

# Harvesting the Vibration Energy

Marek Matak\*, Peter Šolek

Institute of applied mechanics and mechatronics, Slovak University of Technology, Bratislava, Slovakia

\*Corresponding author: marek.matak@stuba.sk

Received October 21, 2013; Revised November 07, 2013; Accepted November 25, 2013

**Abstract** Ambient energy can in many situations not only augment battery life in autonomous devices, but enable the whole functionality of such devices. Harvesting of ambient energy in any available form is hence very desirable. From available sources of ambient energy, solar and vibration energy are now prevalent forms of harvested energy. Several transduction mechanisms exist for transformation of mechanical energy of ambient vibrations into electric energy. Electromagnetic Transduction seems to be proper mechanism for harsh conditions thanks to its simplicity and robustness. There are many issues though, that need to be worked out yet. This paper proposes basic overview of ambient energy sources, description of vibration energy harvesting mechanisms and identifies common limitations in designs of electromagnetic vibration energy generators.

**Keywords:** ambient energy sources, energy scavenging, mechanical energy transducers, electromagnetic vibration energy harvester

**Cite This Article:** Marek Matak, and Peter Šolek, "Harvesting the Vibration Energy." *American Journal of Mechanical Engineering* 1, no. 7 (2013): 438-442. doi: 10.12691/ajme-1-7-57.

## 1. Introduction

Energy harvesting (or energy scavenging) is process of transformation of ambient energy into useful electric energy. In past decade, energy harvesting has become a viable source of power for low-powered systems. These systems include various sensors and devices operating in remote areas. Utilizing the energy from ambient sources greatly enhances usability of such devices by making them practically maintenanceless and fully autonomous. Autonomous meteorological station could be used as example of such device, where power self-sufficiency is demanded. [14].

Traditionally, any remote device relied on batteries as a source of power for its operation. This is quite disadvantageous as batteries are of limited capacity and require regular replacement. Energy harvesting can partially or fully supplement batteries as a source of electrical power. Sources of ambient energy that can be artificially harvested are solar energy, mechanical energy of vibrations and random movement, temperature gradient, radio frequency and acoustic energy. Power densities of ambient energy sources according to various sources are presented in table.

Table 1. Power density of ambient energy sources

Energy source	Potential power density
Solar (Direct)	10's mW/cm <sup>2</sup>
Solar (indoor)	10's μW/cm <sup>2</sup>
Mechanical vibration	100's μW/cm <sup>3</sup>
Human motion	10's to 1000's μW/cm <sup>3</sup>
Thermoelectric	10's μW/cm <sup>2</sup>
Radio-frequency	100's μW/cm <sup>3</sup>
Airflow	100's μW/cm <sup>3</sup>
Acoustic noise	10's μW/cm <sup>3</sup>

## 2. Ambient Energy Sources

### 2.1. Photovoltaic Energy

Photovoltaic cell converts light energy into electrical energy using photoelectric effect. The source of light energy is usually sunlight. Solar cells are the best known ambient energy transducers found in many applications ranging from pocket calculator to solar energy power plants. Typical applications in autonomous systems are road signs [9] or automated meteorological stations placed in remote locations. Photovoltaic cells offer reasonable power density but this principle is not universally usable as there are environments where sunlight is not present at all or only for limited period of time. [2].

### 2.2. Mechanical Energy

Mechanical energy in form of either mechanical vibrations, body motion or fluid flow can be obtained and transformed into electrical energy [1]. Mechanical vibrations are present in almost every industrial device and therefore are available in most cases as quite reliable source of energy. Principles used for vibration energy harvesting will be further described in this paper. Random motions of humans or animals can be used as a source of power for health monitoring or positioning systems. Flow of fluid (gas or liquid) may be utilized exploiting the oscillating flow of medium such as vortex shedding occurring behind cylindrical cross-sections, although this principle in fact just transforms flow into mechanical vibrations.

### 2.3. Thermal Energy

Phenomena of creating electric potential with temperature difference is called thermoelectricity.

Thermoelectric generators using Seebeck effect are considered to be reliable and maintenanceless, since no moving parts are present, but costly and inefficient [16]. Their use is limited to space and terrestrial applications. Thermoelectricity has great potential once more efficient methods are developed, because most losses in engineering devices result in heat. Also waste heat from technological processes could be harvested. Thermoelectrical systems are easy to integrate within printed circuit board of microdevices. [2].

