [6]

These three categories can be used in constant voltage cycles or in constant charge cycles. In general, the generators supply more energy in constant voltage cycles electrostatic conversion than in constant charge cycles electrostatic conversion. The mechanical motion imposed on the structure where the energy is stored, allows for varying of the value of this capacity. Due to the constant charge (Q = CV), when the plates move away, the voltage across it increases. Finally, the loads are removed from the structure in its minimum capacity. The electrical energy harvested is more important than the energy initially injected. Electrical energy is amplified by the mechanical energy [13]. For the two cycles described above, the energy stored is given by:

- *For the constant charge:*

$$E_{Q.cst} = \frac{1}{2}Q^2\left(\frac{1}{C_{min}} - \frac{1}{C_{max}}\right) \quad (7)$$

- *For the constant voltage:*

$$E_{V.cst} = \frac{1}{2}V^2(C_{min} - C_{max}) \quad (8)$$

Where Q is the electric charge, V is the voltage to the terminals of the structure, C_{max} is the Maximum coupled [Nm], C_{min} is the Minimum coupled [Nm].

As the energy is dissipated in the shock absorber, the force distance product gives the power and the equation of the power $P$is:

$$P = \frac{4YF\omega\omega_C^2}{2\pi}\sqrt{\frac{1}{1+\omega_C^2} - \left(\frac{F}{mY\omega^2\omega_C}\right)^2} \quad (9)$$

Where F is the damping force [N], Y is the displacement of the frame [m], ω is an angular frequency of vibration [rad.s-1], m is the seismic mass [kg], ω_C is an angular frequency of cantilever

[Hz] and given by $\omega_C = \frac{\omega}{\omega_r}$

Table 1 provides the electrostatic force variation for the three configurations where x is the displacement of the inertial mass [14].

Table 1: Electrostatic force variations

Structure	**Voltage constrained**	**Charge constrained**
In plane overlaps	F_e constant	*Fe*=1/x2
in plane gap closing	*Fe*=1/x2	F_e=1/x
out of plane gap closing	F_e=1/x	F_e constant

With regards to electrostatic conversion of vibration energy, various authors have designed developed, simulated and fabricated different structures for improving the output voltage and power.

Chiu et al. [15] analyzed and modelled the nonlinear dynamics of a DC battery-charged vibration-to-electricity energy converter. The optimal design and maximum output power were obtained by solving the nonlinear equations of motion. They concluded that optimized converters can generate significant power only for a limited range of design and operation parameters.

Paracha et al. [16] illustrated experimentally the ability to scavenge mechanical vibration energy in order to provide electrical power to a resistive load, which the use of an electrostatic silicon-based MEMS transducer fabricated in a CMOS compatible technology. The researchers found that the converted power lies between 60nW and 100nW, with external vibrations at 250Hz and an acceleration amplitude of 0.25g. Paracha et al. have proposed a new simple approach for the calculation of the maximum power that can be generated from a spring-mass system excited with a sinusoidal force, based on an electrical impedance network analogy.

Lee et al. [17] provided a comparison of the energy harvesting capabilities of three different electrostatic mechanisms and discussion on the relations among the contributing parameters involved in maximizing the energy output that can be harvested from an electrostatic micromechanical system (MEMS) device. The three mechanisms considered were: in plane-overlap, in-plane gap closing and out-of-plane gap closing converters. In the authors' analytical modelling, the mass of the movable loads and the cross-sectional areas of the devices' active regions were set to be the same for all the mechanisms, while assuming that these electrostatic mechanisms operate in ideal vacuum environment. A few cases studied showed that the in-plane gap closing structure has the potential of producing a higher (approximately 1.6 to 1.8) amount of energy per unit volume as compared to the out-of-plane gap closing mechanism, provided the thickness of the mass in the in-plane structure is greater than the critical value.

Cottone et al. [18] developed a novel vibration energy harvester design consisting of a double mass contactless frequency-up converter with buckled clamped-clamped beams. The introduced concept aims at increasing the energy harvesting efficiency for low-frequency vibrations. In buckled beam bistable configuration, Cottone et al. found that the electrostatic generator showed a gain factor of 100% in harvesting low-frequency vibrations (20-40Hz) versus the normal operation mode. The authors claim that this concept can be applied to different transduction techniques.

Kempitiya et al. [19] proposed a technique for enhancing the power output from vibration-based charge-constrained electrostatic energy harvesters. Synchronous energy conversion producing net energy gain with minimal overhead power dissipation without need for complicated sensing mechanisms served as a major merit and key contribution of the proposed control technique. According to Kempitiya et al., the proposed microwatt power generation circuit is a possible candidate for powering emerging communication transceivers and portable electronics.

Galayko et al. [20] carried out an investigation of dynamic behavior of an electrostatic Vibration Energy Harvester (e-HEV) which uses gap-closing capacitive transducers and operates in a constant charge mode. The authors investigated issues related with stability. Galayko et al. discovered that depending on the magnitude of external vibrations, three different kinds of pathologic behavior is possible: at low amplitude, at large amplitude and at middle amplitude. The study showed that none of this behavior was like what was observed for constant voltage biased capacitive transducer.

