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Review of Micro Magnetic Generator

[*] Lin DU, Gengchen SHI, Jingjing ZHAO
Beijing Institute of Technology, Beijing, 100081, China
[*] Tel.: 086-15101117889
[*] E-mail: dldulin@163.com

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Abstract: This paper discusses the research progress of micro magnetic generator systems. Micro magnetic generator systems convert energy from the environment to electric energy with advantages as high reliability, high power density, long life time and can be applied to extreme environment. This paper summarizes methods for improving generator performance of micro magnetic generator, including rotational magnetic generator, vibrational magnetic generator and hybrid magnetic generator, analyzes and compares their design and performance, and concludes key technologies and ongoing challenges for further progress. The paper is instructive and meaningful to for research work of related field. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Energy harvesting, Micro power, Micro Electro Mechanical Systems, Magnetic generator, Review.

1. Introduction

With the development of wearable devices, wireless sensor networks and micro electromechanical systems, the demand for compact, high stability and longtime working energy sources in the milli Watts (mW) to micro Watts (μW) power range has significantly increased in recent years [1-2]. Traditional chemical batteries are unable to meet the demand for its life span, replacement and disposal [3-10]. In this case, it is necessary to develop energy harvesting systems [11].

Various research groups have studied energy harvesting devices [12-14] for scavenging ambient energy such as solar energy [15], thermal energy [16-17], mechanical energy [18-20] and magnetic energy [21]. Each species of energy harvester has its own features. Solar energy harvester has the highest compatibility with semiconductor processing technology with simple structure and stable performance. However, it is not convenient for embedded systems and not efficient in dim environment [22]. Thermal energy scavenger is in small size and light weight and noiseless during energy conversion; however, thermal gradient over MEMS scale is very small [23]. Piezoelectric energy harvester based on piezoelectric effect is of high energy density and can be widely used; while its performance is not stable and the energy generated is difficult to gather [24]. Electrostatic energy results from triboelectrification, induction or point discharge which is difficult to gather and needs pre-voltage. Magnetic generator is based on Faraday's law of electromagnetic induction [25]: the relative motion of magnet and coil generates induced electromotive force in coil. Micro magnetic generator systems convert energy from the environment to electric energy with advantages as high reliability, high power density, long life time and can be applied to extreme environment.

Since David P. Arnold introduces generators fabricated before 2007 in reference [28] comprehensively, this article reviews achievements of micro magnetic generator pubished after year 2007, analyzes and compares their design and performance, and concludes key technologies and ongoing challenges for further progress.

Magnetic genertion includes rotational magnetic generator, vibrational generator and hybrid generator [26]. Rotational magnetic generator drives its rotor by mechanical energy from the enviroment. Since it is short in axial dimension, it can be small in size [27]. Vibrational magnetic generator can havest vibration energy widely spread in the environent such as vibration of cars, buildings, industial divices and motion of human body [28], etc. Vibrational magnetic generator is a typical mass-spring-damping system [29]. When the vibration frequency matches with natural frequency, the output power reaches maximum. So far there are two types of hybrid generator: One converts vibration to rotation by using eccentric mechanism; the other one combines piezoelectric mechanism and magnetic mechanism.

2. Micro Rotational Generators

Magnetic generator usually contains multipolar magnet and planar coil, as shown in Fig. 1 [30]. Mechanical energy from the environment drives the rotor spindle and the spindle leads to the spin of rotor magnet. When rotor rotates relative to the stator coil, there will be induced electromotive force in coil.

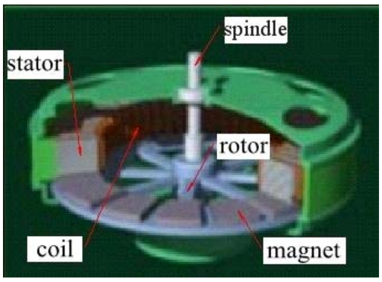


Fig. 1. Diagram of rotational magnetic generator.

According to Faraday's law of electromagnetic induction: the relative motion of magnet and coil generates induced electromotive force in coil, induced voltage can be deduced from Eq. 1.

$$U(t) = -\frac{d\phi(t)}{dt} = -S\frac{dB(t)}{dt}, \quad (1)$$

where U(t) is the induced voltage, Φ is the change of the magnetic flux through the area around the coil, t represents time, B strands for magnetic flux density and S is the coil surrounding area.

Researches on magnetic generator have been focus on improving output power for so many years. Eq. 1 indicates that there are two methods to improve power density or to increase output voltage:

1) Increase the magnetic flux density through the coil;

2) Enlarge the area around the coil.

From what have been published, researchers also develop generators based on the above two points.

2.1. Increase Magnetic Flux Density

There are three methods to increase magnetic flux density:

1) Use magnet of high magnetic flux density;
2) Decrease gap between magnet and coil;
3) Laminate magnetism material in the coil core.

