

# Working Principles of Vibroelectric Nano Generator in Wireless Sensor Networks: A Review

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**Abstract.** Wireless sensor networks are solely dependent on battery limits the operation as well as maintenance effort. Vibroelectric nano generator able to prolong the operation by converting ambient vibration and power the equipment. The working principles includes Piezoelectric, Electromagnetic, Triboelectric, Magnetostrictive and Flexoelectric. This paper discussed the principle operations and key function materials, the advantages and disadvantages are specified. Hybrid incorporated with solar, thermal or radio frequency is considered as current trend of nano generator with further improvement as future work.

## 1. Introduction

Generating electricity from the environment has granted substantial attention recently due to advancement wireless sensor networks (WSN), microelectromechanical systems (MEMS) and Internet of Things (IoT) [1]–[4]. Existing WSN is heavily rely on battery or wired connection as energy sources [4], however the main obstacle for batteries are limited energy density, restricted life cycle, inevitable periodic replacement, labour cost, current leakage (even if not in use) as well as hazardous disposal after usage [4], [5].

Therefore, vibration energy which is abundant from ambient is explored to substitute batteries and wired power, subsequent providing a reliable and continuous supply of energy with lower installation and maintenance cost [4], [6], [7]. Vibroelectric nano generator (VENG) is ideal for long-life WSN for structural health monitoring (SHM)[6], [8], in many applications such as aerospace & deep sea operation, mining field, nuclear reactor sensor and implantable bio-sensing device[5].

## 2. Source of Ambient Energy

Ambient energies were not substantial for utilization due to intermittent characteristic and considerable high wattage electronics before 2000. WSN benefited with recent advancement of nanotechnology where WSN energy usage rated around 8~12mW[4], [9]. Fig.1 shows the potential energy sources available in ambient[7], [10], [11].

Fig.1 Potential energy sources from ambient to power WSN[11]

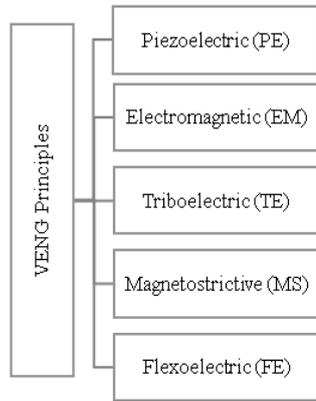


## 3. Principles

Vibration energy can be captured and converted into electricity for low-power electronics or battery[10]. Among the principles, Piezoelectric (PE) is the most common. Fig.2 shows the variety of working principles for VENG.

Fig.2 The principles of VENG

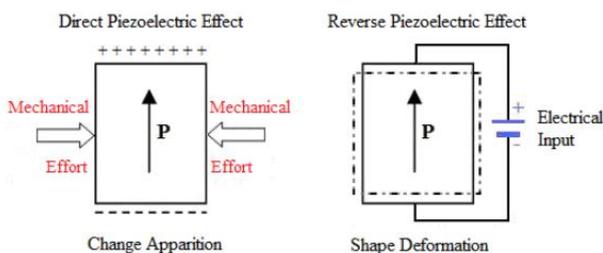
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### 3.1. Piezoelectric

Piezoelectric (PE) material produces electric or voltage when the material experienced mechanical stress or strain [5], [12]. The common PE materials are aluminium nitride (AlN), gallium arsenide (GaAs), lead zirconate titanate (PZT), quartz (SiO<sub>2</sub>), polymer polyvinylidene fluoride (PVDF) and recently discovered PE nanogenerators Zinc Nanowires (ZnO) [5], [13]. Fig.3 shows PE effects when experiencing mechanical effort and vice versa[14].

