

Electrodynamic and Magnetolectric Vibration Energy Harvesting Devices: Architectures, Design and Characterization

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Abstract—The design of vibration energy harvesting system presents variety of solutions. The main challenges in the design are the optimization of energy outcome relative to the working frequency and amplitude of vibration sources. In this paper we present main possible strategies to harvest energy from common existing vibration sources. We propose to focus on the two main principles which are the electrodynamic and magnetolectric energy harvester. A linear and nonlinear developed solutions for electrodynamic principles and existing magnetolectric energy harvester are presented.

Index Terms—Vibration, Energy harvesting, Electrodynamic, Magnetolectric, Frequency..

I. INTRODUCTION

Energy harvesting open up new ways in several fields of science and technology. Possible implementation of energy harvesters include self powering of autonomous devices such as biomedical devices and wireless sensor nodes. Among environmental energy sources, vibration is especially attractive because of the relative high energy density and its availability in industrial applications (Table1). Commonly used vibration energy harvesting techniques are electrodynamic, piezoelectric, electrostatic and magnetolectric. Generally, electrody-

Vibration Sources	Acceleration (m/s ²)	Frequency (Hz)
Car engine	12	200
Base of three-axis machine tool	10	70
Blender casing	6.4	121
Car instrument panel	3	13
Door frame just after door closes	3	125
Small microwave oven	2.5	121
Heating, ventilating	0.2-1.5	60
Small microwave oven	2.5	121
Windows next to busy road	0.7	100
Compact disk (CD) on notebook	0.6	75
Second story floor of busy office	0.2	100
Clothes dryer	3.5	121

TABLE I
AMBIENT VIBRATION SOURCE [1].

namic generators harness power from environmental kinetic energy using the relative motion between a permanent magnet

and a coil based on Faraday’s law. Varieties of electrodynamic energy harvester have been proposed by different research facilities [2-6]. In addition electrodynamic converters are already commercially available [7-8].

On the other hand, piezoelectric materials have been used to convert mechanical stress to electric energy due to the piezoelectric effect [9-13]. Piezoelectric converters are in most cases based on simple cantilever beam which is fixed at one end. Electrostatic converters are capacitive structures made of two plates separated by air, vacuum or other dielectric materials [14-17].

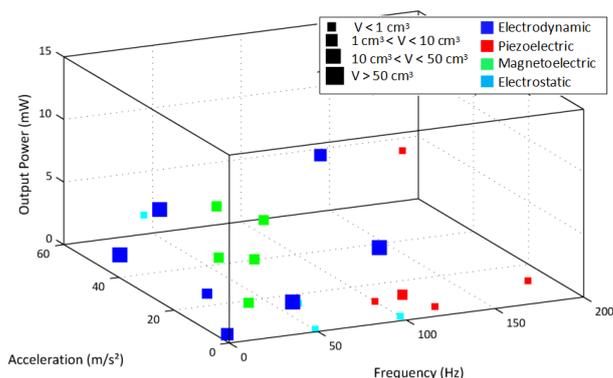


Fig. 1. Output power relative to the frequency and acceleration of previous cited vibration transducers prototypes.

Scientists also have tried to harvest kinetic energy based on the magnetolectric effect of magnetostrictive and piezoelectric laminate composite, that is, when a variable magnetic field is applied, the magnetostrictive material is strained which induces a stress on the piezoelectric material which generates electric energy[18-19]. Vibration converters performance is highly depending on the characteristics of the excitation source and its size.

Figure 1 presents the output power of previous cited prototypes. The energy outcome is presented relative to the converter size, the used harvesting principle, frequency and acceleration of the excitation source. As it is shown, we have four types of vibration energy harvesting techniques. For the

Piezoelectric harvester, the frequency is higher than 100 Hz. For the electrostatic, limited output power is reached (Fig.1). This paper considers the design and architectures of electrodynamic and magnetoelectric vibration energy harvesting devices. It is organized in three sections. In section 1, an overview about developed electrodynamic energy harvester is presented. In section 2, the magnetoelectric principle and existing magnetoelectric converter are detailed. At the end, a comparison of the energy harvesters using such principles is detailed.

II. ELECTRODYNAMIC CONVERTER

In this section main electrodynamic energy harvesters design are illustrated and evaluated. The principle of such converter is based on the Faraday's law to convert the mechanical energy to electrical one. Due to the presence of vibration source, the variation of the magnetic flux leads to generate energy through the coil. Different converters are realized in this purpose. linear and nonlinear main existing solutions are detailed in the following.