2.1.1. Using Magnet of High Magnetic Flux Density

In 2008, Florian Herrault, *et al*. from Georgia Institute of Technology, USA developed generators consists of stator coil and 2-mm-diameter multipolar magnetic rotor [31]. Two-pole NdFeB generators show superior performance to two-pole SmCo generators on the order of 45 %.

Therefore, using magnet of high magnetic flux density increases the magnetic flux density of the gap between magnet and coil directly. So far NdFeB is of high magnetic flux density and widely spread with low cost. Hence, nearly all the magnetic generators use NdFeB as magnet for providing magnetic field in recent years.

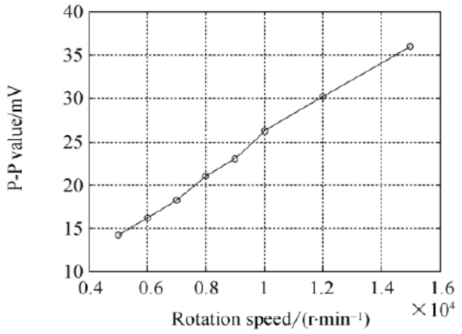
2.1.2. Minimizing Air Gap Between Magnet and Coil

In 2011, Sun Shaochun, *et al.* from Beijing Institute of Technology, China developed a three-phase synchronous micro magnetic generator [32]. Experimental result in Fig. 2 presents that induced voltage is proportional to rotation speed and indicates induced voltage is nonlinear with the air gap that as the air gap increases, induced voltage drops rapidly. In this case, the air gap should be minimized to obtain the maximum induced voltage.

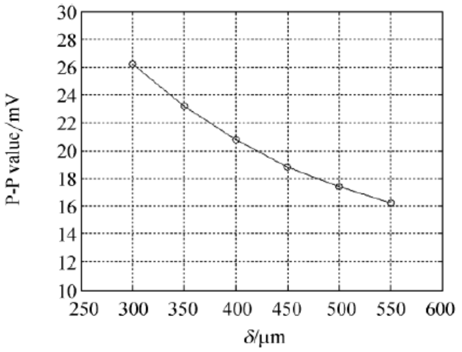
2.1.3. Lamination of Magnetic Stator Coil

To enhance electrical performance, Florian Herrault, *et al.* from Georgia Institute of Technology and Massachusetts Institute of Technology, USA reported generator with laminated magnetic stator core. The laminated version is fabricated by creating through-wafer circular trenches in the silicon wafer, and a ferromagnetic material was subsequently electroplated in these trenches [33].

Open-circuit voltage and power measurements of rotor speeding up to 200 krpm using nonmagnetic and magnetic shows that integration of a stator back iron increased the device output voltage by 50 % and output power by 225 % for any rotational speed. So lamination of magnetism material into stator core to improve magnetic flux density is effective to increase induced voltage.



(a)



(b)

Fig. 2. (a) Induced voltage changes with rotational speed, (b) Induced voltage changes with air gap.

2.2. Enlargement of Coil Surrounding Area

To increase coil surrounding area, there are following methods:

1) Connect multilayer coils in series;
2) Decrease width and space of coil line;
3) Proper geometric shape of coil.

2.2.1. Multilayer Coils in Series

In 2007, C. T. Pan from National Sun Yat-Sen University, Taiwan, China [1] developed an in-plane rotary electromagnetic microgenerator whose Cu planar micro coil is manufactured using the filament winding method. The use of the flexible PET substrate enables folding and stacking, and four layers of micro coil are stacked. In order to explain the effect of the number of layers of the micro coil on power generation, four samples with different numbers of layers are tested. The experimental voltage generator results for different angular velocities indicate induced voltage is proportional to the angular velocity and explain the effect of the number of layers of the micro coil on the induced voltage, revealing that the more layers on the micro coil, the greater the induced voltage.

2012, R. Cordero, *et al.* from Universidad del Turabo and Michigan Technological University, USA [34-35] manufactured a multi-stacked copper-clad polyimide coil of 20 layers. The performance presented in Table 1 shows that multi-layer coil improves electrical generator property.

The area around the coil is proportional to the layer number of coil, so connect multilayer coils in series directly improves induced voltage multiplied.

2.2.2. Decrease Width and Space of Coil Line

The generator C. T. Pan, *et al.* developed uses coil width of 30 μm; Sun Shaochun, *et al.*, R. Cordero, *et al.*, Y. J. Chen, *et al.*, fabricated generator using coil width of 100 μm. With the improvement of fabrication technology, width and space of coil line will decrease further to increase the area around the coil and then induced voltage.

2.2.3. A Proper Coil Shape

In 2013, Y. J. Chen, *et al.* from National Sun Yat-Sen University, Taiwan, China designed coils in different basic geometric shapes, including square-shaped coils, circle-shaped coils and sector-shaped coils [36-37]. The results of the experiment show that sector-shaped micro coil is the best pattern, compared to the other two. Generator with sector-shaped coil obtains the maximum output power is because that sector-shape has the maximum surrounding area. Different shapes of coil impact the area around the coil that a proper shape of coil contributes to its electrical performance.

