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GENERATING ENERGY FROM LOW ENVIROMENTAL VIBERATION BY USING ELECTROSTATIC ENERGY HARVESTER

توليد الطاقة من الإهتزازات البيئية المنخفضة بإستخدام حاصدة الطاقة الإلكتروستاتيكية

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN MECHATRONICS ENGINEERING

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ABSTRACT

This research focuses on vibration energy harvesting using electrostatic converters. It synthesizes the various works carried out on electrostatic devices, from concepts, models and up to prototypes; Integration of structures and functions has permitted to reduce electric consumptions of sensors, actuators and electronic devices. Therefore, it is now possible to imagine low-consumption devices able to harvest energy in their surrounding environment. One way to proceed is to develop converters able to turn mechanical energy, such as vibrations, into electricity: this research focuses on electrostatic converters using electrets. It develops an accurate analytical model of a simple but efficient cantilever-based electret energy harvester. Therefore, it proves that with vibrations of resonant frequency it is theoretically possible to harvest energy in μW per gram of mobile mass. This power corresponds to the maximum output power of a resonant energy harvester according to the model of William and Yates. The Simulations results are validated by model of William and Yates and other devices, the work includes Design, modeling and simulation by SOILDWORK, ANASYS and MATLAB of electro-mechanical and electrical properties of the structure, description of its behavior in operating model and phases of activity. Simulation results were compared with measured values of the produced prototype chip by other studies. These results can suggest possible modifications to the proposed structure for further optimization and application environment adaptation.

الملخص:

هذا البحث يركز على حصاد طاقة الاهتزاز باستخدام المحولات الالكتروستاتيكيه. ويجمع مختلف الأعمال التي أجريت على الأجهزةالالكتروستاتيكيه، من المفاهيم والنماذج وحتى النماذج المصغرة. وقد أتاح الدمج بين الهياكل والاداء في الحد من استهلاك الكهرباء في أجهزة الاستشعار وأنظمة التشغيل والأجهزة الإلكترونية،أصبح من الممكن الآن أن نتصور الأجهزة ذات الاستهلاك المنخفض قادرة على حصد الطاقة من البيئة المحيطة بها. ومن الطرق المطوره للمضي قدما في تطوير المحولات القادرة على تحويل الطاقة الميكانيكية، مثل الاهتزازات، إلى كهرباء:لذلك يركز هذا البحث على محولات كهرباء باستخدام الطبقات الكهربائيه المشحونه. ويطور نموذج تحليلي دقيق لحاصدات الطاقه البسيطة والفعالة بإستخدام طاقة الإلكتريت القائم على الكابولي. وبالتالي، فإنه يثبت أنه مع اهتزازات الناتجه عن تردد الرنين أنه من الممكن نظريا لحصاد الطاقة بوحده المايكرو واط لكل جرام من الكتلة. هذه القدرة تتوافق مع قدرة الطاقة الانتاجية القصوى من حصادات الطاقة الرنانة وفقا لنموذج وليام وييتس. وقد تم التحقق من صحة نتائج المحاكاة عن طريق المقارنه مع نموذج وليام وييتس وبعض الاجهزه السابقة، ان التصميم والنمذجة والمحاكاة الكهربائية الميكانيكية والكهربائية وخصائص الهيكل، ووصف سلوكها في نموذج التشغيل ومراحل النشاط لقد تمت بإستخدام SOILDWORK ، ANASYS وMATLAB. وتمت مقارنة نتائج المحاكاة مع القيم المقاسة من الشريحة النماذج المنتجه من دراسات أخرى. هذه النتائج يمكن أن تشير الي التعديلات المحتملة على الهيكل المقترح لمزيد من التحسين والتكيف مع بيئة التطبيق.

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LIST OF SYMBOLS AND ABBREVIATION

VEH	Vibration energy harvester
M beam	Material of the beam
E	Young's Modulus of Silicon
L	Position of the center of gravity of the mass
h	Thickness of the beam
w	Width of the beam / Width of the electret
2Lm	Length of the mobile mass
m	Mobile mass (structural steel)
ω	Angular frequency of vibrations
Q m	Mechanical quality factor of the structure
M electrets	Material of the electret
$\varepsilon 0$	Relative permittivity (air)
εr	Dielectric constant of the electret
d	Thickness of the electret
V	Surface voltage of the electret
g0	Thickness of the initial air gap
λ	Length of the electrode
F(mec)	mechanical damping force
F(elec)	electrical damping force

CHAPTER ONE

INTRODUCTION

1.1 GENERAL INTRODUCTION:

Energy harvesting (also known as power harvesting or energy scavenging) is the process by which energy is derived from external sources (e.g. solar power, thermal energy, wind energy, salinity gradients, and kinetic energy), captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor_networks, and energy harvesters provide a very small amount of power for low-energy electronics. While the input fuel to some large-scale generation costs money (oil, coal,...), the energy source for energy harvesters is present as ambient background and is free. For example, temperature gradients exist from the operation of a combustion engine and in urban areas, there is a large amount of electromagnetic energy in the environment because of radio and television broadcasting, energy harvesting devices converting ambient energy into electrical energy have attracted much interest in both the military and commercial sectors. Some systems convert motion, such as that of ocean waves, into electricity to be used by oceanographic monitoring sensors for autonomous operation. Future applications may include high power output devices (or arrays of such devices) deployed at remote locations to serve as reliable power stations for large systems. Another application is in wearable electronics, where energy harvesting devices can power or recharge cellphones, mobile computers and radio communication equipment. All of these devices must be sufficiently robust to endure long-term exposure to hostile environments and have a broad range of dynamic sensitivity to exploit the entire spectrum of wave motions; energy can also be harvested to power small autonomous sensors such as those developed using MEMS technology. These systems are often very small and require little power, but their applications are limited by the reliance on battery power. Scavenging energy from ambient vibrations, wind, heat or light could enable smart sensors to be functional indefinitely, Vibration energy harvesting is an attractive technique for potential powering of wireless sensors and low power devices. While the technique can be employed to harvest energy from vibrations and vibrating structures, a general requirement independent of the energy transfer mechanism is that the vibration energy harvesting device operates in resonance at the excitation frequency. Most energy harvesting devices developed to date are single resonance frequency based, and while recent efforts have been made to broaden the frequency range of energy harvesting devices, [1]

1.2 PROBLEM STATEMENTS:

Fossil fuels are finite and environmentally costly. Sustainable, environmentally benign energy can be derived from nuclear fission or captured from ambient sources. Large-scale ambient energy (e.g. solar, wind and tide), is widely available and large-scale technologies are being developed to efficiently capture it.

At the other end of the scale, there are small amounts of ‘wasted’ energy that could be useful if captured. Recovering even a fraction of this energy would have a significant economic and environmental impact. This is where energy harvesting (EH) comes in. for example wirelesses and embedded systems are commonly powered using batteries. For applications where the system is expected to operate for long durations, energy becomes a severe bottleneck and much effort has been spent on the efficient use of battery energy. For this reason it is a major problem to get electricity needed to operate these devices

1.3 OBJECTIVES OF THE RESEARCH:

This research a non-resonant vibration based on MEMS energy harvester, which generates energy from low frequency vibrations with low displacement amplitude. The focus of this research is on generating energy efficiently from low-frequency vibration. In particular, explored MEMS-scale energy harvester, build a demonstration modeling, simulation and optimized to illustrate how energy can be generated using low-frequency vibrations. The final step for this research is constructing of a mathematical model to be used to simulate and optimize a proposed design.

1.4 CHAPTERS ORGANIZATION:

The first chapter introduces a brief background to renewable energy and introduces the energy harvesting theories. In addition, the objectives of the present research were mentioned in this chapter. The second chapter introduces briefly some of the previous research on the same idea and the solution and problems discussed. The third chapter goes through the methodology of design, modeling and simulation the energy harvester. In addition, calculating and analysis the material used in this device. The results of the data calculation will be shown and discussed in the fourth chapter and the comparison between the results of the different materials used in energy harvester will be highlighted in this chapter. Lastly, chapter five concludes, identifies the best designs among the alternatives and offers recommendations for further research.

CHAPTER TWO

LITERATURE REVIEW

2.1 APPLICATIONS OF WIRELESS SENSOR NETWORK:

A huge number of sensor network applications have been reported ranging from initial research investigations [2]. Abroad range review of applications is given in [3] as the basis of the design space model.

2.1.1. Environmental monitoring:

Environmental monitoring is one of the widely considered areas for the application of WSN (wireless sensors network) .A lot of researches have been conducted in this area Measurement of glacier dynamics, sea bed pressure, temperature, conductivity, current, and turbidity monitoring observation of temperature, salinity, and current profile of the upper ocean [4], monitoring of the grape growing conditions [5], are some of examples of applications of WSN in environmental monitoring.

2.1.2 Health

Health applications for WSNs contain patient monitoring, drug administration, tracking of patients at home and doctors in hospitals. Body sensor networks are used in the medical sector. The wireless monitoring of patients and data about the patient's condition can be analyzed for abnormal reaction and side effects [6]. An analysis of the performance of medical sensor body area networking is presented in [4], which also endorsed the advantage of using IEEE802.15.4 and ZigBee for medical sensor technologies. Also, WSN for rehabilitation have been used in several clinical applications. In [7], the authors classified the existing solutions from a process point of view and they divided them into two main classes that are described in Fig(1.1) Also, using WSN for rehabilitation supervision brings some benefits.

2.1.3 Safety, security and military Applications

WSNs have been established to support rescue teams in saving people concealed in avalanches [4,5], trailing of military vehicles using networks of nodes by un-manned aerial vehicle(UAV), anti-tank land-mines with self-monitoring capability [4,7], determination the location of a sniper and the direction of the bullet ,monitoring of buildings and emergency response personnel with the goal of improving security in dealing with fires and other life threatening situations in [6], a power electronic circuit is presented for extracting usable electrical power from a backpack-based energy harvesting system and the power output for different weights is presented in Fig(2.1) . Here, electricity generation for 40 lbs., 60 lbs., and 80 lbs. is presented due to different walking speeds .From figure(2.1) , it is very clear that the generation of electricity is high for higher speed as well as for higher weight.

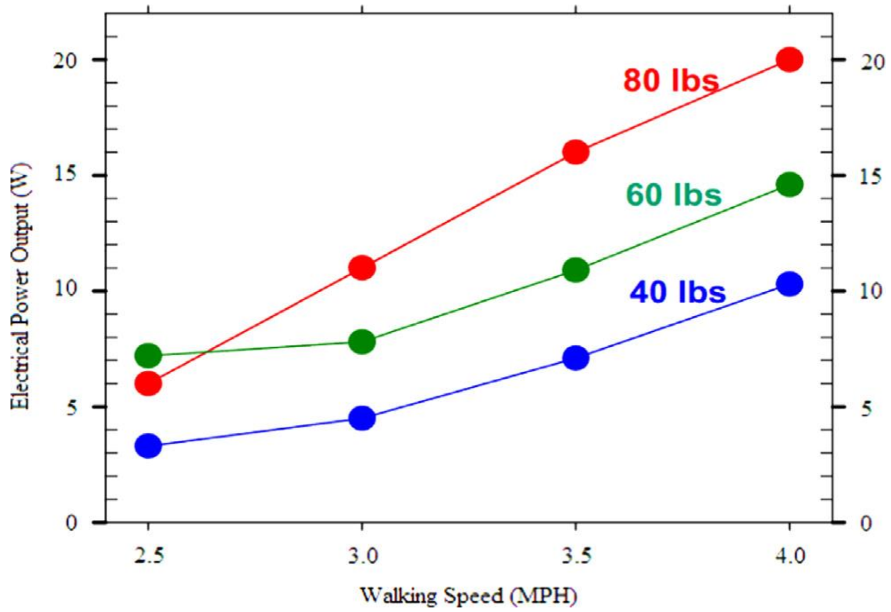


Figure (2.1): Electricity generation during walking [2]