## 2.4. Radio Frequency Energy

Radio frequency energy harvesting is known since late fifties, but practical use has arisen only recently. Basic idea of radio frequency energy harvesting is to scavenge energy from wireless signals that are ubiquitous in modern environment. [2] These might be TV or radio broadcast, mobile network, wireless networks, radar... A simple RF energy harvesting system is comprised by transducer – typically antenna or antenna array harvesting ambient energy. Harvested energy is then rectified, filtered and used to recover DC. Direct current is used either to directly supply power to device, or to recharge batteries or capacitors [12]. Example of possible use of RF energy harvesting is recharging of cell phones. [15].

## 2.5. Acoustic Energy

Acoustic energy of both natural and artificial origin (technological processes, traffic) is clean, ubiquitous and abundant source of energy. Device using Helmholtz resonator with piezoelectric cantilever beams placed inside is described by [11]. When the resonator is excited at its acoustic eigenfrequency, an amplified resonant wave develops inside the resonator. Piezoelectric beams are designed to match the eigenfrequency of resonator. [11].

## 2.6. Conclusion

According to Roundy [3], solar and vibration energy are best suited as a source of power for electronic devices as both fit the most power density and availability requirements for autonomous systems. However, it must be said again that there is no solution in existence that will fit in all situations. These two solutions are often not overlapping, in environments where sunlight is present are often vibrations absent and vice versa. Technology of solar cells has already reached certain state of maturity and solar cells are commercially available. Therefore, vibration energy harvesting is much less common or known and offers much more opportunities for researchers.

## 3. Mechanical Energy Harvesting

Ambient mechanical energy is often present in environments and structures where other energy harvesting methods are of limited or no usefulness. As mentioned before, source of mechanical energy can be movement of industrial structure due to its operation, movement of human body or flow of medium. The frequency of mechanical motion depends on its source, and equals less than 10 Hz for human motions [8], approximately 30 Hz for machinery vibrations [8]. Frequency of flow induced vibrations depends of velocity

of fluid flow and shape of device used to induce vibrations and can be determined for example by using Strouhal number for circular cross sections .

Principle of vibration energy harvesters is in most cases mass-spring-damper system with one degree of freedom. Considering physical principles used to transform kinetic energy into electrical energy, there are four transduction mechanisms: electrostatic, piezoelectric, electromagnetic and magnetostrictive (magnetoelectric).

### 3.1. Electrostatic Harvesters

Electrostatic harvesting of mechanical energy is based on varying vibration-dependent capacitance of variable capacitors (varactors). Ambient vibrations induced displacement of charged plates of varactors and mechanical energy is converted into electrical energy. Advantage of this principle of harvesting is ease of integration of such devices into printed circuit boards of MEMS, no need for smart materials and high output voltage (2~10 V) . Disadvantages of electrostatic devices are their dependence on external voltage source. [13].

### 3.2. Piezoelectric Harvesters

Piezoelectric materials are generating electric charge when a mechanical load is applied and therefore are in advance used to convert mechanical energy in form of pressure or force into electric energy [3]. Energy harvesting device employing piezoelectric conversion mechanism typically consists of cantilever beam coated with piezoelectric material and a mass placed on the tip of a beam. According to [14], piezoelectric energy harvesters require no external voltage source, output voltage is relatively high, their compact dimensions allow for MEMS integration. Coefficient of electromechanical coupling is high. On the other side, piezoelectric materials such as PZT are often brittle and tend to change their properties through operational life. [13].

### 3.3. Electromagnetic Harvesters

Electromagnetic mechanism of vibration energy harvesting is based on Faraday's law of electromagnetic induction stating that "an electrical current will be induced in any closed circuit when the magnetic flux through a surface bounded by the conductor changes". One of the most effective ways of achieving this for energy harvesting is by use of permanent magnet and coil [8]. Electromagnetic harvesters are simple and rugged, do not require any smart materials or source of voltage, but are difficult to manufacture in micro scale. Output voltage is low (0,1 V). [13].