Table 1. Structural parameters and performance of generators.

No.	Volume (cm^3)	Speed (krpm)	Voltage (V)	Normalized Voltage ($mV \cdot krpm^{-1}$)	Power (W)	Power Density ($W \cdot cm^{-3}$)	Coil Layer	Magnet material
1	0.05	2.2	0.111	50	4.1×10^{-4}	0.008	4	NdFeB
2	0.003	392	0.12	0.3	6.6×10^{-3}	1.95	2	NdFeB /SmCo
3	0.11	200	0.464	2.32	1.05	9.5	—	NdFeB
4	0.077	10	0.0093	0.926	3.6×10^{-4}	0.0046	2	NdFeB
5	1.253	4	3.2	800	5.8×10^{-3}	4.629×10^{-3}	20	NdFeB
6	0.761	13.3	0.218	16.39	2.5×10^{-3}	0.0033	2	NdFeB

2.3. Performance of Rotational Generators

Structural parameters and performance of generators of the generators above are summarized in Table 1.

Correspondence of the number in Table 1 and the author: 1 - C. T. Pan, *et al.*, 2007; 2 - Florian Herrault, *et al.*, 2008; 3 - Florian Herrault, *et al.*, 2009; 4 - Sun shaochun, *et al.*, 2011; 5 - R. Cordero, *et al.*, 2012; 6 - Y. J. Chen, *et al.*, 2013.

3. Micro Vibrational Magnetic Generators

Vibrational magnetic generator usually contains magnet and coil. According to Faraday's law of electromagnetic induction, distance changes between magnet and coil (vibration) leads to magnetic flux through the coil varying and generates induced electromotive force in coil. Vibrational generators are generally designed as a mass-spring-damping system which the mechanical parts move associated with transducers under the influence of the external vibration [38]. Thus, the maximum output power is commonly achieved at their resonances.

Researches on magnetic generator have been always focusing on improving output power. For vibrational generator, there are three methods to improve power density or to increase output voltage:

1) Resonance with high external vibration;

2) Increase magnetic flux density of the air gap between the magnet and the coil;

3) Enlarge area around the coil.

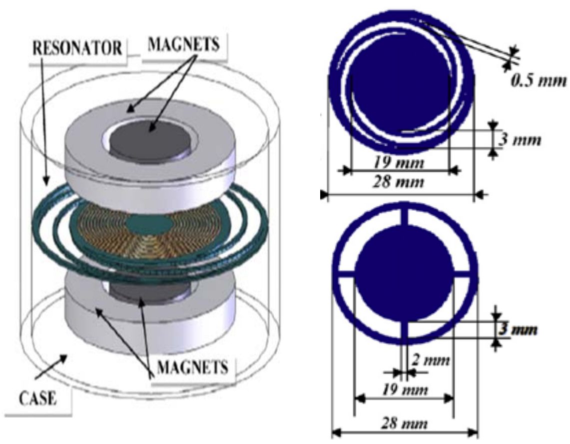
3.1. Increase Resonant Frequency

The majority of generators designed for vibration energy harvesting are based upon a mass-spring-damping system which produces maximum power when its resonant frequency matches the ambient vibration frequency. However, in such case, the output power drops significantly if the predominant ambient frequency and the device resonant frequency do not match. Many of these natural vibration sources rely on random or semirandom phenomena, and their energy is spread over a certain band, for example, transportation and car vibrations (< 20 Hz), human motion (< 10 Hz), guard rail on the street (< 50 Hz), etc. To match the ambient frequency, researchers designed generator for low frequency harvesting and generator of tunable frequency. Since voltage generated is proportional to the vibration frequency, generator with frequency upconversion technology is also presented.

3.1.1. Energy Harvester for Low Ambient Frequency

In 2010, Jong Cheol Park from Kwangwoon University, Korea presented micro-fabricated electromagnetic power generator to convert the low level ambient vibration of several hertz and low acceleration under 1 g into electric energy. The proposed micro-power generator is comprised of three micro-components such as bulk-micromachined silicon spiral spring, low loss copper micro-coil, and NdFeB magnet to be assembled with low cost PDMS packaging substrate [39]. With total size of $1\times1\times0.6$ cm^3, the fabricated device generated output power of 115.1 μW and load voltage of 68.2 mV to the load resistance of 18.1 Ω from the vibration of 54 Hz with acceleration of 0.57 g.

In 2011, Emilio Sardini of University of Brescia, Italy developed generator for low frequency vibrations (1-100 Hz). It is constituted by two sets of magnets and a thin moveable structure between each set, as presented in Fig. 3 [40-41]. The moveable structure, over which a flat inductor is fabricated, oscillates between the two sets. Two resonator structures, were designed. The resonator can operate at their mechanical resonant frequency with an acceleration of 9.81 m/s^2, and the experimental results have shown that for a linear resonator, a vibration frequency of about 100 Hz with generated powers of about 290 μW which can be observed for a load of 76 Ω, while, for the polymeric resonator made by Latex, the vibration frequency is around 40 Hz with a maximum power of 153 μW.