2.2 APPROACH AND METHODOLOGY:

For a vibrating system, the available power is proportional to the square of the acceleration and inversely proportional to, the oscillation frequency, meaning that higher accelerations and lower frequencies carry more power. Ambient vibration is typically associated with environments where the acceleration change and the oscillation amplitude tend to be quite high at low frequency, like those corresponding to human body movements. Thus, the use of ambient vibration as an energy source is attractive, because of its abundance. In nature, most of this vibration is found in the low-frequency range (1-10Hz). Vibration harvesting techniques based on electromagnetic, piezoelectric, and electrostatic transduction have been reported widely. Even though power has been generated, the operation of those devices is reported to be at frequencies of over several hundred Hz, as shown by devices operating at the kHz range. The goal of this research is to conduct research that will allow harvesting of energy from low-frequency vibration sources. The challenge centers on the need to harness the power of large oscillation amplitudes (over 1mm) at low frequencies on the MEMS-scale. Overcoming this obstacle could mean that environmental, wearable, or implantable biomedical applications will not be limited by battery lifetime [8]

2.3 HARVESTING ENERGY FROM VIBRATION:

Energy is convenient in most of the built environments [4]. The vibration amplitude and its frequency are the factors on which the energy mining from vibration sources depends. It also relies on the amount to which the existence of an energy harvesting device distresses the vibration. This consecutively relies on the harvesting device mass, which is relative to the vibrating mass. Vibration sources differ significantly in amplitude and dominant frequency [6]. Measurement for a number of vibration sources have been presented in Roundy et al. [17], which show that the amplitude and frequency varies from ($12m/s^2$) at 200Hz for a car engine compartment to ($0.2m/s^2$) at 100Hz for the floor in an office building with the majority of sources measured having a fundamental frequency in the range (60–200Hz). Vibration existing in most of the environments is made up of a number of frequencies instead of a single frequency. Another significant matter is that the dominant vibration frequency relies in many circumstances, on the functioning parameters of the apparatus, which causes the vibration .Thus, for example, the dominant vibration frequency on a domestic fan varies when partial obstruction of the air flow is occurring. Correspondingly, testes on an energy scavenging node deployed for the extraction of energy from a pump of a marine vessel shows that the energy production fell significantly because of the fluctuations in pump speed [7]. J. Baker et al [8] has described the use of a piezoelectric cymbal transducer for generating electricity using the vibration of car engine. The efficiency of this system was found to be 7.5% .After connecting this device with rectifier, smoothing capacitor, and buck converter, the maximum output was found almost (30microW). For charging the car battery from this harvested energy, much higher power level is needed. Discenzo et al. [9] has suggested force-driven piezoelectric generators for the medical applications. They intended to get the input energy from the fluctuating pressure in a blood vessel. They have worked with a square sheet of ($1cm^2$) made of the piezoelectric material and for the 1Hz frequency, they harvested a round (1 micro W). Yates et al. [10] reported the measured result for an inertial generator using the vibration of a flexible membrane. The authors have found almost (0.33 micro w) harvested energy for 4.4 kHz input vibration. The research group of the Chinese University of Hong Kong [11] has reported an electromagnetic generator using vibration are found (40 micro W) of power for an input vibration of between (60–120Hz). Edward et al. [12] have described a novel WSN system that harvests the vibrations created by passing traffic on a bridge. This vibration is transformed into functional electrical energy by means of a linear electromagnetic generator, which allows harvesting of up to (12.5 micro W) of power with an excitation frequency of 3.1 Hz. A different mechanical energy harvesting based on the electrostatic micro generator was suggested by Sterken et al. [13]. In this system, a micro electrostatic converter comprised of a vibration sensitive adjustable capacitor was polarized by an electret and it revealed that power generation competences up to (50 micro w) for 0.1cm^2 surface areas were attainable. Ching et al. [14] have proposed an active electronic interface for an energy harvester comprising a vibration based electromagnetic transducer. The transducer delivers a peak voltage of 3.25V when functioned close to its mechanical resonance frequency about 10.4Hz.

2.3.1. Converters and Electrostatic devices – Overview

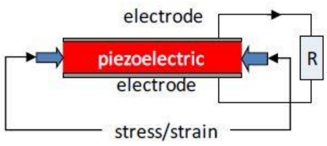
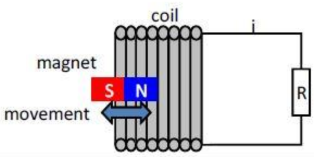
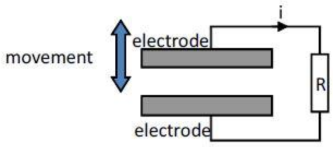
Three main converters enable to turn mechanical energy into electricity: piezoelectric devices, electromagnetic devices and electrostatic devices (Table 1).

- **Piezoelectric devices:** they use piezoelectric materials that present the ability to generate charges when they are under stress/strain.

- **Electromagnetic devices:** they are based on electromagnetic induction and ruled by Lenz’s law. An electromotive force is generated from a relative motion between a coil and a magnet.

- **Electrostatic devices:** they use a variable capacitor structure to generate charges from a relative motion between two plates.

Table 2.1: Mechanical-to-electrical converters for small-scale devices [2]

Piezoelectric converters	Electromagnetic converters	Electrostatic converters
Use of piezoelectric materials	Use of Lenz's law	Use of a variable capacitor structure
		

Obviously, each of these converters present both advantages and drawbacks depending on the application (amplitudes of vibrations, frequencies).

2.4. Advantages and Drawbacks of converters:

A summary of advantages and drawbacks of electrostatic devices is presented in Table 2.2 in most cases, piezoelectric and electrostatic devices are more appropriate for small scale energy harvesters (<1-10 cm³) while electromagnetic converters are better for larger devices.

This research is focused on electrostatic vibration energy harvesters. These VEH are well-adapted for size reduction, increasing electric fields, capacitances and therefore converters' power density capabilities. They also offer the possibility to decouple the mechanical structure and the converter (which is not possible with piezoelectric devices). Finally, they can be a solution to increase the market of EH-powered WSN by giving the possibility to develop "low-cost" devices as they do not need any magnet or any piezoelectric material that can be quite expensive

Table2.2 Advantages and drawbacks of converters [27]

	Piezoelectric devices	Electromagnetic devices	Electrostatic devices
advantages	-high output voltages -high capacitance -No need to control any gap	-high output currents -long life time proven -robustness	-high output voltages -Possibility to build low-cost systems -Coupling coefficient easy to adjust -high coupling coefficient reachable -size reduction increases capacitance
drawbacks	-expensive(material) -coupling coefficient linked to material properties	-low output voltages -hand to develop MEMS devices -may be expensive (material) -low efficiency in low frequency and small size	-low capacitance -high impact of parasitic capacitances -need to control µm dimensions -no direct mechanical –to- electrical conversion for electret free converters

2.5. ELECTRET-FREE ELECTROSTATIC VIBRATION ENERGY HARVESTERS (EVEH) :

2.5.1. Devices

The first MEMS electrostatic comb based VEH was developed at the MIT by Meninger et al. in 2001 [15]. This device used an in-plane overlap electrostatic converter. Operating cycles are described and it is proven that the voltage-constrained cycle enables to maximize output power (if the power management electronic is limited in voltage). Yet, for the prototype, a charge-constrained cycle was adopted to simplify the power management circuit even if it drives to a lower output power.

Electrostatic devices can be particularly suitable for Vibration energy harvesting at low frequencies (<100Hz). In 2002, Tashiro et al. [16] developed a pacemaker capable of harvesting power from heartbeats. The output power of this prototype installed on the heart of a goat was 58µW.

In 2003, Roundy [17] proved that the best structure for electrostatic devices was the in-plane gap closing and would be able to harvest up to 100µW/cm³ with ambient vibrations (2.25m/s² at120Hz). Roundy et al. then developed an in-plane gap closing structure able to harvest 1.4 nJ/ cycle.

In 2005, Despesse et al. developed a macroscopic device (Figure 2.1(a)) able to work on low vibration frequencies and able to harvest 1mW for a vibration of 0.2G at 50Hz [18]. This prototype has the highest power density of e VEH ever reached. Some other MEMS devices were then developed by Basset et al [19] (Figure 2.1(b)) and Hoffmann et al. [20].

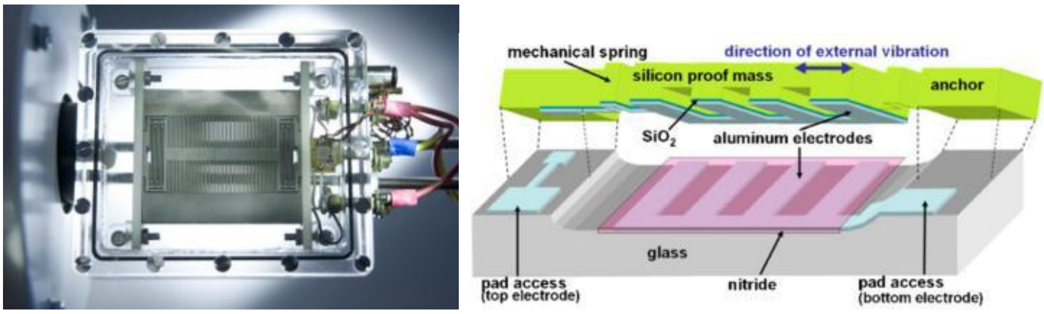


Figure 2.2.Electrostatic vibration energy harvesters from (a) Despesse et al. [18] and (b) Basset et al. [19].

2.5.2. State of the art – Overview

An overview of electret-free electrostatic vibration energy harvesters is presented in Table 2.3.

Table2.3 Electret-free electrostatic vibration energy harvesters from the state of the art [27]

Author	Ref	Output power	Surface	Volume	Polarization voltage	Vibrations
Tashiro	[19]	36 µW		15000 mm^3	45V	1,2G@6Hz
Roundy	[24]	11 µW	100 mm^2	100 mm^3		0.23G@100Hz
Mitcheson	[25]	24 µW	784 mm^2	1568 mm^3	2300 V	0.4G@10Hz
Yen	[26]	1,8 µW	4356 mm^2	21780 mm^3	6 V	1560Hz
Despesse	[21]	1050 µW	1800 mm^2	18000 mm^3	3 V	0.3G@50Hz
Hoffmann	[23]	3.5 µW	30 mm^2		50 V	13G@1300-1500Hz
Basset	[22]	61nW[1]	66 mm^2	61.49mm^3	8 V	0.25G@250Hz

2.6 ELECTRET-BASED ELECTROSTATIC CONVERTER

Electret-based electrostatic converters are quite similar to electret-free electrostatic converters. The main difference relies on the electret layers that are added on one (or two) plate(s) of the variable capacitor, polarizing it.

2.6.1 Electrets:

Electrets are dielectric materials that are in a quasi-permanent electric polarization state (electric charges or dipole polarization). They are electrostatic dipoles, equivalent to permanent magnets (but in electrostatic) that can keep charges for years. The word electret comes from “electricity magnet” and was chosen by Oliver Heaviside in 1885. [27]

2.6.2. Definition and electret types:

Electret’s polarization can be obtained by dipole orientation (Figure 2.2(a)) or by charge injection (Figure 2.2(b)) leading to two different categories of electrets:

- Oriented-dipole electrets (dipole orientation)
- Real-charge electrets (excess of positive or negative charges on the electret’s surface or on the electret’s volume)

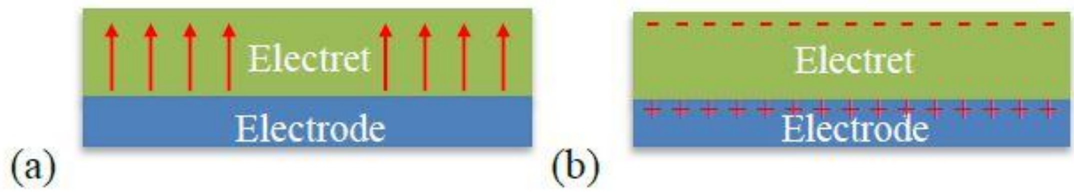


Figure2.3. Standard electrets for electret-based electrostatic converters (a) dipole orientation and (b) charge injection [27]

Electret-based converters are electrostatic converters, and are therefore based on a capacitive structure made of two plates (electrode and counter-electrode (Figure 2.3)). The electret induces charges on electrodes and counter-electrodes to respect Gauss’s law. Therefore, Qi, the charge on the electret is equal to the sum of Q1 and Q2, where Q1 is the total amount of charges on the electrode and Q2 the total amount of charges on the counter-electrode (Qi=Q1+Q2). A relative movement of the counter-electrode compared to the electret and the electrode induces a change in the capacitor geometry (e.g. the counter-electrode moves away from the electret, changing the air gap and then the electret's influence on the counter-electrode) and leads to a reorganization of charges between the electrode and the counter-electrode through load R (Figure 2.4). This results in a current circulation through R and one part of the mechanical energy (relative movement) is then turned into electricity.