### 3.4. Magnetostrictive Harvesters

Magnetostrictive energy scavengers use the Villari effect of magnetostrictive materials such as Metglas 2605SC. Magnetostriction is a property of ferromagnetic materials that causes them to change their shape as a result of magnetization or vice versa, causes a change of magnetic field as effect of mechanical strain. Magnetostrictive harvesters offer some advantages such as high coupling coefficient and high flexibility that make them suitable for high frequency applications. Stated

disadvantages are difficult integration with MEMS, non-linear effect, need of pickup coil .

### 3.5. Principles of Operation

Basic principles of operation of vibration energy harvesters were proposed by Williams and Yates [6]. Transducers consists of seismic mass  $m$  attached to housing by spring,  $k$ . Damping element represents both damping of spring and damping due to conversion of mechanical energy into electrical energy. When generator is vibrated, inertial mass moves out of phase with movement of the generator housing. Relative motion between seismic mass and generator housing can drive suitable transducer to generate electrical energy. Since the generator is inertial device, it only needs to be fixed to vibrating structure at one point [6].

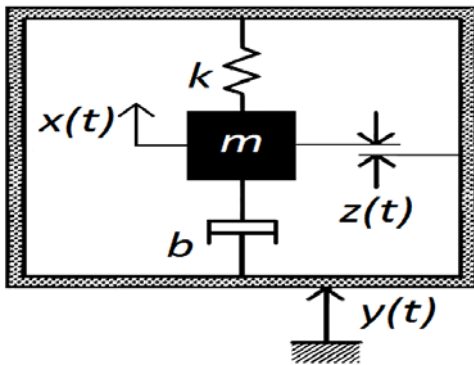


Figure 1. Inertial vibration energy harvester

The means of energy extraction may consist of magnetic seismic mass moving past a coil for electromagnetic energy harvesting, beam made of piezoelectric or magnetostrictive material for piezoelectric or magnetostrictive harvester, or variable capacitor plates mounted on spring for electrostatic harvester.

For linear spring and damping elements, equation of motion of inertial harvester is:

$$m\ddot{z} + b\dot{z} + kz = m\ddot{y} \quad (1)$$

Considering harmonic excitation  $y = Y \sin(\omega t)$

$$m\ddot{z} + b\dot{z} + kz = m\omega^2 Y \sin(\omega t) \quad (2)$$

Multiplying equation (2) by  $\dot{z} = \dot{x} - \dot{y}$  and rearranging, we get expression:

$$\frac{dy}{dt} \left( \frac{m\dot{x}^2}{2} + \frac{kx^2}{2} \right) + b\dot{z}^2 + (b\dot{z} + kz)\dot{y} = 0 \quad (3)$$

Where first member represents time rate of increase of kinetic and strain energies, second member represents power dissipated by damping and third member of equation is instantaneous power into system. The damping coefficient  $b$  consists of mechanical and electrical contributions and may be expressed as  $b = b_m + b_e$  [7].

Steady-state solution of equation (2) is

$$z = Z \sin(\omega t - \phi) \quad (4)$$

$$Z = \frac{m\omega^2 Y}{\sqrt{(k - m\omega^2)^2 - b^2\omega^2}} \quad (5)$$

Average power output of generator is:

$$P_{av} = \frac{bm^2\omega_n^6 Y^2}{2 \left( (k - m\omega^2)^2 + b^2\omega^2 \right)} \quad (6)$$

Assuming that power would be largest when system is close to resonance, set  $\omega = \omega_n$  [7].

$$P_{av} = \frac{\omega_n^3 m Y^2}{4\xi} \quad (7)$$

Damping can be into electrical and mechanical part in form:

$$\xi = \xi_m + \xi_e \quad (8)$$

In order to achieve maximal power output of device, ratio of electrical and mechanical damping should be carefully designed. In other words, proper design of electronics of harvesting device is crucial in order to achieve efficient energy harvesting. As stated in [1], vibration energy harvesters are mechatronic systems and should be treated as such during the process of design.

Linear damping as a sum of mechanical and electrical damping effects is fair representation for electromagnetic harvesters, less for piezoelectric [7]. Anyway, this simple model is used as many interesting conclusions may be drawn from it. In order to broaden operational frequency range, it is common practice to use nonlinear spring elements. Article compares two designs of springs made of five different materials.