**Fig.3** Electromechanical conversion of Piezoelectric Phenomena[14]



The advantages of PE are simplicity in term of structures, the basic model made of thin layer PE. PE does not greatly affected by external or internal electromagnetic waves [15]. However PE is shortcoming in term of life span especially depolarization, known as electric fatigue after some switching[15], [16]. Ceramic type PE undesirable properties of brittleness and lower coupling coefficient in general. PVDF material show deprived adhesion to electrode materials and low coupling coefficient however comprise of flexible nature [15], [17]. In addition, PE performance and lifetime deteriorated in high temperature operations[15], [16]. PZT is more desirable by scientists due to relatively high coupling coefficient compared with other PE materials although PZT is brittle [17], [18].

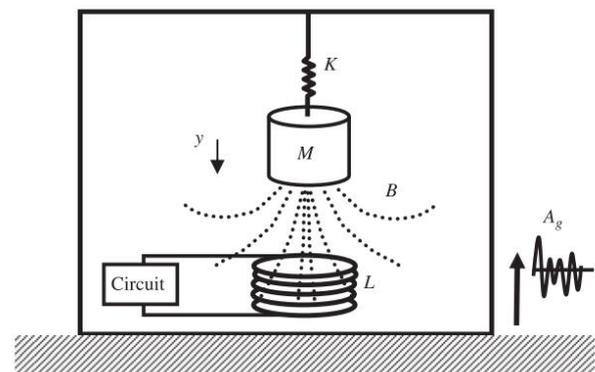
### 3.2. Electromagnetic

Electromagnetic (EM) VENG converts the ambient vibration's mechanical energy to electrical when relative motion occurs between a magnetised body and conductive coil, according to Faraday's law: an electromotive force (V) is generated

$$V = N \frac{d\Phi}{dt} \quad (1)$$

where N is number of turn for the conductive coil,  $\Phi$  is the magnetic flux over a single loop[12].

**Fig.4** The configuration of simple EM VENG[19]



A simple EM configuration is shown in Fig.4, the motional electromotive force (emf) is

$$\begin{aligned} \text{emf} &= \int dL \cdot (v \times B) \text{ or} \\ \text{emf} &= -d \int B \cdot dA / dt \end{aligned} \quad (2)$$

where dL is the differential length vector along the inductor coil, B is the magnetic field vector, and v is the velocity vector of the magnet. The differential elemental area is dA, so  $\Phi = B \cdot dA$  [19].

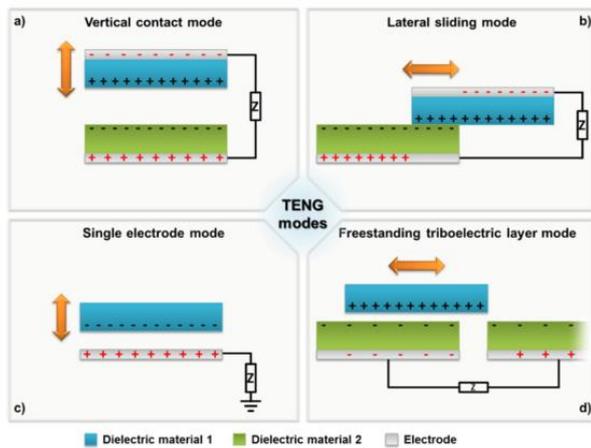
EM operates in scenario of resonator construction for low frequency conversion, higher conversion efficiency compared to PE VENG [15], [19]. EM required low internal impedance circuit results the generation of high power and current but lower voltage compared PE[20]. While EM performs well in meso-scale, the difficulty to fabricate magnetic coil in micro/nano-scale is a challenge. EM is also vulnerable to electromagnetic waves interference, and

experiencing damping friction loss, coil windage loss as well as magnet deterioration[15], [19], [21].

### 3.3. Triboelectric

Triboelectric (TE) generates static electricity with motion between 2 surfaces of a charged capacitor, resulting variation of potential difference [5], [12]. The principle of TE is illustrated in Fig.5, where electrostatic charges occurred on 2 different material surfaces are contacting each other, the potential of TE charges decrease after vibration energy mechanically separates the 2 surfaces, the potential drop initialize electrons to flow between the electrodes attached each surfaces and connected with a circuit [22].