The equivalent model of electret-based electrostatic converters is presented below.

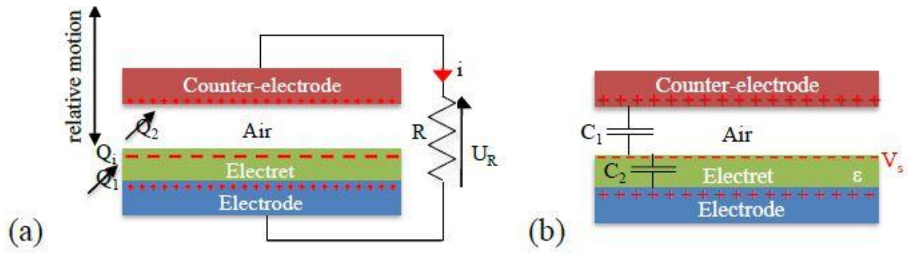


Figure.2.4. Electret-based electrostatic conversion – Concept [27]

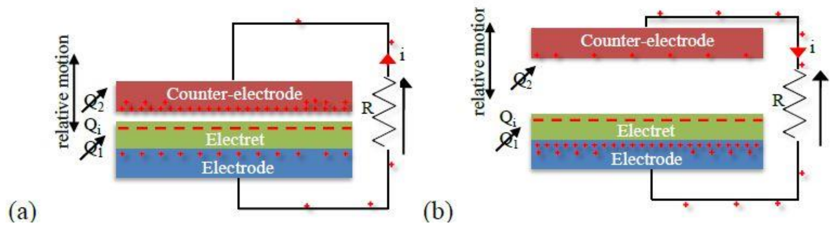


Figure2.5.Electret-based electrostatic conversion – Charge circulation [27]

2.7. ELECTRET-BASED ELECTROSTATIC (VEH) DESIGN:

Electret-based devices were developed to enable a direct vibration-to-electricity conversion (without cycles of charges and discharges) and to simplify the power management circuits.

2.7.1 History

The idea of using electrets in electrostatic devices to make generators goes back to about 40 years ago. In fact, the first functional electret-based generator was developed in 1978 by Jefimenko and Walker [21]. From that time, several generators exploiting a mechanical energy of rotation were developed (Jefimenko [21], Tada [22], Genda [23] or Boland [24]). Figure 2.5 presents an example, developed by Boland in 2003 [24**,** 25] of an electret-based generator able to turn a relative rotation of the upper plate compared to the lower plate into electricity.

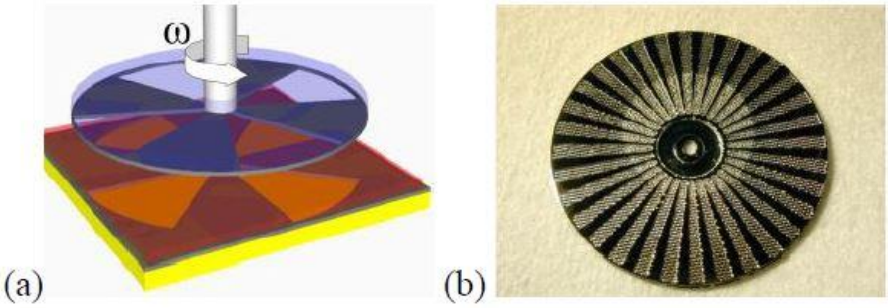


Figure 2.6Boland's electret-based generator prototype [25] (a) perspective view and (b) stator

With the development of energy harvesting and the need to design autonomous sensors for industry, researchers and engineers have decided to exploit electrets in their electrostatic vibration energy harvesters as their everlasting polarization source.

This section presents some examples of electret-based vibration energy harvesters from the state-of-the-art. We have decided to gather these prototypes in 2 categories: devices using full-sheet electrets (electret dimensions or patterning higher than 5mm) and devices using patterned electrets (electret dimensions or patterning smaller than 5mm). Indeed, it is noteworthy that texturing an electret is not an easy task as it generally leads to a weak stability (important charge decay) and requires MEMS fabrication facilities

a. Devices using full-sheet electrets

Full-sheet-electret devices can exploit a surface variation or a gap variation. In 2003, Mizuno [26] developed an out-of-plane gap closing structure using a clamped-free beam moving above an electret. This structure was also studied by Boisseau et al. [27]. This simple structure is sufficient to rapidly demonstrate the principle of vibration energy harvesting with electrets. Large amount of power can be harvested even with low vibration levels as soon as the resonant frequency of the harvester is tuned to the frequency of ambient vibrations.

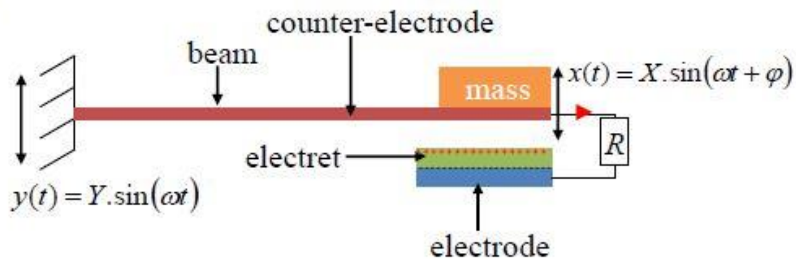


Figure 2.7Cantilever-based electret energy harvesters [15]

The first integrated structure using full-sheet electrets was developed by Sterken et al. from IMEC [28] in 2007. A diagram is presented in Figure 2.7: a full-sheet is used as the polarization source. The electret layer polarizes the moving electrode of the variable capacitance (C_{VAR}). The main drawback of this prototype is to add a parasitic capacitance in series with the energy harvester, limiting the capacitance's variation and the converter's efficiency.

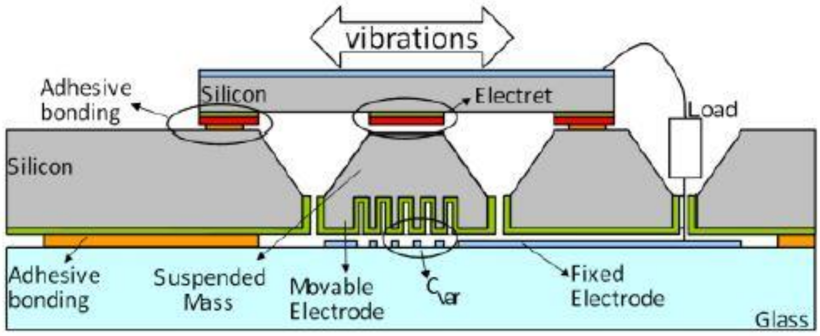


Figure 2.8 IMEC's first electret-based vibration energy harvester [32]

Today, most of the electret-based vibration energy harvesters use patterned electrets and exploit surface variation.

b. Devices using patterned electrets

The first structure using patterned electrets was developed by the university of Tokyo in 2006 [29]. Many other devices followed, each of them, improving the first architecture [24, 30-31]. For example Miki et al. [32] improved these devices by developing a multiphase system and using non-linear effects. Multiphase devices enable to limit the peaks of the electrostatic force and thus to avoid to block the moving mass.

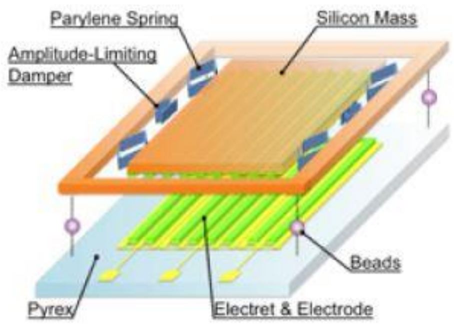


Figure 2.9 Multiphase electret energy harvester exploiting non-linear springs [31-32].

c. Mechanical springs to harvest ambient vibrations

Developing low-resonant frequency energy harvesters is a big challenge for small-scale devices. In most cases, ambient vibrations' frequencies are below 100Hz. This leads to long and thin springs difficult to obtain using silicon technologies (form factors are large and structures become brittle). Thus, to reduce the resonant frequency of vibration energy harvesters, keeping small dimensions, solutions such as parylene springs [33] were developed. Another way consists in using microballs that act like a sideway. Naruse has already shown that such a system could operate at very low frequencies (<2 Hz) and could produce up to 40 μW [33] (Figure 2.10).

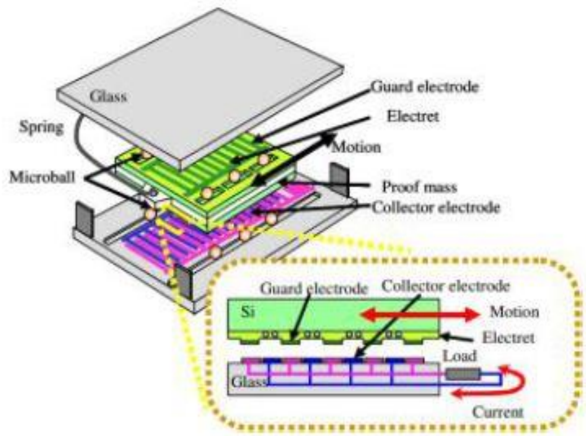


Figure 2.10 Device on micro balls from [33]

Besides, a good review on MEMS electret energy harvesters can be found in [34]. The next subsection presents an overview of some electret-based prototypes from the state of the art.

Table 2.3 shows a significant increase of electret-based prototypes since 2003. It is also interesting to note that some companies such as Boisseau [27] started to study these devices and to manufacture some prototypes.

Thanks to simple cantilever-based devices developed for example by Mizuno [26] the theoretical model of electret-based devices can be accurately validated. [27],

Table2.4. Electret-based energy harvesters from the state of the art [27]

Author	Output Power	Electret Potential (V)	Active Surface	Vibrations /Rotations
Jefimenko	25 mW	500V	730 cm²	6000 rpm
Tada	1.02 mW	363V	90 cm²	5000 rpm
Boland	25 µW	150V	0.8 cm²	4170 rpm
Genda	30.4 W	200V	1.13 cm²	1'000'000 rpm
Boland	6 µW	850V	0.12 cm²	7.1G@60Hz
Tsutsumino	38 µW	1100V	4 cm²	1.58G@20Hz
Lo	2.26 µW	300V	4.84 cm²	14.2G@60Hz
Sterken	2nW	10V	0.09 cm²	1G@500Hz
Lo	17.98 µW	1500V	6 cm²	4.93G@50Hz
Zhang	0.13 pW	100V	4 cm²	0.32G@9Hz
Yang	46.14 pW	400V	0.3 cm²	3G@560Hz
Suzuki	0.28 µW	450V	2.33 cm²	5.4G@37Hz
Sakane	0.7 mW	640V	4 cm²	0.94G@20Hz

Naruse	40µW	_	9 cm²	0.4G@2Hz
Halvorsen	1µW	_	0.48 cm²	3.92G@596Hz
Kloub	5µW	25V	0.42 cm²	0.96G@1740Hz
Edamoto	12µW	600 V	3 cm²	0.87G@21Hz
Miki	1µW	180V	3 cm²	1.57G@63Hz
Honzumi	90 pW	52V	0.01 cm²	9.2G@500Hz
Boisseau	50µW	1400V	4.16cm²	0.1G@50Hz

CHAPTER THREE

DESIGN & MODELING

3.1 ELECTRET-BASED ENERGY HARVESTERS USING CANTILEVERS:

This electret-based energy harvester is a microsystem able to convert mechanical energy from Vibrations into electricity. It is part of vibration energy harvesters whose general model is presented hereafter.