(a) (b)

Fig. 3. (a) Generator structure; (b) two resonator structures.

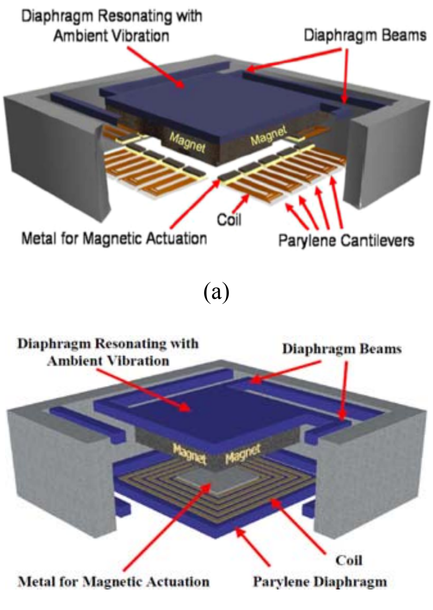
3.1.2. Frequency Tunable Generator

The output power drops significantly if the predominant ambient frequency and the device resonant frequency do not match. There are generally two possible solutions to this problem. The first is to combine a number of resonators with closely spaced natural frequencies. However, there is a tradeoff between the system bandwidth and the volume. The second solution is to tune the resonant frequency of a single generator periodically so that it matches the frequency of ambient vibration at all times.

2010, Dibin Zhu from University of Southampton, UK presents a new tunable electromagnetic vibration-based micro-generator. Frequency tuning is realized by applying an axial tensile force using a pair of tuning magnets [42]. The resonant frequency has been successfully tuned from 67.6 to 98 H when various axial tensile forces were applied to the structure. The generator produced a power of 61.6-156.6 μW over the tuning range when excited at vibration of 0.59 m/s^2.

3.1.3. Increase Vibration Frequency

The efficiency of vibration-based harvesters is proportional to excitation frequency. In 2009, Ibrahim Sari, *et al.* from Middle East Technical University, Turkey [43] proposed generator to convert low-frequency environmental vibrations to a higher frequency by employing the frequency upconversion (FupC) technique. The fabricated generator size is 8.5×7×2.5 mm^3. It is composed of two mechanical structures: 1) the upper diaphragm and 2) the array of 20 cantilevers located right below the diaphragm, as shown in Fig. 4(a) [44]. It has been shown that the generator can effectively harvest energy from environmental vibrations of 70-150 Hz and generates 13.5 mV voltage with 6.6 nW power.



(a)

(b)

Fig. 4. Model of generator: (a) first generator module, (b) second generator module.

Integrating 20 consecutive cantilevers into the first generator module, however, did not yield proportionate scaling of the output power compared to a single cantilever. This was due to the variation between the natural frequencies of the cantilevers, which resulted in phase shifts across the cantilever outputs, reducing the available aggregate power. In the following year, Serol Turkyilmaz, *et al.* from Middle East Technical University, Turkey presented the second generator electromagnetic vibration-to-electrical MEMS energy scavenger, as shown in Fig. 4(b) [45], which was optimized by using a monolithic resonating diaphragm instead of cantilevers. With the size of 10×8.5×2.5 mm^3, the maximum voltage is 15.2 mV and the maximum power obtained is 119 nW from vibration frequency of 114 Hz.

However, tuning does not provide value when the vibrations change and are not known a priori. In 2011, Tzeno Galchev, *et al.* from University of Michigan, USA fabricated an inertial power generator for scavenging low-frequency nonperiodic vibrations called the Parametric Frequency-Increased Generator (PFIG). The internal volume of the generator is 2.12 cm^3 (3.75 cm^3 including the casing), as shown in Fig. 5 [46]. The Parametric Frequency-Increased Generator (PFIG) utilizes a large inertial mass to couple kinetic energy from the ambient into the generator structure and to pass a portion of this kinetic energy to one of two FIGs. The FIGs then convert this mechanical energy into electrical energy via electromagnetic induction. The developed PFIG can generate a peak power of 163 μW and an average power of 13.6 μW from an input acceleration of 9.8 m/s^2 at 10 Hz, and it can operate at frequencies up to 65 Hz.

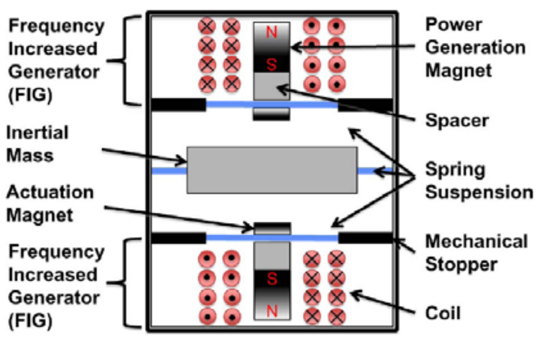


Fig. 5. PFIG structure.