**Fig.5** The four fundamental of TE VENG: (a) Vertical motion, (b) Sliding, (c) single-electrode, and (d) Freestanding [22], [23]



TE VENG able to operates without smart materials unlike PE VENG, thus likely higher system life span. Nevertheless, TE generates relatively small energy density, and external voltage sources is required for VENG operation[15]. The output voltage is tremendously high (usually more than 100V), which is less compatible to MEMS or WSN practically [15].

### 3.4. Magnetostrictive

Magnetostrictive (MS) materials for example iron-gallium alloy (Galferol) and Metglas deforms once an altering magnetic field is induced, the deformation sequentially apply stress to PE material for electricity production[12], [24]. MS VENG is grounded on Villari effect principle as shown in Fig.6, where entirely ferromagnetic materials intrinsic potential of MS due to internal electrons motion of the particles, orbital magnetic moment is superpositioned into atomic magnetic moment when the electron spins about its particular axis[25], [26].

**Fig.6** (a) Natural magnetism and arbitrary orientation of magnetic moments without external field, (b) the alignment of moment under external magnetic field [26]

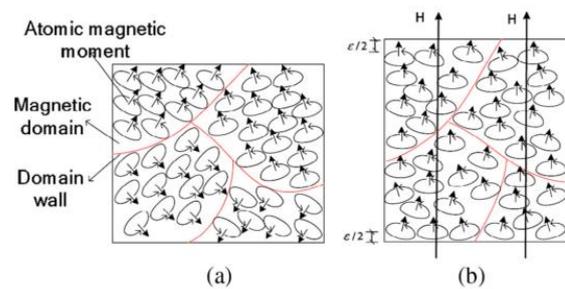
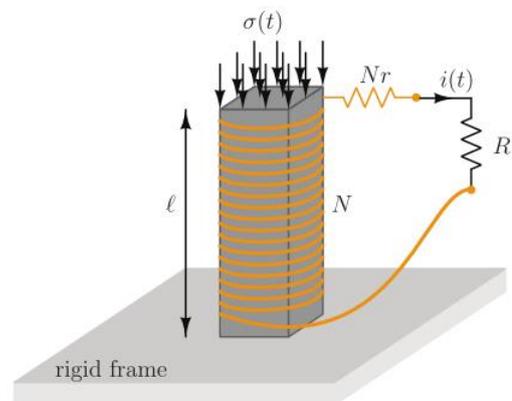


Fig.7 show the basic MS VENG model, a MS material with  $l$  length is surrounded by a solenoid with  $N$  turns, assuming periodic forcing  $\sigma = \sigma(t)$ , the  $H$ -field of the current  $i$  equals  $H_i = Ni/l$ ,  $H_0$  is the biased magnetic field and  $R$  is the circuit load resistance. The power ( $P$ ) generated equal as following [27]

$$P = R i^2 \quad \text{or} \\ P = R l^2 (h - H_0)^2 / N^2 \quad (3)$$

**Fig.7** The basic model of MS VENG [27]



MS VENG generally demonstrate high energy density and extended life cycles [25], MS material induces magnetic field during strain, and electrical current is

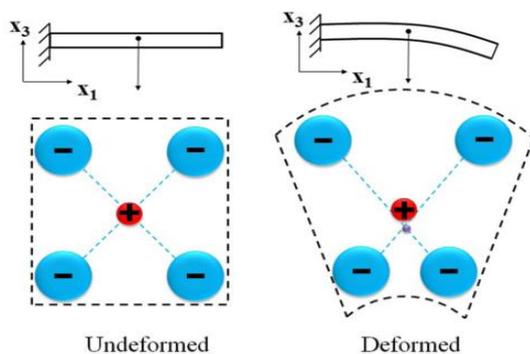
picked up by the coil due to the changing magnetic field according to Faraday's law. Jafari et.al. [28] claimed MS VENG performed better low frequency harvesting compared to PE type [28]. Simulations were conducted on Galfenol rods, magnetic flux density of 1.1 Tesla(T) by a MS VENG was attained sufficient to power VENG for WSN[29].