3.1.1 William and Yates' general model for vibration energy harvesters:

Regardless of the conversion principle (electrostatic, electromagnetic or piezoelectric), resonant energy harvesters can be modeled as a mobile mass (*m*) suspended to a support by a spring (*k*) and damped by forces (*felec* and *fmec*). When a vibration occurs $y(t) = Y\sin(\omega t)$, it induces a relative displacement of the mobile mass $x(t) = X\sin(\omega t - \varphi)$ compared to the frame (Figure 3.1). Part of the kinetic energy of the moving mass is lost due to mechanical damping (*fmec*) while the other part is converted into electricity, which is modeled by an electrostatic force (*felec*) in electrostatic energy harvesters. Ambient vibrations are generally low in amplitude (typically *Y*=25µm) and the use of amass-spring structure enables to take advantage of a resonance phenomenon that amplifies the amplitude of vibrations perceived by the mobile mass and the harvested energy. Newton's second law gives the differential equation that rules the movement of the mobile mass (3.1)

$$m\ddot{x} + f_{mec} + kx + f_{elec} = -m\ddot{y} \tag{3.1}$$

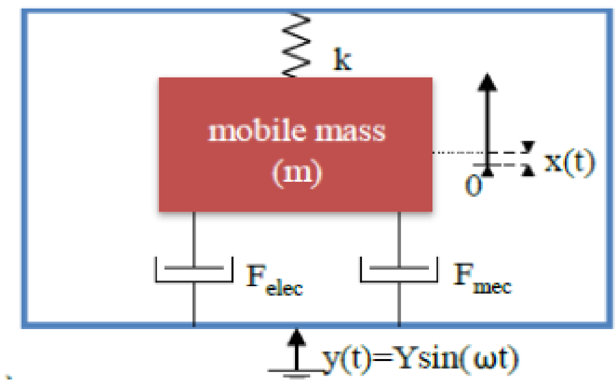


Figure 3.1.Mechanical system

When forces can be modeled as viscous forces, $f_{elec} = b_e \dot{x}$ and $f_{mec} = b_m \dot{x}$, where b_e and b_m are respectively electrical and mechanical damping coefficients, William and Yates [35] have proven that the maximum output power of a resonant energy harvester submitted to an ambient vibration is reached when the natural angular frequency (ω_0) of the mass-spring system is equal to the angular frequency of ambient vibrations (ω) and when the damping rate $\xi_e = b_e/(2m\omega_0)$ of the electrostatic force f_{elec} is equal to the damping rate $\xi_m = b_m/(2m\omega_0)$ of the mechanical friction forcef_{mec} . This maximum output power $P_{w\&y}$can be simply expressed with (3.2), when $\xi_e = \xi_m = \xi = 1/2Q_m$

$$P_{W\&Y} = \frac{mY^2\omega_0{}^3 Q_m}{8} \qquad (3.2)$$

As *PW&Y* is a good approximation to know the output power of vibration energy harvesters when forces are modeled as viscous forces, comparing the output power (*P*) of a resonant energy harvester to *PW&Y* gives a legitimate factor of merit α*W&Y*:

$$\alpha W\&Y = \frac{P}{P_{W\&Y}} \qquad (3.3)$$

Nevertheless, in many studies, the weight of the mobile mass is not given while the surface area of the electrodes (*S*) is often provided. Therefore, to compare systems, we had developed, in a previous study, another factor of merit, normalized by the active surface *S* in place of the mass [36]:

$$\chi = \frac{P}{Y^2\omega^3 S} \qquad (3.4)$$

3.2. CONVERSION PRINCIPLES:

Electrostatic converters are capacitive structures made of two plates separated by air, vacuum or any dielectric materials. A relative movement between the two plates generates a capacitance variation and then electric charges. These devices can be divided into two categories:

- Electret-free electrostatic converters that use conversion cycles made of charges and discharges of the capacitor (an active electronic circuit is then required to apply the charge cycle on the structure and must be synchronized with the capacitance variation).
- Electret-based electrostatic converters that use electrets, giving them the ability to directly convert mechanical power into electricity, and this type will be used in this research.

3.2.1. Electret-based electrostatic converters:

Electret-based electrostatic converters are quite similar to electret-free electrostatic converters. The main difference relies on the electret layers that are added on one (or two) plate(s) of the variable capacitor, polarizing it.

3.2.1.1. Electrets:

Electrets are dielectric materials that are in a quasi-permanent electric polarization state (electric charges or dipole polarization). They are electrostatic dipoles, equivalent to permanent magnets (but in electrostatic) that can keep charges for years. The word electret comes from “electricity magnet” and was chosen by Oliver Heaviside in 1885.

Electret-based converters are electrostatic converters, and are therefore based on a capacitive structure made of two plates (electrode and counter-electrode (Figure 3.3)). The electret induces charges on electrodes and counter-electrodes to respect Gauss’s law. Therefore, Qi, the charge on the electret is equal to the sum of Q1 and Q2, where Q1 is the total amount of charges on the electrode and Q2 the total amount of charges on the counter-electrode (Qi=Q1+Q2). A relative movement of the counter-electrode compared to the electret and the electrode induces a change in the capacitor geometry (e.g. the counter-electrode moves away from the electret, changing the air gap and then the electret's influence on the counter-electrode) and leads to a reorganization of charges between the electrode and the counter-electrode through load R (Figure 3.4). This results in a current circulation through R and one part of the mechanical energy (relative movement) is then turned into electricity

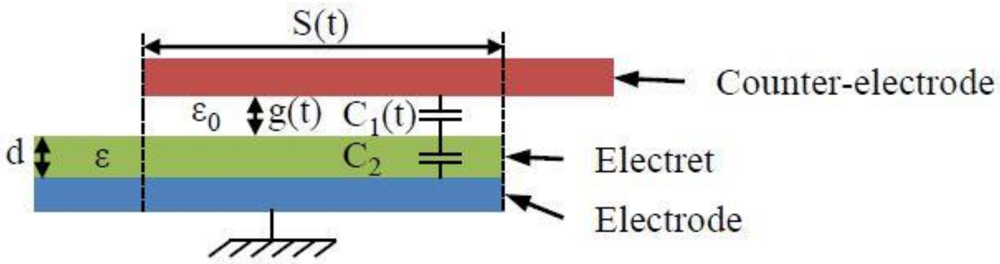


Figure.3.2 Electret-based electrostatic conversion

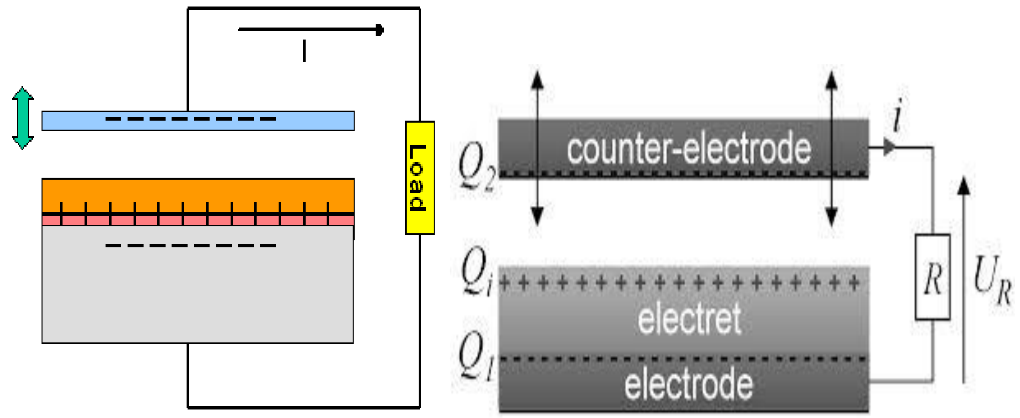


Figure 3.3 Electret-based electrostatic conversions – Charge circulation

3.3. ANALYTICAL MODEL OF THE 'CANTILEVER-BASED ELECTRET ENERGY HARVESTER:

To determine the output power of the energy harvester for a given vibration *y(t)*, it is necessary to solve the equation of motion and to find the quantity of charge transferred to the output. Therefore, the goal of this section 3.3 is to develop the analytical model of the 'cantilever-based electret energy harvester' parameterized in Figure 3.8(b) for mechanical and electrostatic parts.

3.3.1. Model of the mechanical system:

The clamped-free beam with a mass at the free end can be modeled as a damped mass-spring structure as presented in Figure (1) and by adding the effect of weight $\vec{w} = m\vec{g}$ .The mechanical friction forces can be modeled as viscous forces $f_{mec} = b_m \dot{x}$ .and the electrostatic force is the derivative of the electrostatic energy of the capacitor *We* with respect to the displacement *x*. *We* is equal to the charge on the upper electrode *Q2* squared, divided by two times the capacitance as a function of time *C (t)*. Thereby, the mechanical system is ruled by (3.5).

$$\mathrm{m\ddot{x}} + \mathrm{f_{mec}} + \mathrm{kx} + \mathrm{f_{elec}} = -\mathrm{m\ddot{y}} \Longrightarrow m\ddot{x} + \mathrm{b}_m.\dot{\mathrm{x}} + \mathrm{k.x} - \frac{\mathrm{d}}{\mathrm{dx}}\left(\frac{\mathrm{Q}^2}{2C(t)}\right) - \mathrm{mg} = -\mathrm{m\ddot{y}} \quad (3.5)$$

To maximize the output power of the energy harvester, the natural angular $\omega_0 = \sqrt{(k/m)}$ of the mass-spring structure has to be tuned to the angular frequency of the ambient vibrations (ω). Moreover, according to equations from mechanical structures theory, the spring constant *k* can be deduced from the beam geometric parameters as follow:

$$k = m\omega^2{}_n = \frac{3EI}{L^3} = \frac{EWh^3}{4L^3} \quad (3.6)$$

Because of the mass, the behavior of the beam has to be studied on two parts. A drawing of the structure is presented in figure 6 and shows the deformation of the cantilever δ*(z)* as a function of the position on the cantilever *z* for a forced deflection *x* at *z*=*L*. The first $z \in [0, L_2 = L - L_m]$, Does not have an additional mass: its behavior corresponds to the one of a clamped-free beam whose deflection at the end (*x1*) is imposed and given by

$$\delta(z) = \frac{x_1}{2{L_1}^3} z^2 (3L_1 - z) \quad (3.7)$$

The second part that has the additional mass $z \in [L_1, L_2 = L + L_m]$ follows the deflection of part 1: the derivative of the deflection (δ *(z)*) with respect to the position (*z*) for part 2 is constant and equal to the derivative of the deflection of part1 at *z*=*L1* (3.8).

$$c = \left.\frac{d\delta(z)}{dz}\right|_{z=L_1} = \left.\frac{d\delta(z)}{dz}\right|_{z\epsilon[L_1,L_2]} = \frac{3}{2}\frac{x_1}{L_1} with\ x_1 = x - cL_m \quad (3.8)$$

Therefore, for a given static deflection (*x*) on the position L of the beam, the deformation of the beam can be simply expressed as a function of the parameters in both parts:

$$\begin{cases} \delta(z) = \frac{x_1}{2{L_1}^3} z^2 (3L_1 - z) \ldots\ldots\ldots part1 \\ \delta(z) = c(z - L) + x \ldots\ldots\ldots\ldots\ldots part2 \end{cases} \quad (3.9)$$

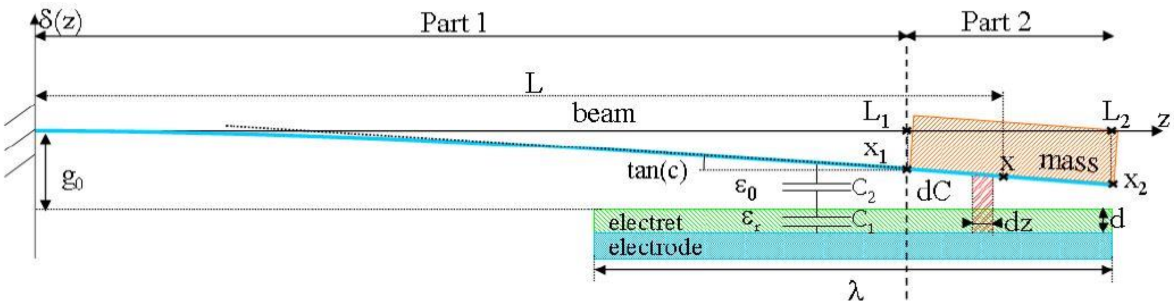


Figure 3.4 Deformation of the cantilever for an imposed deflection (*x*).