Chiu et al. [21] designed and analyzed a micro vibration-to-electricity converter. In the design, the output power was 2004μW/cm^2 for the optimal load of 8MΩ. The device was fabricated in SOI wafer, mechanical and electrical measurements were conducted. Impedance measurements showed an unwanted parasitic conductance which resulted in the failure of output power measurement.

2.3 Piezoelectric conversion

The word "piezoelectric" means electricity caused by pressure. The first researchers to have studied this phenomenon were Jacques and Pierre Curie in 1880. They found out an unusual feature of some crystalline materials. Whenever they are submitted to the mechanical strength to the crystalline materials, the crystals became electrically polarized. The piezoelectricity is charge separation within a material in response to an applied strain or it is the property of certain materials to electrically polarize when it deformed [22]. The piezoelectricity is manifested by two effects that are direct piezoelectric effect and converse piezoelectric effect. These two domains are illustrated in Figure 3.

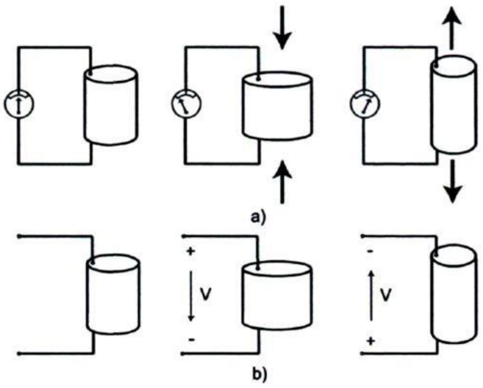

Figure 3: (a) Direct piezoelectric effect and (b) Converse piezoelectric effect.

The direct and converse piezoelectric effects can be expressed mathematically by two linearized equations. These mathematical models have four variables (two mechanical and two electrical variables) and can be converted by a set of nine equations are called constitutive piezoelectric law. The IEEE standard on piezoelectricity gives various series of constants used in conjunction with the axes notation [23]. According to this standard, the Electric displacement D and Strain S are given by equations (10) and (11):

$$D = d\sigma + \varepsilon^{\sigma}E \qquad (10)$$

$$S = s^{E}\sigma + dE \qquad (11)$$

Where D is the polarization [C/m^2], d is the piezoelectric charge coefficient [m/V or C/N], S is the strain [m/m], σ is the stress [N/m^2], E is the electric field [N/C or V/m], ε^{σ} is the dielectric constant (permittivity) under constant stress [F/m], s^E is the compliance when the electric field is constant [m^2/N] (the superscript E denotes that the electric field is constant).

Piezoelectric materials

The piezoelectric material can be applied depending on the mode 33 or mode 31 according to the mechanical stress is perpendicular or parallel to the electrodes. In tension and compression force, they are producers of voltages of opposite polarity proportionate to the force applied which can be in the mode 33 or mode 31, refer Figure 4 [6]. Subsequently, in contrast to this, it has been confirmed that if one of these crystals' voltage generation is subjected to an electric field, it shortened or grows in proportion to the intensity of the field and depending on the polarity the field.
These behaviors show the piezoelectric effect.

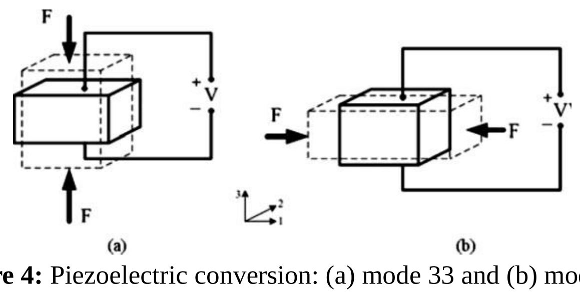

Figure 4: Piezoelectric conversion: (a) mode 33 and (b) mode 31.

There are many types of piezoelectric materials used for harvesting the ambient vibration energy like ceramics, crystalline, macro fiber composite (MFC), polyvinylidene. The most commonly used are the polyvinylidene fluoride (PVDF) and ceramics of lead zirconate titanate (PZT) [24]. Table 2 shows the properties of these materials. In general, the piezoelectric material is coupled to a resonant structure which imposes a strain or vibration. Due to the piezoelectricity, this deformation is converted into electrical charge by different ways which are compression, slap and bending.

Table 2: Properties of some common piezoelectric materials [5]

Several studies have been carried out to harvest energy ambient from vibration to electrical energy using the piezoelectric material.

Chen et al. [25] modelled a novel piezoelectric cantilever bimorph micro transducer electromechanical energy conversion based on basis approach. The analytical model showed that the vibration-induced voltage was proportional to the excitation frequency of the device but inversely proportional to the length of cantilever beam and the damping factor. Chens' et al. experimental results demonstrated that the maximum output voltage deviated very little from the analytical model.