The advantages of MS over PE are less prone to aging, depolarization, charge leakage and brittleness [24]. MS materials have higher flexibility and able to sustain severer environment but requires external magnetic field during operation[30].

### 3.5. Flexoelectric

Flexoelectric (FE) characteristic exist in all dielectrics materials, where strain gradients allows development polarization even the material is non-piezoelectric[31], [32], shown in Fig.8 a FE materials experiencing polarization when deformed[16].

**Fig.8** Polarization due to bending of a centrosymmetric FE beam[16]



FE polymers are able to sustain great strains which ideal for VENG in wearable applications since human/animal movement requires high train/stroke [31], and considerable FE effects in micro/nano-scale conceivably outperforming PE in some situations [16]. However in order for FE VENG to generate an energetic cycle, pseudo-piezoelectric mode is included in the system which required supplementary bias voltage [31]. Other than that, due to limited FE studies, the current FE designs exhibit immature FE coefficient, and unfamiliar degradation property in nano-scale. The common FE material is barium strontium titanate(BST) is ferroelectric with high dielectric permittivity, which generates narrow and sharp dielectric peak during the ferroelectric to paraelectric phase transition temperature, hence inappropriate for wide temperature range applications[33]. Lastly, fabrication of FE VENG

system in nanostructures is comparatively complicated[33].

Mahanty et. al.[34] tested a flexible sponge-like nanaogenerator (FSNG) with ZnO as PE materials and povly-vinylidene fluoridehexafluoropropylene (P-VDF-HFP) as FE materials. The FSNG achieves a power density of 1.21mW/cm<sup>2</sup> and energy conversion efficiency around 0.3%, with 9V of open-circuit potential difference, 1.3 μA/cm<sup>2</sup> of short circuit current, when a mechanical impact of 0.36 MPa stress amplitude is applied above the surface[34].

### 4. Comparison

Each principle take respectively advantages and disadvantages, the relatively comparison in shown in Table I [5], [35]. EM VENG is more applicable in large scale structure such as building and transportation with low vibration frequency (<20Hz), while PE is feasible to micro/meso-scale provided the vibration frequency is high (>100Hz). Others VENG methods show potential in micro/nano-scale system such as MEMS and WSN, however the technology is not as mature as EM & PE.

**Table 1.** The advantages and disadvantages of corresponding VENG[5], [35]

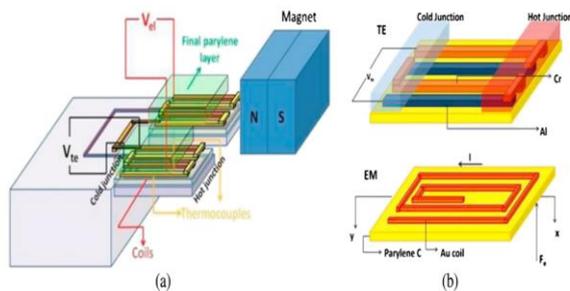
Principle	Properties	
	Advantage	Disadvantage
PE	<ul style="list-style-type: none"> <li>- Simple structure in small scale</li> <li>- High output voltage (&gt;5V)</li> <li>- High Coupling Coefficient</li> </ul>	<ul style="list-style-type: none"> <li>- Low output current</li> <li>- Low strain limit</li> <li>- Brittle</li> </ul>
EM	<ul style="list-style-type: none"> <li>- Simple construction in large scale</li> <li>- Low output Impedance</li> <li>- Higher output current</li> </ul>	<ul style="list-style-type: none"> <li>- Low output voltage (&lt;1V)</li> <li>- Limitation in downsizing</li> <li>- Affected by electromagnetic field</li> </ul>
TE	<ul style="list-style-type: none"> <li>- Very high output voltage (&gt;100V)</li> <li>- No need of smart material</li> <li>- Ease of voltage rectifying and frequency tuning</li> </ul>	<ul style="list-style-type: none"> <li>- Bias Voltage is required</li> <li>- High impedance needed</li> <li>- Low output current</li> </ul>
MS	<ul style="list-style-type: none"> <li>- High energy density</li> <li>- Long life cycle</li> </ul>	<ul style="list-style-type: none"> <li>- Affected by Electromagnetic field</li> <li>- Limitation in downsizing</li> </ul>