Figure 3.5 presents the beam deformation resulting from equation (3.9) for a beam of *L*=30mm and *Lm*=2mm and for an imposed static displacement of *x*=300µm compared to the deformation performed by FEM calculation (Comsol® Multiphysics). It proves that our calculations fit with FEM results . [27]

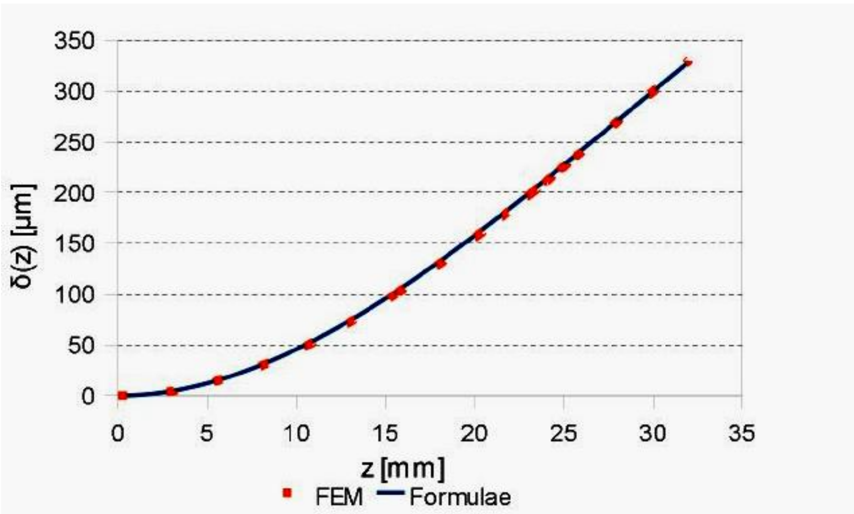


Figure 3.5 Deformation of the cantilever for an imposed static deflection (*x*). [27]

Nevertheless, the problem we want to solve is not static but dynamic. Therefore, it is useful to verify that the beam deformation behavior is the same in dynamic and in static. We have verified this using FEM it confirms that the deformation in dynamic and in static can be considered as equivalent. Thus, it is can consider that the deflection in dynamics can be simply expressed with (3.9) assuming that *x* is the imposed deflection on the mass gravity point.

3.3.2. Modeling of the electrostatic system*:*

The equivalent model of the energy harvester is presented in figure (3.6), where *Q2* is the charge on the counter-electrode, *V* the surface voltage of the electret and *C(t)* the capacitance between the beam and the electrode. This capacitance corresponds to the serial capacitance formed by the electret dielectric material capacitance *C1* and the air gap capacitance *C2(t).* Kirchhoff's laws give the differential equation that governs the electrostatic system (3.10):

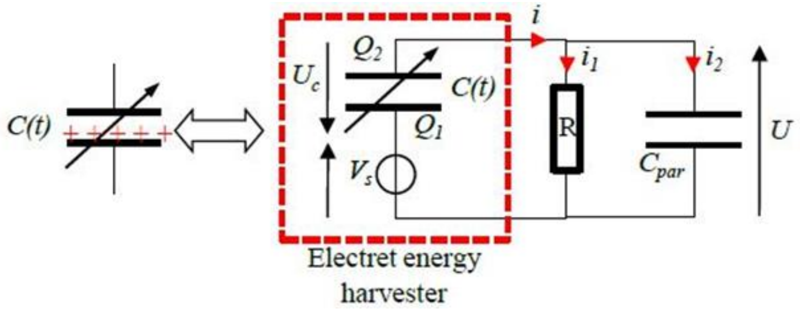


Figure 3.6 Equivalent electric model of the energy harvester.

$$\frac{dQ_2}{dt} = \frac{V}{R} - \frac{Q_2}{R} \times \left[\frac{1}{c(t)}\right] = \frac{V}{R} - \frac{Q_2}{R} \times \left[\frac{1}{c_1} - \frac{1}{c_2(t)}\right] \qquad (3.10)$$

Moreover, the electrostatic energy stored in the capacitor is:

$$W_e = \frac{1}{2}\frac{Q^2{}_2(t)}{c(t)} \qquad (3.11)$$

To solve (3.10), it is necessary to know the capacitance of the electrostatic converter as a function of the imposed deflection (*x*). Knowing the cantilever deformation, and considering a capacitor of infinitesimal length (*dz*) (figure 3.6), one can get the infinitesimal capacitance on both part (*dCp1* and *dCp2*) for a given x.[27]

$$\begin{cases} dc_{p1}(x) = \frac{\varepsilon_0 w.dz}{g_0 - \delta(z) + \frac{d}{\varepsilon_r}} \, with \, \delta(z) = \frac{x_1}{2L_1{}^3} z^2 (3L_1 - z) \quad part1 \\ dc_{p1}(x) = \frac{\varepsilon_0 w.dz}{g_0 - \delta(z) + \frac{d}{\varepsilon_r}} \, with \, \delta(z) = c(z - L) + x \quad part2 \end{cases} \qquad (3.12)$$

By integrating these expressions, the total capacitance between both electrodes is:

$$c(x) = c_{p1}(x) + c_{p2}(x) = \varepsilon_0 w \int_{L_2 - \lambda}^{L_1} \frac{dz}{g_0 - x\frac{z^2(3L_1 - z)}{2L_1{}^3} + \frac{d}{\varepsilon_r}} + \frac{\varepsilon_0 w}{c} \ln \frac{g_0 + \frac{d}{\varepsilon_r} + cL_m - x}{g_0 + \frac{d}{\varepsilon_r} - cL_m - x} \qquad (3.13)$$

The integral defining *Cp1(x)* cannot be analytically calculated and will be numerically computed. This capacitance expression has been compared to a FEM simulation and the curves presented in figure 3.7 show that results are in excellent agreement. These results were also compared to the formula of a simple plane capacitor neglecting fringe effects $c(x) = (\varepsilon_0 w)/(g_0 - x + d/\varepsilon_r)$ .Where *S* is the surface of the electrodes, *g0* the initial gap and *x* the imposed deflection. With our parameters (*Lm*=2mm, *L*=30mm, *g0*=505µm, *d*=100µm, *w*=12.33mm, ε*r*=2, ε_0=1.000589,λ=10mm), we have found that the model of the simple plane capacitor estimate (up to 35%) the maximal capacitance of the energy harvester.[27]

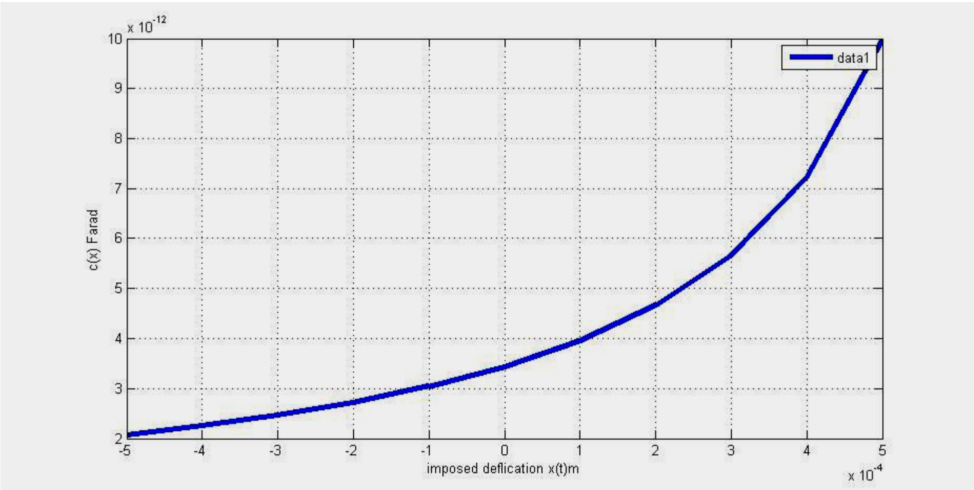


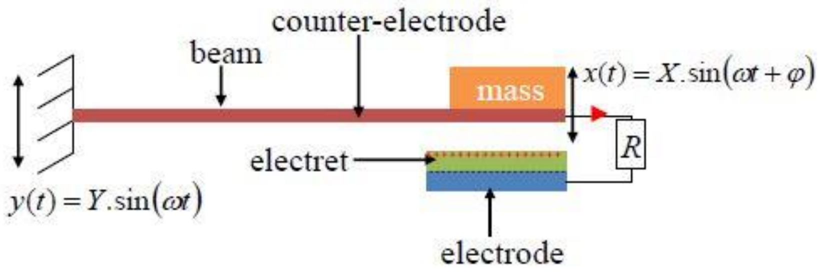
Figure 3.7.Capacitance between the electrodes (*C*) versus forced displacement (*x*)
(*Lm*=2mm,*L*=30mm, *g0*=505µm, *d*=100µm, *w*=12.33mm, ε*r*=2, λ=10mm).

This accurate value of the capacitance for a given deflection is then applied in the mechanical system introduced in 3.2.3.

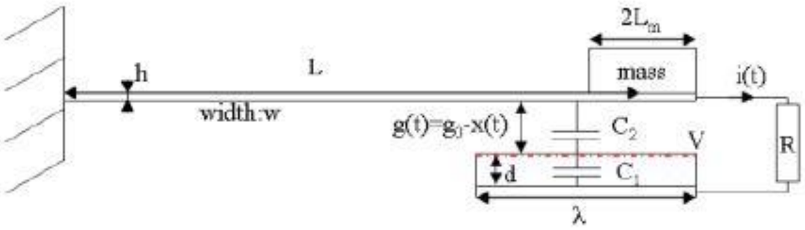
3.4. Complete analytical model:

Device:

The prototype presented in Figure 3.8 consists in a clamped-free beam moving with regards to an electret due to ambient vibrations. The mechanical-to-mechanical converter is the mass-beam system and the mechanical-to-electrical converter is made of the electrode-electret-air gap-moving counter-electrode architecture [27].



(a)



(b)

Figure 3.8.Example of a simple out-of-plane electret-based VEH (cantilever), (a) diagram, (b) parameters

Table 3.1: parameters and dimensions of the VEH device

M_{beam}	Material of the beam	Silicon
E	Young's Modulus of Silicon	160 G pa
L	Position of the center of gravity of the mass	30 mm
H	Thickness of the beam	0.3mm
W	Width of the beam / Width of the electret	13 mm
$2L_m$	Length of the mobile mass	4 mm
M	Mobile mass (structural steel)	5g
ω	Angular frequency of vibrations	Rad/s $2\pi \times 50$
Q_m	Mechanical quality factor of the structure	75
$M_{electret}$	Material of the electret	FEB
ε_0	Relative permittivity (air)	$\varepsilon_0 = 8.854\ 187\ 817... \times 10^{-12}$ F/m
ε_r	Dielectric constant of the electret	2

D	Thickness of the electret	0.127mm
V	Surface voltage of the electret	1400 V
g_0	Thickness of the initial air gap	2mm
λ	Length of the electrode	22.8mm

In order to get the output power of the energy harvester, mechanical and electrostatic systems have to be coupled. From (3.5) and (3.10), one can find that the system of equations that governs the energy harvester is (3.14).

$$\begin{cases} m\ddot{x} + b_m.\dot{x} + k.x - \frac{d}{dx}\left(\frac{Q^2}{2C(t)}\right) - mg = -m\ddot{y} \\ \frac{dQ_2}{dt} = \frac{V}{R} - \frac{Q_2}{Rc(t)} \end{cases} \tag{3.14}$$

Obviously, this system cannot be solved by hand. Yet, by using a numerical solver (e.g. MATLAB), this becomes possible. It is also imaginable to use Spice by turning this system of equations in its equivalent electrical circuit