3.1.4. Air Channel to Decrease Damping Effect

In 2011, Peihong Wang, *et al.* from Anhui University and Shanghai Jiao Tong University, China developed an electromagnetic vibration energy harvester with sandwiched structure and air channel, as presented in Fig. 6 [47]. With size of 9×7×5 mm^3, it mainly consists of a top coil, a bottom coil, an NdFeB permanent magnet and a nickel planar spring integrated with silicon frame. If the structure is with air channels, the inner air will flow freely and so will not damp the vibration of magnet–spring system. The load voltage generated by the prototype is 162.5 mV when the prototype is at resonance and the input vibration acceleration is 8 m/s^2 and the maximal load power obtained with air channels is about 21.2 μW when the load resistance is 81 Ω. The maximal output power of vibration energy harvester without air channels is13.2 μW. So the air channel is very helpful to increase the output power.

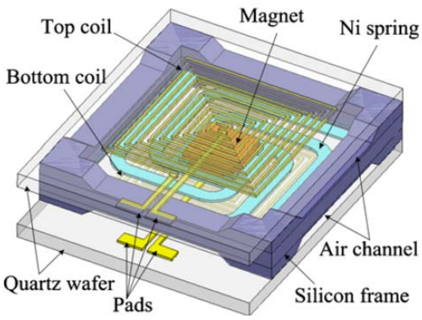


Fig. 6. Generator structure with air channel.

3.2. Increase Magnetic Flux Density of Air Gap

3.2.1. Ferromagnetic Material in Coil Cores

For energy harvesting purposes, in 2009, B. Mack from University of Freiburg, Germany fabricated an electromagnetic micro generator array. The array consists of a PCB with an array of 3×3 coils being opposed by a magnetic polydimethylsiloxane (PDMS) membrane with an array of 3×3 NdFeB magnets, as presented in Fig. 7 [48]. Coil cores are glued into the holes in the PCB and different coil cores are tested and compared: Mu-metal cores, Fe cores and hollow glass cores. The distance d of PCB and membrane is variable and can be adjusted using a micrometer screw. Experiment results show that ferromagnetic cores contribute to generator performance. The maximum measured voltage is 1.2 mV when exciting the converter array with an acceleration of 60 m/s².

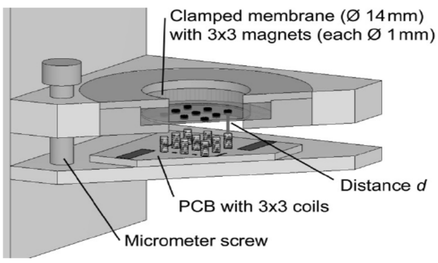


Fig. 7. Schematic view of generator.

3.2.2. Decrease Air Gap

In 2011, Wang Peng, *et al.* from Chinese Academy of Sciences, China fabricated micro electromagnetic energy harvester using MEMS micromachining technology. It mainly consists of folded beams, a permanent magnet and copper planar coils, as shown in Fig. 8 [49].

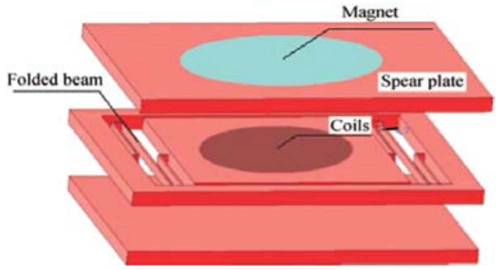


Fig. 8. Schematic structure.

The permanent magnet is placed on the spear plate and the space between the magnet and coils can be adjusted. The testing results show that at the resonant frequency of 242 Hz, the prototype can generate 0.55 W of maximal output power with peak–peak voltage of 28 mV for 0.5 g external acceleration. Calculated result shows that the flux density will decrease sharply with increasing space between the magnet and coils. A smaller space between the magnet and coils is attributed to a higher output performance.

3.3. Increase Coil surrounding Area

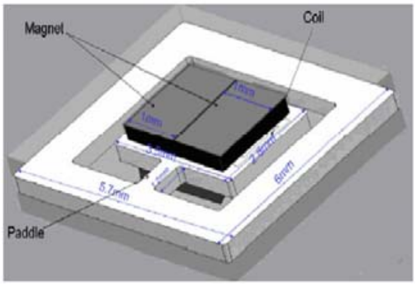
In 2011, C. Cepnik, *et al.* from University of Freiburg, Germany [50] fabricated coils with a fully automated process on PCB. With the coil wire thickness of only 25 μm, the 3D coils enable to effectively use the magnetic field and generate an output power of 0.62 μW at 1 m/s^2 within a total harvester volume of 0.46 cm^3.