Principle	Properties	
	Advantage	Disadvantage
FE	- High strain limit	- High dielectric permittivity - Low stress limit

### 5. Hybrid

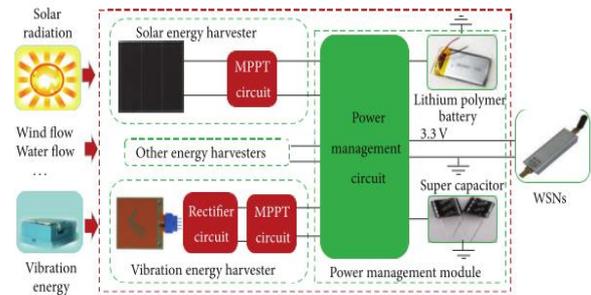
Hybrid VENG utilizes other ambient energy source instead of vibration energy only. The objective is to maintain a continuous energy supply and complement each the intermittent ambient availability [36]. The ambient sources such as sunlight, thermo gradients, and electromagnetic waves were explored to combined in the hybrid VENG[13]. For example, thermoelectric and EM VENG was conducted by Töreyn et. al. [5], using Chromel-Alumel (Cr-Al) as thermoelectric material while Neodymium Iron Boron (NdFeB) magnet as EM components of the cantilever hybrid VENG design[5]. The ambient temperature acted as heat source for the thermoelectric module as shown in Fig.8. The designed prototype size at 9.5mm x 8 mm x 6mm generated peak voltage of 16.7mV and power of 1.91nW with vibration frequency at 3.45kHz[5].

**Fig.9** Schematic diagram of Thermoelectric and EM Hybrid VENG[5]



There are numerous energy sources compatible with vibration energy to form a hybrid system, among are solar radiation, wind flow, acoustic energy, microbial fuel cell and water stream as shown in Fig.10 [7], [20], [37]. H. Li et al. investigated a solar-vibration hybrid VENG which was effective and consistent for continuous energy supply of WSN, the tests were in consideration of 24-hour surrounding fluctuations including rainy and night conditions [7]. As well with Y.He et al, designed a Photovoltaic-PE VENG hybrid, and assisted by Li-ion battery and super-capacitor as energy storage[38].

**Fig.10** Potential architecture of multisource energy harvesting system [7]



A hybrid VENG consists of 3 input sources of energy namely radio frequency signal, thermal and vibration, capable of delivering 3.3 V of output voltage, 6.5 mW of output power and 90% of efficiency when all input sources are simultaneously harvested[36]. The drawback is inclusion of multiple powered hybrid encounter issue such as system integration, higher fabrication cost and overall volumetric packaging for WSN.

### 6. Conclusion

Vibration energy from ambient is preferable to stretch the mission life of conventional battery for WSN application[11]. The main challenge of VENG is unable to harvest effectively in the stochastic and wide bandwidth of ambient vibration[15]. Reliable and cost effective VENG fabrication methods are required since WSN and MEMS micro scaling are expected to continue, thus micromachining techniques are the gap for commercialization of VENG[39]. Hybrid VENG incorporated with other ambient energy such as thermal, solar and radio frequency can fulfil the vibration-based generator shortage, and future work shall be concentrated in system integration, fabrication cost and packaging.

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