### 3.6. Considering the Transduction Mechanism

Two prevalent transduction mechanisms for vibration energy harvesters are piezoelectric and electromagnetic. Both mechanisms are compared in article [10], where conclusion is drawn that piezoelectric systems are well suited for micro-scale applications, while electromagnetic systems are preferable for medium scale devices. Simplicity and rugged nature of electromagnetic generator would be appreciated in situations where micro-scale of generator is not a must.

## 4. Electromagnetic Energy Harvesters

Despite being around for quite a long time, as first inertial generator was reportedly proposed by Williams and Yates [6] in 1995, there are still many issues to be worked out. Publication presented a concise comparison of current and past electromagnetic harvesters and identified several problems that plague nearly all mentioned designs of generators. According to Spreeman and Manoli [5]:

- Existing electromagnetic vibration energy harvesters tend to be manufactured in scales from 0,1 cm<sup>3</sup> up to 100 cm<sup>3</sup> and their output performance ranges from hundreds of nano-Watts to hundreds of mili-Watts.
- Nearly all harvesters are based on resonance principle and are inherently narrowband.
- Analytical theory is well known and used to evaluate the influence of most important system parameters

on overall performance of system and reassessment of experimental data. On the other side, analytical theory is seldom incorporated into design process of devices.

- Output voltage, mainly for micro-scaled devices is often insufficient for further processing and use.
- Universal goal in enhancement of harvester performance is broadening their operational frequency range. One way of achieving this goal is use of tunable devices, but simultaneous power supply for actuators and controls remains problematic.
- Different constructions of electromagnetic energy harvesters are in existence, however in most cases it is not explained why the particular construction was chosen. These constructions have never been directly compared and it is not clear which one performs best.
- Dimensions of most important parts of transducers are often based on simplified assumptions if not solely on intuition.
- Comparison of results available in literature is difficult, as there is no code or standard for fair comparison.
- In scientific prototypes is tuning of resonance profile of device to vibration profile of source often a secondary task. Usually is design of device first and vibration profile of source is then matched in laboratory conditions.
- Circuits used for harvesting are in many cases limited in performance and hamper the overall performance of device.

Another problem not mentioned by article [5] is fact, that maximum generated voltage and electric power are strongly dependent on external vibration energy and it is at these low frequencies where most ambient vibrations occur. Frequency up-conversion mechanism based on principle of two sets of resonators is proposed as a solution in [18]. Low frequency resonator in form of magnet on spring is tuned to low frequency of ambient vibrations. High frequency resonators in forms of parylene cantilevers with coils and magnets at their free ends are excited by low frequency resonator thanks to interaction of magnets. When released, cantilevers undergo free vibrations at their natural frequency that is much higher than frequency of ambient source. Current is generated in coils on vibrating cantilevers. In article [4], the same problem was identified, but more traditional approach of reducing the stiffness of a spring was chosen.

Based on these facts, authors in [5] propose several key goals crucial in strive for higher efficiency electromagnetic energy harvesting systems:

1. Development of universal optimization principles for dimensioning of respective parts of electromagnetic harvesters.
2. Comparison of most frequently used transducer designs and classification of their output power.

#### 4.1. Architectures of Vibration Energy Harvesters

There are two basic designs with respect to orientation of magnets and coil: magnet in-line coil, where vector of movement of magnet is in line with axis of the coil and magnet across coil, where it is perpendicular [5].

Considering the arrangement of magnet and coil, there is standard configuration, where magnet is moving and coil, or coils are fixed and inverse, where coil is moving and magnets are stationary.

Spreeman and Manoli [5] presented a concise comparison of eight harvesters of various designs using both magnet in-line coil and magnet across coil arrangements with or without backing iron. All devices were of standard configuration with moving magnets. Thorough analysis of each design was carried out in accordance with issues mentioned before by the authors.

In paper [4], inverse arrangement with moving coil was chosen and magnetic fields of four permanent magnet arrangements were simulated using FEM in order to maximize generated electrical power. Ultimate goal of authors was to design efficient energy harvester for low frequency applications, hence design of nonlinear spring and its material was performed with great attention.