Lu et al. [26] proposed a novel maximum power point (MPP) tracking scheme to harvest the maximum power from the vibration system. A Vibration-based energy Scavenging system based on piezoelectric conversion for micro-power applications was presented. Lu et al. measurement results showed that the power harvesting efficiency of the overall circuitry was higher than 90%.

Elvin et al. [27] developed a novel damage detection sensor that was self-powered was able to transmit information wirelessly to a remote receiver. The performance of the sensor was illustrated through the theoretical and experimental analysis of a simple damaged beam. The results showed that a sensor powered through the conversion of mechanical to electrical energy is viable for detecting damage.

Sodano et al. [28] developed a model to predict the amount of power capable of being generated through the vibration of a cantilever beam with attached piezoelectric elements. The model was verified using experimental results and proved to be very accurate independent of excitation frequency and load resistance. The model provides a design tool for developing power harvesting systems by assisting in determining the size and extent of vibration needed to produce the desired level of power generation.

Qiu et al. [29] introduced research activities of vibration control and energy harvesting using piezoelectric elements and a nonlinear approach. A new approach for energy harvesting from mechanical vibrations is also derived from the nonlinear approach based on Synchronizes Switch Damping.

2.4 Comparison of different conversion

Table 2: Properties of some common piezoelectric materials [5]

Material	**$BaTiO_3$**	**PZT 5A**	**PZT 5H**	1 **PVDF**
*d*31(×10-12 CN-1)	78	-171	-274	23
*d*33(×10-12 CN-1)	149	374	593	-33
*g*31(×10-3VmN-1)	5	-11.4	-9.1	216
*g*33 (×10-3VmN-1)	14.1	24.8	19.7	330
*k*31	0.21	0.31	0.39	0.12
*k*33	0.48	0.71	0.75	0.15
Relative permittivity ($\varepsilon/\varepsilon_0$)	1700	1700	3400	12
Young's modulus (GPa)	67	50	50	2

Mitcheson et al. [30] investigated the trends from the last 10 years of inertial micro-generator literature. They have shown that piezoelectric generators have a wider operating range at low frequency than electromagnetic generators, but as generator dimensions increase, the frequency to which piezoelectric transducers outperform electromagnetic transducers decreases. Roundy [31] provided a general theory that can be used to compare different approaches and designs for vibration-based generators. The theory can be applied to electromagnetic, piezoelectric, magnetostrictive, and electrostatic transducer technologies. Table 3 gives a summary of advantages and disadvantages of different conversion techniques.

3. Conclusion

The purpose of this study is to present a review of different conversion techniques used to harvest energy from ambient vibrations. These are Electromagnetic, Electrostatic and Piezoelectric conversions. Each of these technologies has their own advantages and disadvantages. Studies of researchers like Beeby et al. [5] have presented a comprehensive comparison.

Electromagnetic conversions offer a well-established technique of electrical power generation and the effect has been used for many years in a variety of electrical generators. There is a wide variety of spring/mass configurations that can be used with various types of material that are well suited and proven in cyclically stressed applications. Comparatively high output current levels are achievable at the expense of low voltages (typically <1 V).

Table 3: Summaries of different conversion techniques (Advantages and disadvantages).

Types of conversion	**Development level**	**miniaturization**	**Power output density**	**Specific problems**
Electromagnetic	- Advanced macroscale, limited to the microscale	- Difficult at the integration of materials	- High at the macroscale - Decreases with volume	- Low output voltage - Difficult integration
Electrostatic	- Advanced macroscale and microscale	- Easy integration of materials - Problem at the realization of the structure	- Low at the macroscale - Increases with decreasing volume	- Need for polarization source. - High voltage - Mechanical guidance
Piezoelectric	- Average in the macroscale and microscale	- Slightly lower performance of materials in thin layers	- High at the macroscale - Decreases at the microscopic level due to the properties of materials	- Materials in thin layers a little less efficient than solid materials - Limit performance due to the coupling coefficient of the material

High-performance bulk magnets and multi-turn, macro-scale coils are readily available. *Electrostatic conversions* are easily realizable as a MEMS and much processing know-how exists on the realization of in-plane and out-of-plane capacitors. Energy density of the generator can be increased by decreasing the capacitor spacing, facilitating miniaturization. The energy density, however, is also decreased by reducing the capacitor surface area. High transduction damping, at low frequencies, is achievable by incorporating small capacitor gaps and high voltages. Electrostatic conversions require an initial polarizing voltage or charge. This is not an issue in applications that use the generator to charge a battery, as this can be used to provide the necessary initial excitation level. Electrostatic conversions 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 output voltage produced by the devices is relatively high and often results in a limited current-supplying capability.

Piezoelectric generators offer the simplest approach, whereby structural vibrations are directly converted into a voltage output by using an electrode piezoelectric material. There is no requirement for having complex geometries and numerous additional components. Piezoelectric conversions are the simplest type of generator to fabricate and can be used in force and impact coupled harvesting applications. One major advantage is that this conversion principle is particularly well suited to micro-engineering since several processes exist for depositing piezoelectric films. The piezoelectric method can produce relatively high output voltages but only at low electrical currents.

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