A. Linear Energy Harvesting

The linear converters are based on the use of moving magnets or moving coil which is ensured by the use of mechanical spring. Such types of converters have linear behavior and are modeled as mass spring system. The devices using moving coil lead to moving electronic which reduce system reliability (Figure 2.a). An implementation of such system was realized in 1998 by R. Amirharajah *et al.*[3]. The proposed converter delivers $400 \mu\text{W}$ for excitation frequency of 2 Hz and acceleration of 2 m s^{-2} . The use of moving magnet is

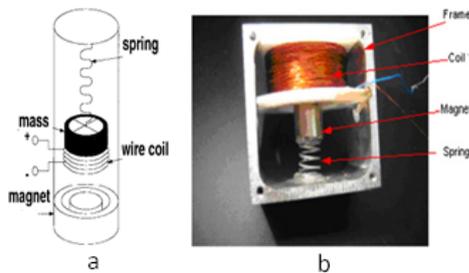


Fig. 2. Linear electrodynamic energy harvesting design [2-3]

more reliable (Figure 2.b). Different devices were achieved using this principle. In 2007, S. Cheng *et al.* develop a vibration energy harvester able to deliver 12.5 mW for an excitation of 68 Hz and an acceleration of 9.8 m.s^{-2} [2]. In this case, due to the prone fatigue of mechanical spring, the harvester life time is limited. A high energy outcome is reached only at one resonant frequency.

In order to have wide band energy harvesting system, the use of coupled oscillators. The system consists on the use of a pair of oscillators composed of two masses, two springs and two dampers. This enables to have generator with larger operational frequency band. Nevertheless, using such method

leads to have a non-compact energy harvesting system, limited and low energy outcome.

B. Non-linear Energy Harvesting

Advanced researches use magnetic springs which are more reliable and cause less mechanical frictions. Two main types of non linear electrodynamic converters can be defined. The monostable architecture is based on the use of one moving magnet and two or three fixed magnets and the higher energy outcome is obtained for a fixed frequency (Figure 3.a). This generator was developed by C. Lee *et al.* in 2010 and able to generate 15 mW with load resistance equal to 4.4Ω within an excitation frequency of 8.55 Hz and amplitude vibration of 8 cm [20]. In this case, the amplitude of excitation is too high which corresponds to limited existing natural sources. Another non linear converter was realized by S. D. Kown *et al.* in 2013 which is based on the use of multi-magnets placed in repulsive way (figure 3.b). This converter is able to generate 0.12 mW for an excitation frequency of 4.1 Hz [21]. In 2013, we develop an electrodynamic generator based on magnetic spring principle. In this design, we use stacked ring magnets placed in repulsive direction (figure 3.c). This results on doubling the magnetic flux surrounding the coil and then enhancing the energy outcome of the generator [22]. This leads to generate 0.8 mW for low amplitude vibration of 1 mm, an excitation frequency of 26 Hz and a load resistance of 35Ω . The second type consists on the bistable generators. They are able to generate high energy for wide-band frequency. one of the main important configuration was developed by Mann and Owens in 2010 [23]. The design consists on the use of magnetic spring principle for the moving magnet. In order to harvest energy for wide-band frequency, the moving magnet is surrounded by multi-outer magnets (Figure 3.d).

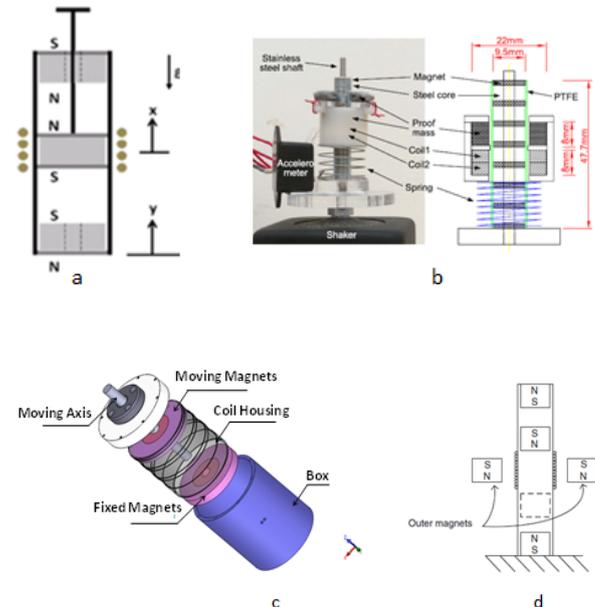


Fig. 3. Non-linear electrodynamic energy harvesting design [20-23]