3.5 MATLAB and SIMULINK:

Making block diagram by Simulink program represents system's equations

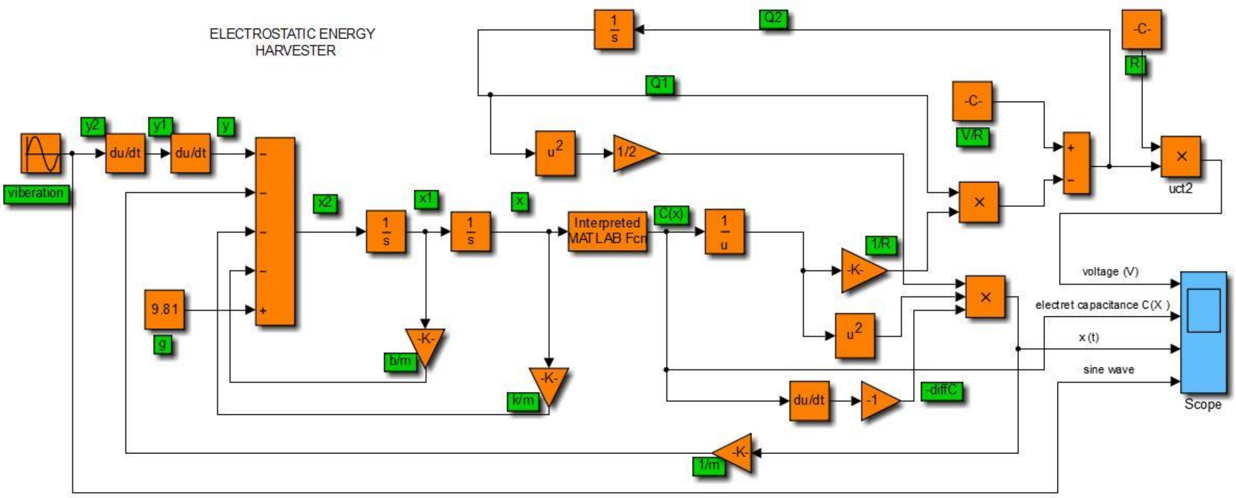


Figure 3.9 Equivalent Simulink / Matlab models of electret-based vibration energy harvesters

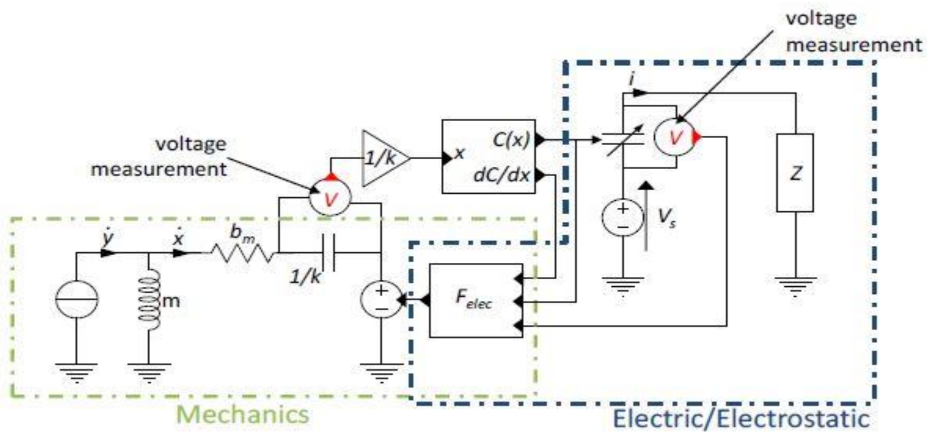


Figure 3.10 Equivalent electrical models of electret-based vibration energy harvesters

3.6 DESIGN THE MODEL:

Using SOLIDWORK and CATIA programs, creating this model consist of four parts (base, beam, electrode layer and mass)

Table 3.2: parameters properties of the VEH device model

Object Name	*mass11.178-1*	*beam-1*
State	Meshed	
Graphics Properties		
Visible	Yes	
Transparency	1	
Definition		
Suppressed	No	
Stiffness Behavior	Flexible	
Coordinate System	Default Coordinate System	
Reference Temperature	By Environment	
Material		
Assignment	Structural Steel	silicon
Nonlinear Effects	Yes	
Thermal Strain Effects	Yes	
Bounding Box		
Length X	4.e-003 m	3.2e-002 m
Length Y	1.1718e-002 m	3.e-004 m
Length Z	1.3e-002 m	
Properties		
Volume	6.0934e-007 m³	1.248e-007 m³
Mass	4.7833e-003 kg	2.9066e-004 kg
Centroid X	-4.0456e-003 m	9.9544e-003 m

Centroid Y	1.8225e-002 m	1.2216e-002 m
Centroid Z	2.8659e-002 m	
Moment of Inertia Ip1	1.221e-007 kg·m²	4.0956e-009 kg·m²
Moment of Inertia Ip2	7.3742e-008 kg·m²	2.8896e-008 kg·m²
Moment of Inertia Ip3	6.1111e-008 kg·m²	2.4805e-008 kg·m²
Statistics		
Nodes	2393	1202
Elements	440	152
Mesh Metric	None	

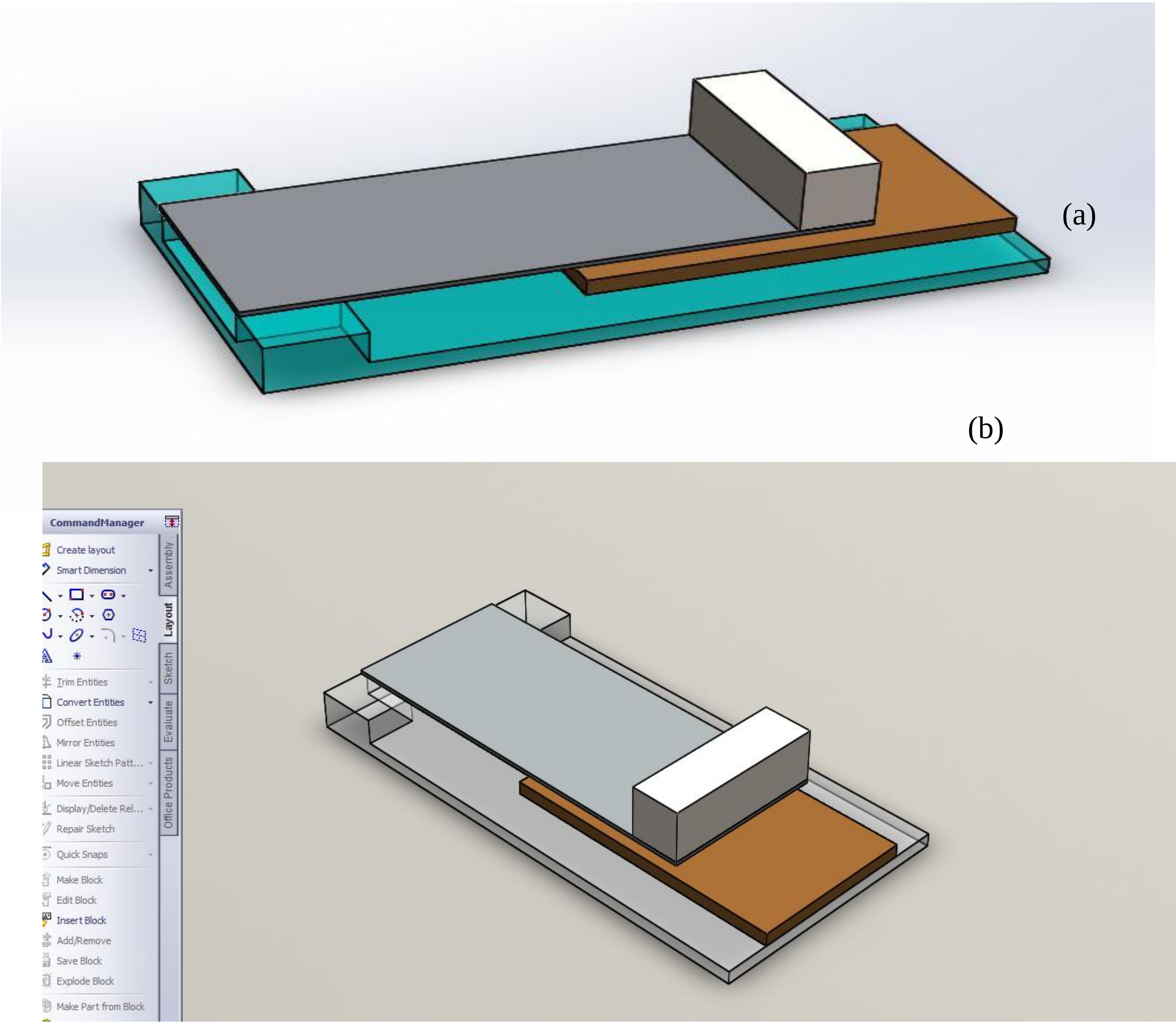


Figure 3.11(a) and (b) Design models of electret-based vibration energy harvesters by SOLIDWORKS

3.7. MOTION SIMULATION AND ANALYSIS:

Convert the design of model by SOLIDWORK program to the ANASYS program for movement analysis and its accompanying stresses.

Steps taken with ANASYS for movement analysis and its accompanying stresses:

- Step 1: Geometry and Material Properties
- Step 2: Loads and Boundary Conditions
- Step 3: FEA Model Details
- Step 4: Sample Results