3.4. Other Generators

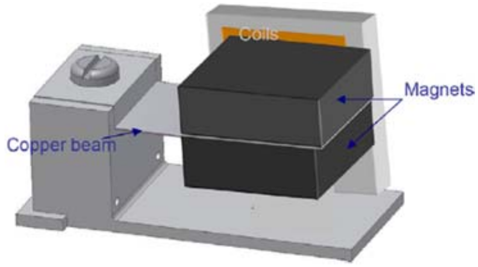
Additionally, other researchers studied energy harvesting systems for industrial fans, airflow and fluid.

3.4.1. Harvesting Systems from Industrial Fans

To work at input resonant frequency of 7400 Hz and acceleration of 1.1 m/s^2 which were measured in commonly used industrial fan, Santosh Kulkarni, *et al.* from Tyndall National Institute, Ireland and University of Southampton, UK [51] fabricated three different designs of power generators in 2007. Prototypes A and B use wire-wound and electroplated coils, respectively, on a DRIE etched silicon paddle. Prototypes A and B have fixed magnets with moving coils and coils are placed between two sets of oppositely polarized NdFeB magnets, as shown in Fig. 9(a). Prototype C uses fixed coils and moving magnets, as shown in Fig. 9(b). Test performance of three prototypes is shown in Table 2.



(a)



(b)

Fig. 9. Generators: (a) Prototypes A/B; (b) prototype C.

Table 2. Performance of micro vibrational magnetic generators.

No.	Volume (cm^3)	Frequency (Hz)	Acceleration (g)	Voltage (V)	Power (W)	Power Density ($W\cdot cm^{-3}$)
1	0.6	54	0.57		1.15×10^{-4}	1.918×10^{-4}
2A	8.62	100	9.81		2.9×10^{-4}	3.37×10^{-5}
2B	8.62	40	9.81		1.53×10^{-4}	1.78×10^{-5}
3		67.6-98	0.59		1.57×10^{-4}	
4	0.1488	113		1.35×10^{-2}	6.6×10^{-9}	4.435×10^{-9}
5	0.2125	114		15.2×10^{-3}	1.19×10^{-7}	5.6×10^{-7}
6	2.12	10-65	9.8		1.63×10^{-4}	7.69×10^{-5}
7	0.315		8		2.12×10^{-5}	6.625×10^{-7}
8			60	1.2×10^{-3}		
9	0.66	242	0.5	2.8×10^{-2}	5.5×10^{-7}	8.33×10^{-7}
10	0.46	340	1	5×10^{-3}	6.2×10^{-7}	1.348×10^{-6}
11A	0.106	8080	3.9		1.48×10^{-7}	1.396×10^{-6}
11B	0.106	9837	9.81		2.3×10^{-8}	2.170×10^{-7}
11C	0.150	60	8.829		5.84×10^{-7}	3.89×10^{-6}
12A	0.864	530		8.1×10^{-2}		
12B	0.191	4100		5.3×10^{-3}		
13		30		1.02×10^{-2}		

3.4.2. Airflow Energy Harvesting Systems

Instead of harvesting mechanical vibration, in 2009, Seong-Hyok Kim, *et al.* from Georgia Institute of Technology, USA and Electronics and Telecommunications Research Institute, Korea [52] designed two types of electromagnetic power generators exploiting direct conversion of airflow:

1) A windbelt-based vibratory linear energy scavenger targeting strong airflows,

2) A Helmholtz-resonator-based generator capable of scavenging energy from weaker airflows. Both devices consist of two tightly coupled parts: a mechanical resonator, which produces high-frequency mechanical oscillation from quasi-constant airflow, and a permanent magnet/coil system, which generates electrical power from the resonator's motion. The windbelt-based energy scavenger, in size of 12×12×6 mm^3, demonstrated a peak-to-peak output voltage of 81 mV at 0.53 kHz, from an input pressure of 50 kPa. The Helmholtz-resonator-based energy scavenger achieved a peak-to-peak output voltage of 4 mV at 1.4 kHz, from an input pressure of 0.2 kPa, which is equivalent to 5 m/s of wind velocity.

3.4.3. Fluid Energy Harvesting Systems

2010, D. A. Wang, *et al.* from National Chung Hsing University, Taiwan, China developed electromagnetic energy harvester for harnessing energy from flow induced vibration. It consists of a flow channel with two copper tubes, a PE diaphragm bonded to the channel, and a permanent magnet glued to the PE diaphragm [53]. When the fluctuating pressure is applied on the surface of the diaphragm, the diaphragm oscillates up and down, which causes the permanent magnet to vibrate at a frequency about the same as that of the pressure in the pressure chamber. The relative movement of the magnet to the coil results in a varying amount of magnetic flux cutting through the coil. According to the Faraday's law of induction, a voltage is induced in the loop of the coil. Experimental results show that an output Peak-peak voltage of 10.2 mV is generated when the excitation pressure oscillates with amplitude of 254 Pa and a frequency of about 30 Hz.

Performance of the generators presented above is summarized in Table 2.