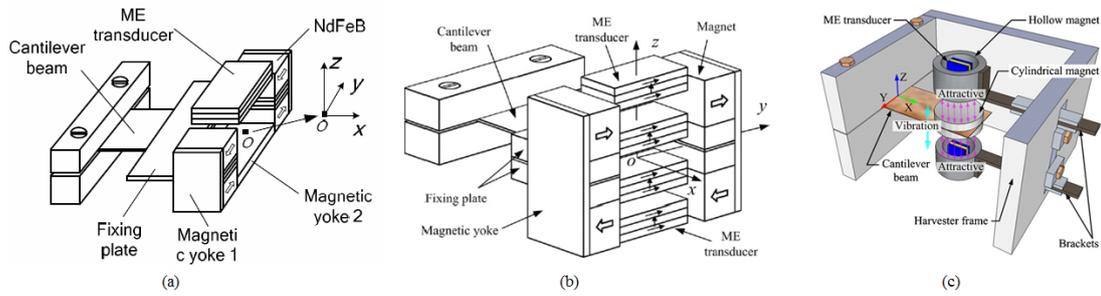


Fig. 4. Magnetolectric energy harvesters with magnetic circuit attached to the end of a cantilever beam. (a)Single transducer reported by X. Dai *et al.* [18](b)Multiple transducers reported by X. Dai *et al.* [19](c) Twin transducers reported by M.Li *et al.* [25]

III. MAGNETOELECTRIC CONVERTER

Magnetolectric effect (ME) in magnetostrictive/piezoelectric laminate composites have recently been used in energy harvesting [24]. Multiplicities of magnetolectric converters have been developed by numerous researchers. The transducers basically are of small size. In addition, they have the advantage of operating at relatively low frequency in comparison with piezoelectric converters. A popular coupling architecture is a three layer magnetostrictive laminate composite formed of thin piezoelectric layer bonded to two magnetostrictive layers and placed in the air gap of a magnetic circuit fixed at the end of a cantilever beam. An implementation of such architecture with Neodymium magnets was reported in 2009 by X. Dai *et al.* at Chongqing University [18]. The prototype delivered a maximum power output of 1.055 mW across 564.7 K Ω load for excitation of 51 Hz frequency with an acceleration of 1g (Figure 4.a). Another implementation of this architecture was published in 2010 by the same researcher group. The proposed harvester employs multiple Terfenol-D/ PMNT/Terfenol-D laminate magnetolectric (ME) transducers to harvest energy from mechanical vibrations as shown in Figure 4.b . Four prototypes were fabricated to investigate the optimal power output of the harvester employing various numbers of transducers in different positions. Results shows that 1.44 mW, 4.07 mW, 3.95 mW and 7.13 mW can be generated at resonance for the four prototypes, respectively [19].

A modification of the previous coupling architecture has been reported by M.Li *et al.* in 2012[25]. In this development two cylindrical magnets arranged on the free end of a cantilever beam, and two hollow magnets with ME transducers inside their cavities have been used (Figure 3.c). The experimental results show that a maximum power of 517 μ W can be generated at a rotation frequency of 9.8 Hz.

Another commonly applied coupling architecture is that of a spherical permanent magnet as a proof mass. Based on this architecture a group from the Defense Science and Technology Organisation in Australia developed a bi-axial magnetolectric energy harvester in 2012 [26]. The aim was to develop a potential means of powering structural health monitoring systems embedded within aircrafts. A bi-axial oscillator is created using a permanent-magnet/ball-bearing