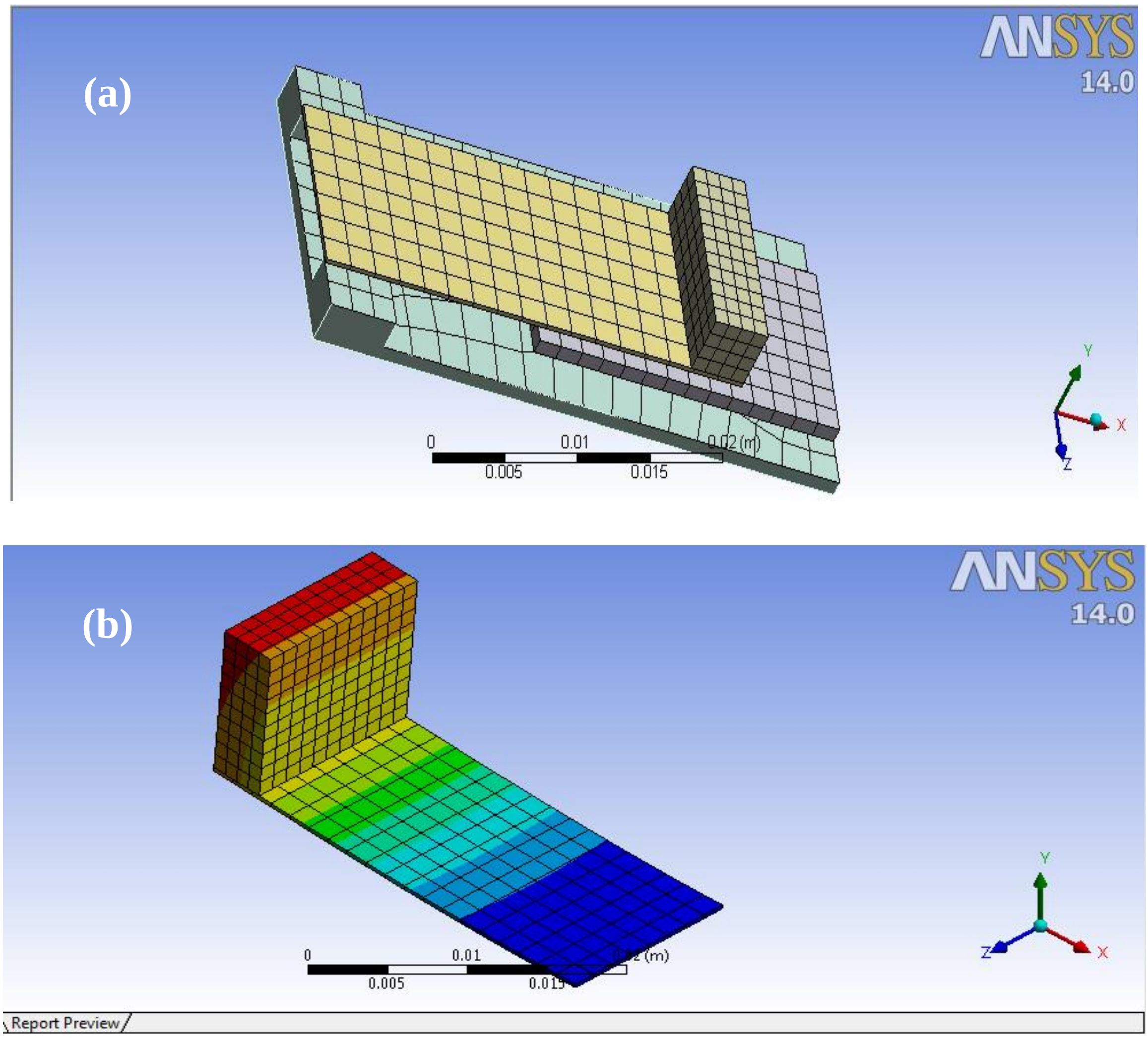
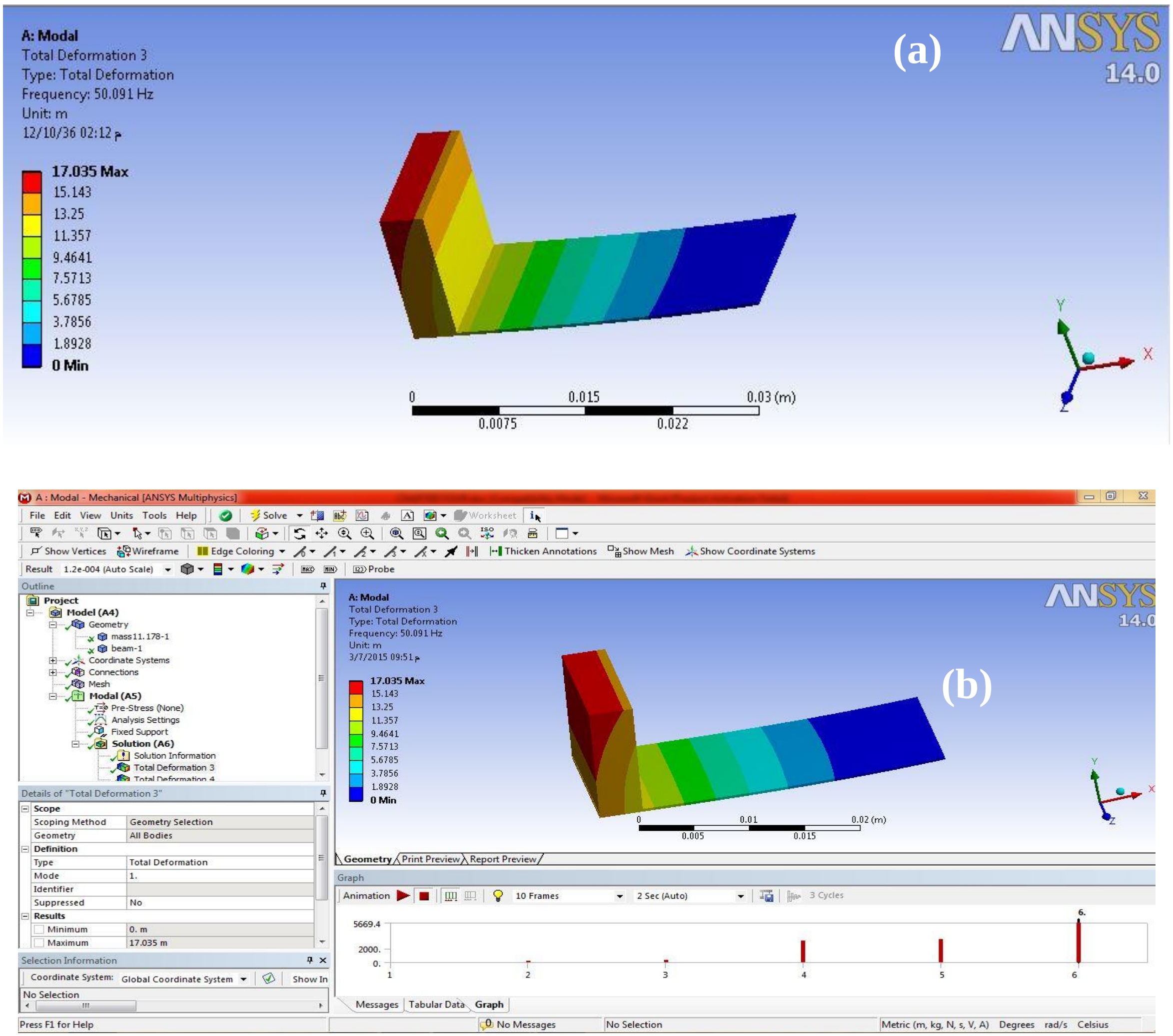


Figure 3.12 (a) and (b) prototype model , mish and stress analysis simulation



Mode	Frequency [Hz]
VEH	50

Figure 3.13 Prototype models of electret-based vibration energy harvesters with ANSYS

The Units used in ANASYS

Table 3.3: units used in ANASYS program

Unit System	Metric (m, kg, N, s, V, A) Degrees rad/s Celsius
Angle	Degrees
Rotational Velocity	rad/s
Temperature	Celsius

3.8 POWER MANAGEMENT CONTROL CIRCUITS (PMCC) DEDICATED TO ELECTROSTATIC VEH (eVEH):

The next section is aimed to present some examples of PMCC for electrostatic VEH.

3.8.1 Need for Power Management Control Circuit (PMCC)

As presented in this chapter, electrostatic vibration energy harvesters are characterized by a high output voltage that may reach some hundreds of volts and a low output current (some 100nA). Obviously, it is impossible to power any application, any electronic device with such a supply source. This is the reason why a power converter and an energetic buffer are needed to develop autonomous sensors. Figure 3.14 presents the conversion chain.

Power Management Control Circuits (PMCC) can have many functions: changing eVEH resonant frequency, controlling measurement cycles here, we focus on the power converter and on its control circuit.

As eVEH output powers are low (generally <100µW), Power Management Control Circuit must be simple and above all low power

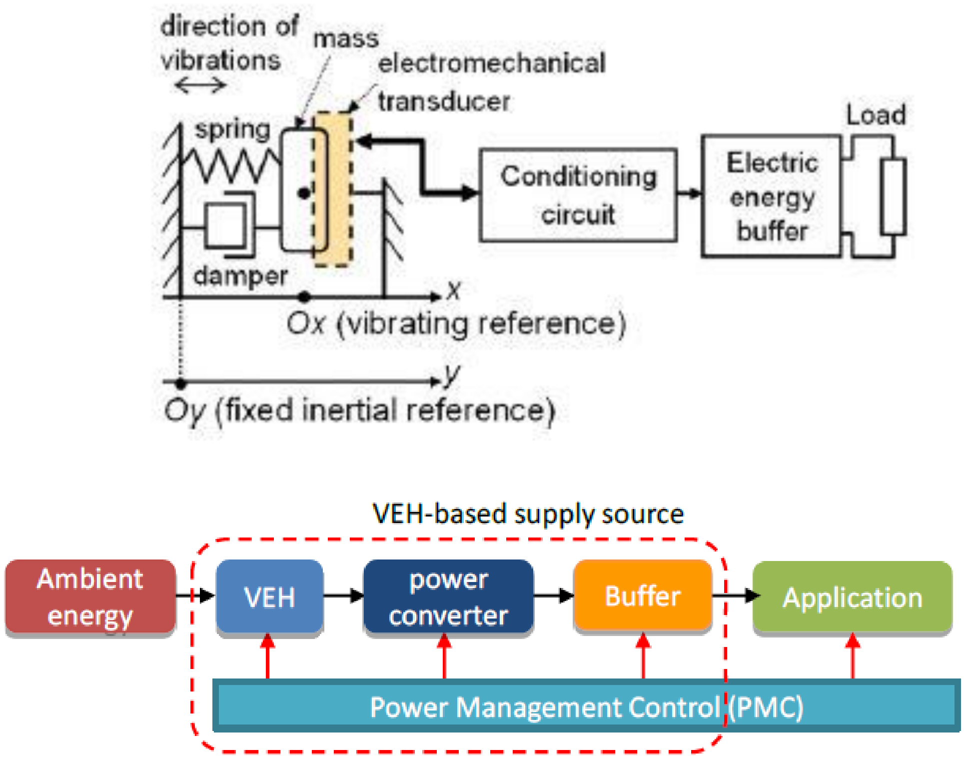


Figure 3.14 Power Management Control Circuit to develop viable VEH [37]

For example, it is difficult to supply a MMPT (Maximum Power Point Tracker) circuits and the number of transistors and operations must be highly limited. We present in the next subsections some examples of Power Management Control Circuit for electret-free and electret-based eVEH.

3.8.2. PMCC for Electret-Based Electrostatic VEH

Electret-based eVEH enable to have a direct mechanical-to-electrical conversion without needing any cycles of charges and discharges. As a consequence, it is possible to imagine two kinds of power converters.

3.8.2.1. Passive power converters

Passive power converters are the easiest way to turn the AC high-voltage low-current eVEH output into a 3V DC supply source for WSN. An example of these circuits is presented in Figure 3.15(a). It consists in a diode bridge and a capacitor that stores the energy from the eVEH.

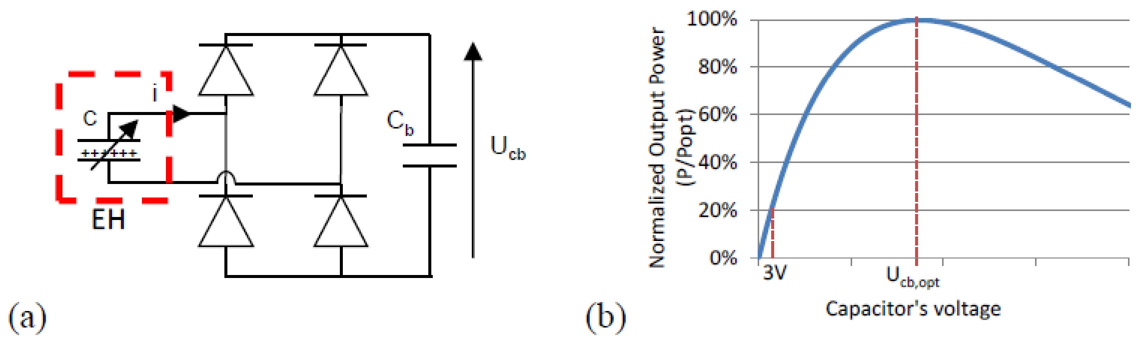


Figure3.15 (a) Simple passive power converter – diode bridge-capacitor and (b) optimal output voltage on Ucb[37]

Such a power converter does not need any PMCC as the energy from the energy harvester is directly transferred to the capacitor. This power conversion is quite simple, but the drawback is the poor efficiency.

Actually, to maximize power extraction from an electret-based electrostatic converter, the voltage across Cb must be close to the half of the eVEH's output voltage in open circuit. This optimal value (Ucb,opt) is generally equal to some tens or hundreds of volts. To power an electronic device, a 3V source is required: this voltage cannot be maintained directly on the capacitor as it greatly reduces the conversion efficiency of the energy harvester (Figure 3.15(b)).[17]

The solution to increase the efficiency of the energy harvester consists in using active power converters.

3.8.2.2. Active power converters

As eVEH' optimal output voltages are 10 to 100 times higher than 3V, a step-down converter is needed to fill the buffer. The most common step-down converters are the buck, the buck-boost and the flyback converters. We focus here on the flyback converter that gives more design flexibilities (Figure 3.16).

Many operation modes can be developed to turn the eVEH high output voltages into a 3V supply source. Here, we focus on two examples: (i) energy transfer on maximum voltage detection and (ii) energy transfer with a pre-storage to keep an optimal voltage across the electrostatic converter.

3.9.2.2.1. Energy transfer on a maximum voltage detection

The concept of this power conversion is to send the energy from the energy harvester to the 3V energy buffer when the eVEH output voltage reaches its maximum.