3.5. Vibrational Generators

Correspondence of the number in Table 2 and the author: 1 - Jong Cheol Park, *et al.*, 2010; 2 - Emilio Sardini, *et al.*, 2011; 3 - Dibin Zhu *et al.*, 2010; 4 - Ibrahim Sari, *et al.,* 2009; 5 - Serol Turkyilmaz, *et al.,* 2010; 6 - Tzeno Galchev, *et al.*, 2012; 7 - Peihong Wang, *et al.,* 2011; 8 - B. Mack, *et al.,* 2009; 9 - Wang Peng, *et al.,* 2011; 10 - C. Cepnik, *et al.,* 2011; 11 - Santosh Kulkarni, *et al.,* 2007; 12 - Seong-Hyok Kim, *et al.,* 2009; 13 - D. A. Wang, *et al.*, 2010.

4. Hybrid Generator

The majority of generators designed for vibration energy harvesting produces maximum power when its resonant frequency matches the ambient vibration frequency. However, the output power drops significantly if the predominant ambient frequency and the device resonant frequency do not match that limits its application. To improve generator efficiency, hybrid generator is also developed. So far there are two types of hybrid generator:

1) One converts vibration to rotation by using eccentric mechanism;

2) The other one combines piezoelectric mechanism and magnetic mechanism working together.

4.1. Energy Harvester Converts Vibration to Rotation

In 2006, D Spreemann, *et al.* from HSG-IMIT Institute, Germany designed a generator that converts linear vibration into a rotary motion, as shown in Fig. 10 [54]. Depending on the geometry and initial conditions, the mechanical excitation of the generator housing leads to rotation of the pendulum. The fine-mechanical generator with 1.5 cm^3 in volume is capable of producing 0.4–3 mW for vibration frequencies ranging from 30 to 80 Hz.

E. Romero, *et al.* from University of Turabo and Michigan Technological University, USA presented a micro-rotational energy harvester topology for extracting electric energy from human body motion at joint locations with volume of 2 cm^3 [55]. The stator is composed of stacked microfabricated planar coils with radial geometry. The rotor is built with multiple permanent magnets with alternating magnetization pattern creating several poles. An eccentric weight ensures that external movement due to body motion is converted in to oscillations or rotations. An average power output of 427 μW was generated when placed on the ankle while walking at 4 mph. Up to 540 μW was produced at the same body location when running at 5 mph.

Fig. 10. Generator converts vibration to rotation.

4.2. Combine Piezoelectric Mechanism and Magnetic Mechanism

In 2013, Bin Yang, *et al.* from National University of Singapore, Singapore [56] investigated in a hybrid energy harvester integrated with piezoelectric and electromagnetic energy harvesting mechanisms. It contains a piezoelectric cantilever of multilayer piezoelectric transducer (PZT) ceramics, permanent magnets, and substrate of two-layer coils. For the type I device, as shown in Fig. 11(a), the magnets are placed at the back side of the end of the PZT cantilever to tune the resonant frequency of the whole structure, while the magnetic coils are placed underneath the magnets. In contrast, the type II and III devices comprise the magnets arranged symmetrically on the double sides of the cantilever end with respect to the PCB coils, which are arranged vertically, as shown in Fig. 11(b) and Fig. 11(c), respectively. The maximum output voltage and power from the PZT cantilever of the type III device are 0.84 V and 176 μW under the vibrations of 2.5 g acceleration at 310 Hz, respectively. And the maximum output voltage and power from the coils are 0.78 mV and 0.19 W under the same conditions, respectively. The power density from the type III device is derived as 790 μW/cm^3 from piezoelectric components and 0.85 μW/cm^3 from electromagnetic elements.

4.3. Hybrid Generators

Performance of the generators presented above is summarized in Table 3.

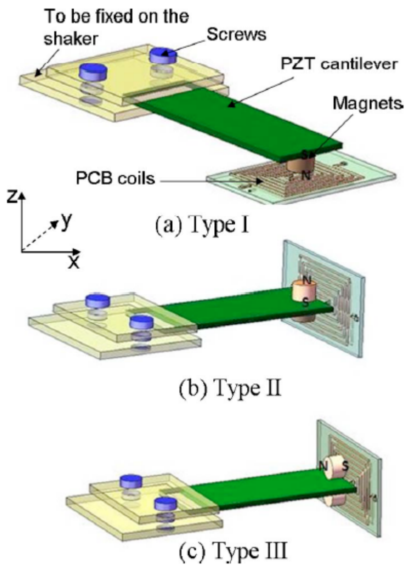


Fig. 11. Hybrid generator (a) type I, (b) type II, (c) type III.

Table 3. Performance of micro hybrid magnetic generators.