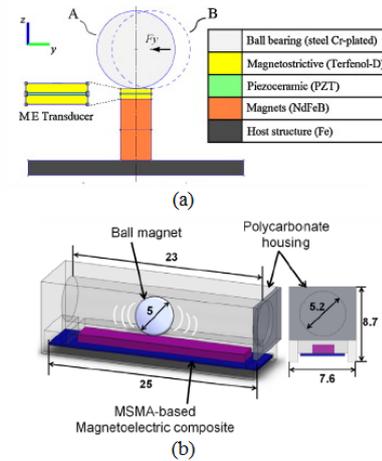


Fig. 5. Magnetolectric energy harvesters with spherical permanent magnet as a proof mass. (a)Schematic diagram of the bi-axial energy harvester reported in [26]. (b)Schematic diagram of the converter reported in [27]

arrangement. The magnet produces a bi-axial restoring force on the bearing and it steers magnetic field through the transducer (Figure 5.a). For excitation with 61 mg rms of acceleration and 9.8 Hz frequency, a peak rms power of 121 μ W has been obtained. The same coupling architecture has also been used in [27] by S.Ju *et al.* from Ewha Womans University in 2013 (Figure 5.b). The transducer is based on a freely movable spherical permanent magnet to transform external vibration into a time varying magnetic field applied to the magnetolectric transducer formed with Ni-Mn-Ga (magnetic shape memory alloy) and PZT. The prototype was capable of generating a maximum output voltage of 10.24 V and output power of 4.1 μ W on a 950 Ω load when it was mounted on a smartphone and shaken by hand.

In 2014, we develop a magnetolectric energy harvester using twin lateral magnetolectric transducers [28]. The coupling architecture is based on two magnetic spring and two transducers placed on the air gap between two rectangular magnets. One of the objectives was to reduce friction using the magnetic spring and to optimize the position of the transducers in the air gap. The prototype was able to generate

a maximum open voltage of 3.5 V for an excitation of 1 mm at a frequency of 29 Hz. The comparison with a single transducer shows that the twin lateral converter reaches especially at resonance frequency the one and half energy outcome.

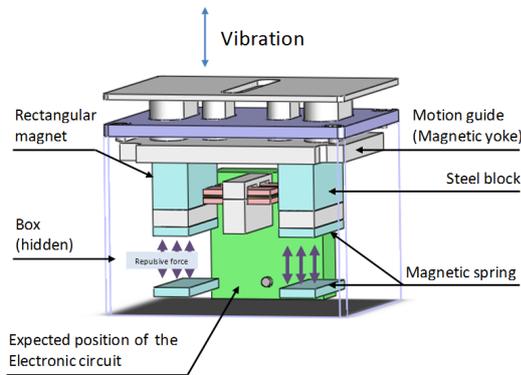


Fig. 6. Design of the proposed magnetolectric converter[28]

IV. COMPARISON

Table 2 presents a comparison of the energy outcome relative to the excitation frequency. The output power in case of electrodynamic converters is from 0.2 mW to 12.5 mW for excitation frequencies from 2 Hz to 100 Hz. For the magnetolectric harvesters, the energy outcome is between 4 μ W to 7.13 mW when applying an excitation frequency from 9.8 Hz to 51 Hz.

	Refernces	Frequency (Hz)	Power output (mW)
Electrodynamic	S. Sheng <i>et al.</i> [2]	68	12.5
	R. Amirtharajah <i>et al.</i> [3]	2	0.4
	G. Naumann <i>et al.</i>	16	0.2
	S. Saha <i>et al.</i> [5]	2.75	2.6
	D.J. Domme [6]	18	5.5
	Perpetuum [7]	100	4.5
	Ferro Solutions [8]	21	9.3
	C. Lee <i>et al.</i> [20]	15	8.55
	S.D. Kown <i>et al.</i> [21]	4.1	0.12
	S. Bradai <i>et al.</i> [22]	26	0.8
Magnetolectric	X. Dai <i>et al.</i> [18]	51	1.55
	X. Dai <i>et al.</i> [19]	23-51	1.44-7.13
	M. Li <i>et al.</i> [25]	9.8	0.517
	S. D. Moss <i>et al.</i> [26]	9.8	0.121
	S. Ju <i>et al.</i> [27]	shaken by hand	0.004
	S. Naifar <i>et al.</i> [28]	29	0.03

TABLE II
ENERGY OUTCOME AND WORKING FREQUENCIES FOR PREVIOUS STATED ENERGY HARVESTERS

V. CONCLUSION

In this paper, an overview about main important developed energy harvesting converters is detailed. In particular, we focus on the linear and non-linear electrodynamic generators and the magnetolectric harvester. The outcome energy for each converter is different. This depends especially on the amplitude and frequency excitation of applied vibration source as first. Also, the size, type of the used principle and the design of the converter should be taken into account to evaluate the power output.

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