Different design of generator is referenced in [11] using magnets as nonlinear springs. Whole device is size of AA battery. New concept of electromagnetic generator is presented in work [19]. In order to broaden the frequency range, nonlinear multi-DOF system was chosen. Comparison of proposed harvester with other past works was done, but again, it is complicated to draw conclusions, as in each work is used different excitation. Another design of harvester is proposed in paper [20] where spring of complicated shape is used to achieve several resonances in given frequency range. Goal of this approach is to design a generator with broad operational frequency range well suited for multi-frequency vibration sources.

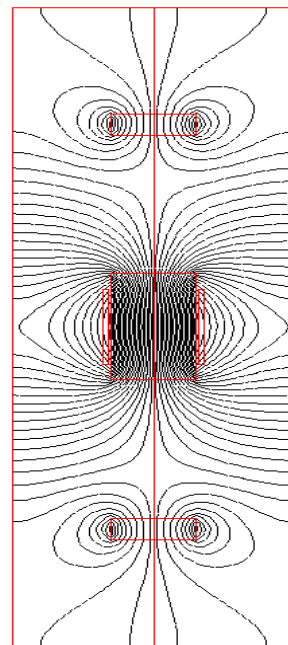


Figure 2. Magnetic flux lines

#### 4.2. FEM Simulations

To support previous claims about thorough analysis of every aspect of harvester in design stage, FEM analysis of two models based on [9] and [4] are performed. As a results of simulations, magnetic flux lines and contour plot of magnetic flux density are plotted. Ansys 13.0 software was used for analysis.



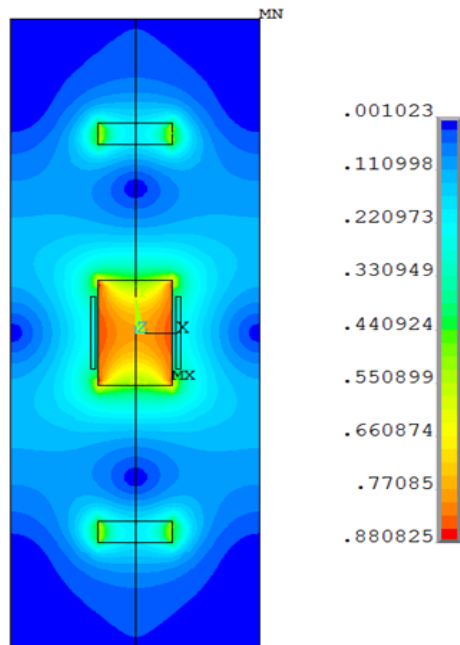


Figure 1. Magnetic flux density

In both cases, neodymium magnets were considered, with coercive force  $H_c=859\ 000\ \text{A/m}$  and residual induction  $B_r=1.16\ \text{T}$ .

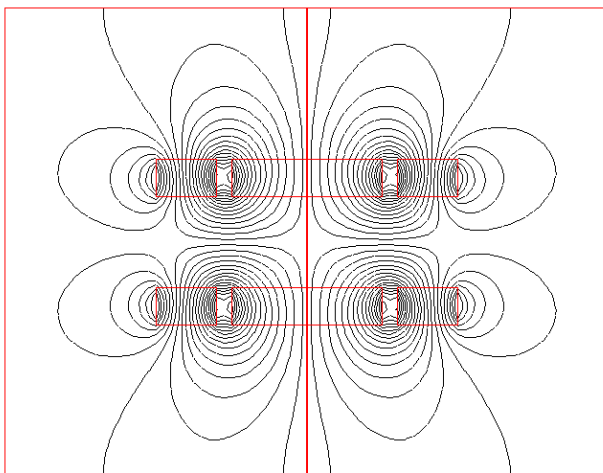


Figure 2. Magnetic flux lines

## 5. Conclusion

An overview of sources of ambient energy available for harvesting was presented. Currently available harvesting techniques were described and ambient vibrations were considered as viable alternative to solar cells. Description of four vibration energy harvesting mechanisms was proposed with respect to pros and cons of each technique. Basic theory of single DOF inertial energy harvester was shown. Electromagnetic mechanism of vibration energy harvesting was chosen as a mechanism of choice for medium scaled systems. Issues common in previously publicized articles were named and some notable recent approaches to design of generators were mentioned.

Strong emphasis was given on multiphysical nature of design of vibration energy harvesters. Basing on this, FEM simulation of magnetic field for two proposed harvesters based on mentioned principles were shown.