No.	Volume (cm^3)	Fre quency (Hz)	Accelera-tion (g)	Voltage (V)	Power (W)	Power Density (W·cm^{-3})
1	1.5	80	1.9	0.08	3×10^{-3}	2×10^{-3}
2	2				5.4×10^{-4}	2.7×10^{-4}
3	0.223	310	2.5	0.84	1.76×10^{-4}	7.9×10^{-4}

Correspondence of the number in Table 3 and the author: 1 – D. Spreemann, *et al.,* 2006; 2 - E. Romero, *et al.,* 2011; 3 - Bin Yang, *et al.,* 2013.

5. Key Technologies and Ongoing Challenges

As what has been discussed above, researchers have always been focus on improving electrical performance and many solutions are proposed. To further improve generator performance, there are still some key technologies that needed to be developed.

5.1. Key Technologies

1) Increase magnetic flux density.

a. Using magnet of high magnetic flux density increases the magnetic flux density of the gap between magnet and coil directly, and it influences induced voltage in the same way. So far NdFeB is of high magnetic flux density and widely spread with low cost. Hence, nearly all the magnetic generators use NdFeB as magnet for providing magnetic field.

b. Coil includes coil substrate and copper wire, Florian Herrault, *et al.* laminate magnetic stator core and B. Mack, *et al.* use ferromagnetic cores and both increase magnetic flux density and induced voltage successfully by reducing magnetic reluctance.

c. Induced voltage is nonlinear with the air gap that as the air gap increases, induced voltage drops rapidly. Minimizing the air gap contributes to a higher magnetic flux density and induced voltage.

2) Enlarge area surrounding area.

a. Series connection of multilayer coil multiplies area around the coil.

b. Different shapes of coil impact the coil surrounding area that a proper shape of coil contributes to its electrical performance.

c. Decrease coil width and space contributes to increase area around the coil. With the improvement of fabrication technology, width and space of line will decrease further to increase the area around the coil and then induced voltage.

3) Increase changing rate of magnetic flux density through the coil

a. For rotational magnetic generator, output voltage is proportional to rotor speed, increment of rotor speed enlarges output voltage directly.

b. Vibrational generator produces maximum power when its resonant frequency matches the ambient vibration frequency. However, the output power drops significantly if the predominant ambient frequency and the device resonant frequency do not match that limits its application. To widen the bandwidth of the generator, there are possible solutions to this problem.

1) Combining a number of resonators with closely spaced natural frequencies to effectively achieve a greater bandwidth. However, there is a tradeoff between the system bandwidth and the volume.

2) Tune the resonant frequency of a single generator periodically so that it matches the frequency of ambient vibration at all times, as presented by Dibin Zhu.

3) Employing frequency upconversion technique to convert low frequency of ambient environment to higher resonance frequency as designs from Ibrahim Sari, *et al*. and Serol Turkyilmaz, *et al*.

5.2. Ongoing Challenges

1) Although the fabrication of ultraminiaturized stator windings benefits from microfabrication processes, it is still challenging to make millimeter-scale high-performance permanent magnetic pieces. In general, the magnetic materials currently shaped by laser machining do not approach the levels possible by bulk manufacture. The laser machining process used to shape the magnets causes some material degradation at the edges of the pieces, resulting in nonmagnetic regions typically a few hundred micrometers in width. Furthermore, imperfect shapes and rough edges cause slight gaps between the pole pieces. These fabrication limitations increase the lateral extent of the transition regions between two opposite magnetic poles (also called “dead zones”), which do not contribute to the magnetic flux. Because of the small size of the

magnets, this may represent a nonnegligible percentage of the total area and thus decrease the performance of the machine [29].

2) Induced voltage is nonlinear with the air gap that as the air gap increases, induced voltage drops dramatically. Assembly accuracy should be assured to minimize the air gap. When testing rotational magnetic generator in the lab, usually magnet is fixed on the rotation axis of motor and coil is placed on the laboratory table and air gap can be adjusted by controlling motor. However, when the generator is assembled and applied to the environment, the air gap cannot reach the accurate level controlled by motor.

3) The increment of area around the coil, such as multilayer in series and reducing coil width, leads to the large out voltage. However, it also increases the length of coil or decreases cross sectional area of coil that leads to increment of coil resistance and limits generator power.

4) Generator contains movable components like bearings and rotor, quick and accurate installation is another problem needed to be solved.

5) Magnetic field distribution is related to shape and size of magnets and cannot be accurately calculated by analytic expression directly. So simulation is necessary to gain the relationship between magnetic field distribution and size of magnets, then, generator performance can be estimated and optimized.

6. Conclusions

With the development of science and technology, the demand for compact, high stability and longtime working energy sources has significantly increased in recent years. Micro magnetic generator systems convert energy from the environment to electric energy with advantages as high reliability, high power density, long life time and can be applied to extreme environment. So it can be used in wearable devices, wireless sensor networks and micro electromechanical systems. So far micro magnetic generator still exists problems like miniaturization, fast and accurate assemble and lower resistance. For micro generation, design theory and method should be improved, manufacture and assembly technology suitable for producing is under study. Researchers dedicate to focus on micro generator and spread its application.

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