## References

- [1] Hadas, Z., Vechet, S., Ondrusek, C., Singule, V., "Development of Energy Harvesting Sources for Remote Applications as Mechatronic system", *Microsyst Technol* (2012) 18:1003-1014.
- [2] Chalasani, S., Conrad, J.M., "A Survey of Energy Harvesting Sources for Embedded Systems", *IEEE Southeastcon* 2008.
- [3] Roundy, S. J., Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion. Dizertačná práca. University of California, Berkeley. 2003.
- [4] Sardini, E., Serpelloni, M., "An efficient electromagnetic power harvesting device for low-frequency applications", *Sensors and actuators A* 172 (2011) 475-482. 2011.
- [5] Spreeman, D., Manoli, Y., *Electromagnetic Vibration Energy Harvesting Devices: Architecture, Design, Modeling and Optimization*, Springer Science + Business Media, 2012.
- [6] Williams, C.B., Yates, R.B., "Analysis of micro-electric generator for microsystems", *The 8th International Conference on Solid-state Sensors and Actuators, and Eurosensors IX. Stockholm, Sweden, June 25-29, 1995*.
- [7] Stephen, N.G., "On energy harvesting from ambient vibration", *Journal of Sound and Vibration* 293 (2006) 409-425.
- [8] Priya, S., Inman, D., *Energy Harvesting Technologies*, Springer Science + Business Media, 2009.
- [9] Tan, Y.K., *Sustainable Energy Harvesting Technologies*. Rijeka: InTech. 2011.
- [10] Poulin, G., Sarraute, E., Costa, F., "Generation of electrical energy for portable devices. Comparative study of an electromagnetic and a piezoelectric system", *Sensors and Actuators A* 116 (2004) 461-471.
- [11] Li, B., Laviage, A. J., "Acoustic energy harvesting using quarter-wavelength straight-tube generator", *Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition*.
- [12] Batchelor, J.C., Taylor, P.S., "Radio Frequency Energy Harvesting Project", *Final Report for Science Faculty REF Fund*.
- [13] Cottone, F. "Introduction to Vibration energy harvesting", NiPS Energy Harvesting Summer School August 1-5, 2011, available: <http://www.nipslab.org/files/file/nips%20summer%20school%202011/Cottone%20Introduction%20to%20vibration%20harvesting.pdf>.
- [14] Jia, Y., Mair, R., Yan, J., Soga, K., Seshia, A., "Vibration energy harvesting for Civil Infrastructure Monitoring", *Department of Engineering, University of Cambridge*, available: <http://eh-network.org/events/eh2013/speakers/2.1.pdf>.
- [15] Park, G., "Overview of Energy Harvesting Systems (for low-power electronics)", *Engineering Sciences & Applications Los Alamos National Laboratory, The First Engineering Institute Workshop: Energy Harvesting*. Available: [http://institutes.lanl.gov/ei/\\_docs/Annual\\_Workshops/Overview\\_of\\_energy\\_harvesting\\_systemsLA-UR\\_8296.pdf](http://institutes.lanl.gov/ei/_docs/Annual_Workshops/Overview_of_energy_harvesting_systemsLA-UR_8296.pdf).
- [16] Paul, D.J., Thermoelectric Energy Harvesting, *School of Engineering, University of Glasgow*. Available: <http://www.nipslab.org/files/Paul.pdf>.
- [17] Roundy, S. J., Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration to Electricity Conversion. The University of California, Berkeley, 2003.
- [18] Kulah, H., Najafi, K., "Energy Scavenging From Low-Frequency Vibrations by Using Frequency Up-Conversion for Wireless Sensor Applications", *IEEE Sensors Journal, VOL. 8, NO. 3, 2008*.
- [19] Ashraf, K., Khirm, M.H.Md., Dennis, J.O., Baharudin, Z., "Improved energy harvesting from low frequency vibrations by resonance amplification at multiple frequencies", *Sensors and Actuators A* 195 (2013) 123-132.
- [20] Liu, H., Qian, Y., Lee, Ch., "A multi-frequency vibration-based MEMS electromagnetic energy harvesting device", *Sensors and Actuators A* 204 (2013) 37-43.