The power management control circuit is aimed at finding the maximum voltage across the energy harvester and to close Kp (Figure 48) to send the energy from the eVEH to the magnetic circuit. Then Ks is closed to send the energy from the magnetic circuit to the buffer Cb. The winding ratio m is determined from the voltage ratio between the primary and the secondary

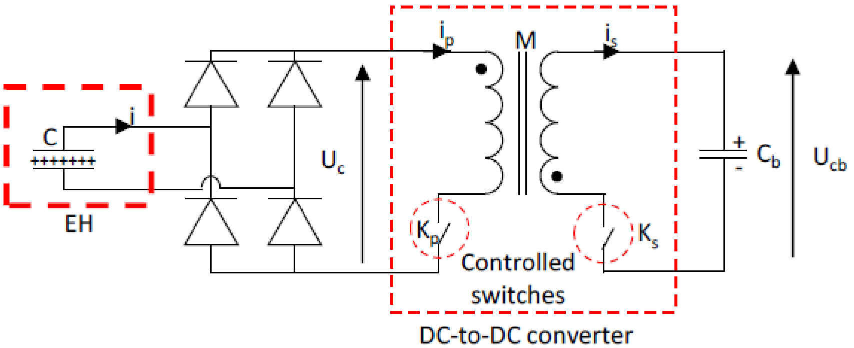


Figure 3.16 Energy transfer on maximum voltage detection [37]

As eVEH capacitances are quite small, parasitic capacitances of the primary winding may have a strong negative impact on the output powers, increasing conversion losses. An alternative consists in using a pre-storage capacitor

3.8.2.2.2. Energy transfer with a pre-storage capacitor

In this operation mode, a pre-storage capacitor Cp is used to store the energy from the eVEH and to maintain an optimal voltage across the diode bridge in order to optimize the energy extraction from the eVEH.

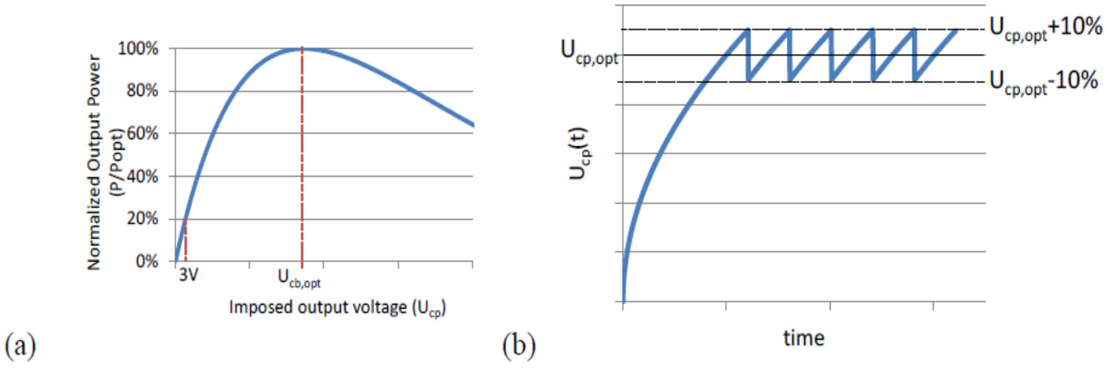


Figure 3.17 (a) eVEH output power vs imposed output voltage and (b) Ucp(t)[37]

The goal of the PMCC is to maintain the voltage quite constant across the diode bridge (+/-10% Ucp,opt). Then, when Ucp reaches Ucp,opt+10%, one part of the energy stored in Cp is sent to Cb through the flyback converter.

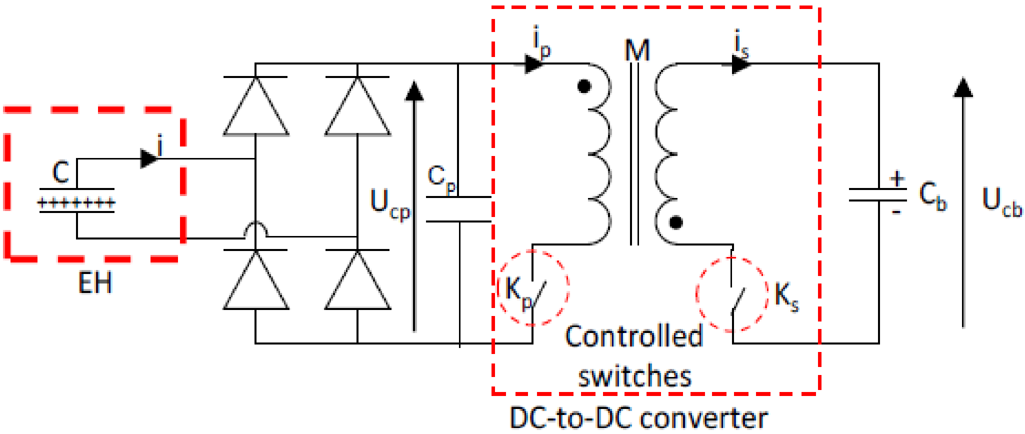


Figure 3.18 Energy transfer with pre-storage [37]

As Cp can be in the order of some tens to hundreds of Nano farads, transformer's parasitic capacitances have smaller impacts on eVEH's output power.

This power conversion principle also enables to use multiple energy harvesters in parallel with only one transformer and above all only one PMCC (which is not the case with the maximum voltage detection).

We have presented some examples of power converters able to turn the raw output powers of the energy harvesters into supply sources able to power electronic devices. Thanks to this, and low power consumptions of WSN' nodes, it is possible to develop autonomous wireless sensors using the energy from vibrations from now on

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. THEORY vs. SIMULATION data

Model analysis can be obtained from the natural resonance frequency of the mechanically undammed (lossless) system reacts to external motion excitation with unlimited deflection .The following figures show the mechanical simulation performed on the structure in numerical solver MATLAB/SIMULINK Figure (4.1 and 4.2) show the amplitude of sine wave (Amplitude of environmental vibration), 1/capacitance (t) , Deflection versus time and output voltage .

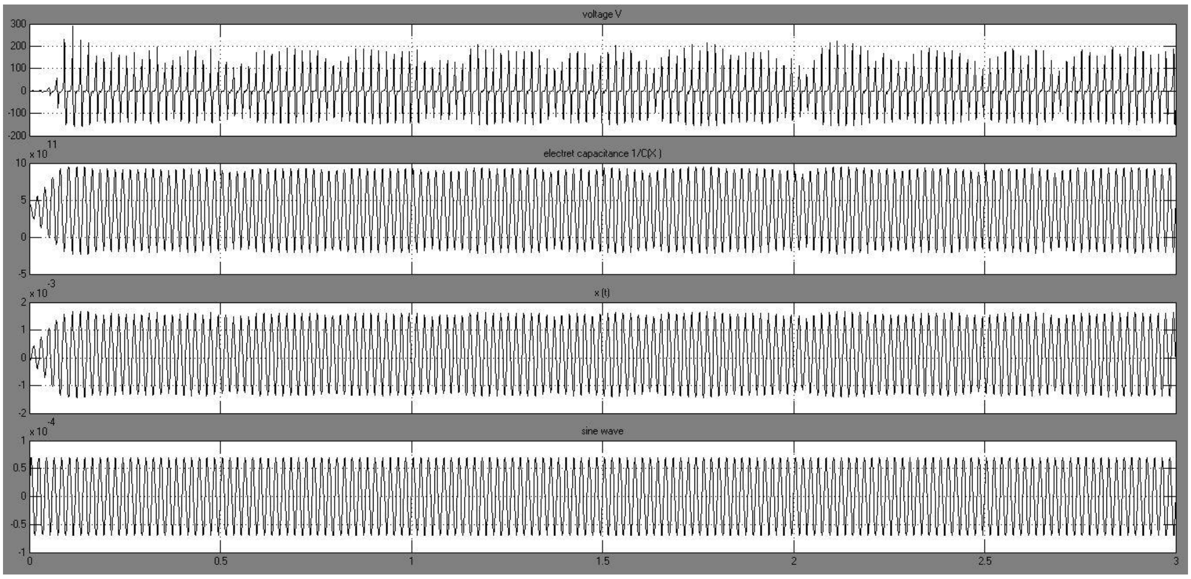


Figure4. 1 Validation of theory with a cantilever-based electret energy harvester R=300MΩ

This simple prototype enables to validate the model of electret-based vibration energy harvesters that was presented in chapter3. It is also interesting to note that this simple prototype has an excellent output voltage that reaches 200 V with a low vibration of 50Hz.

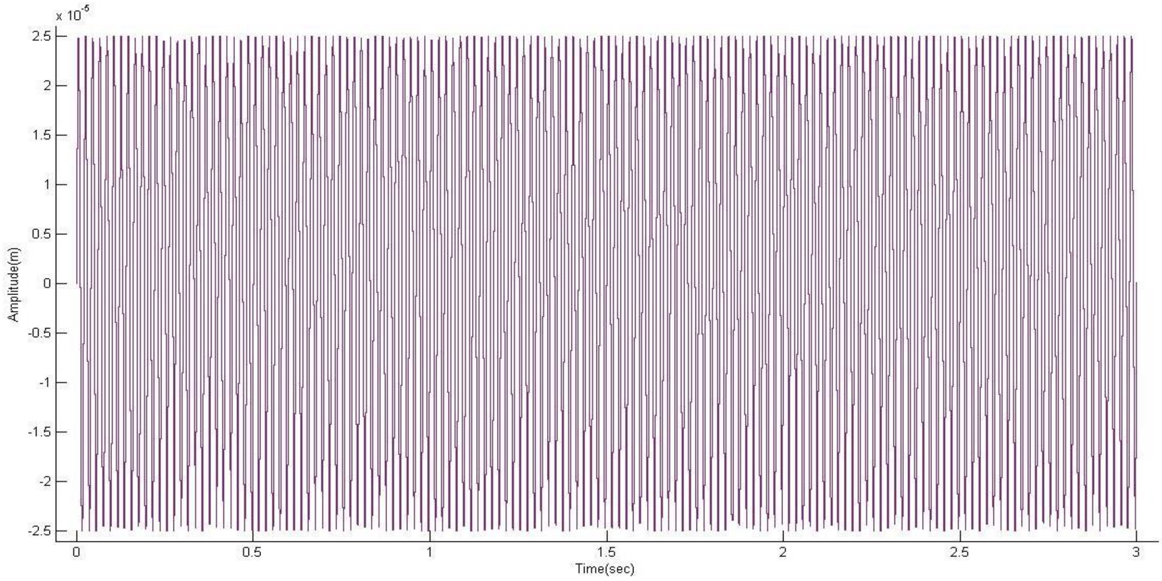


Figure 4.2 (a) Amplitude of environmental vibration

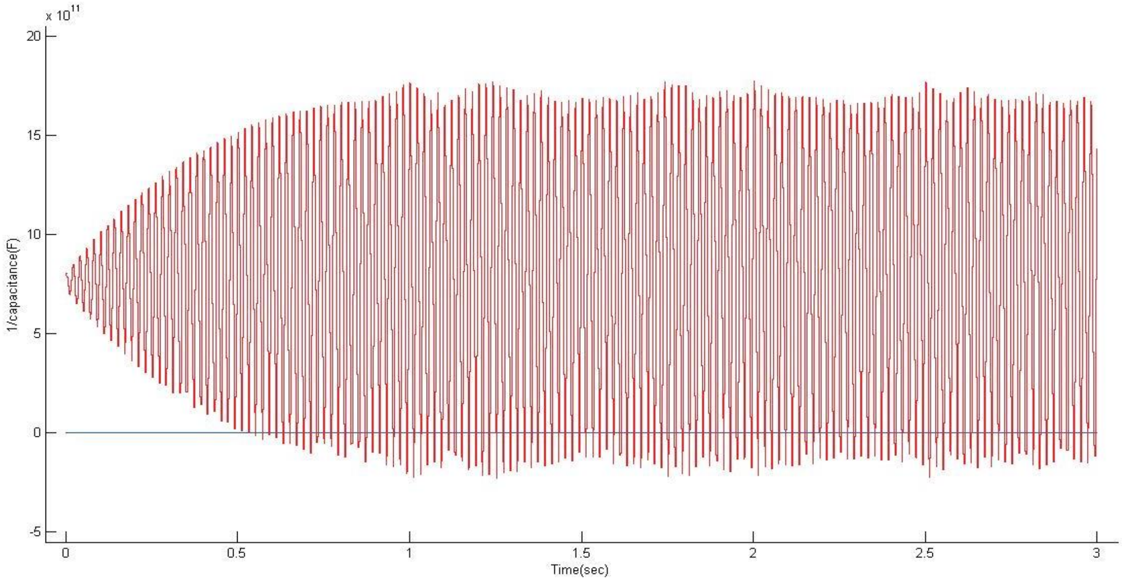


Figure 4.2 (b) 1/capacitance (t)

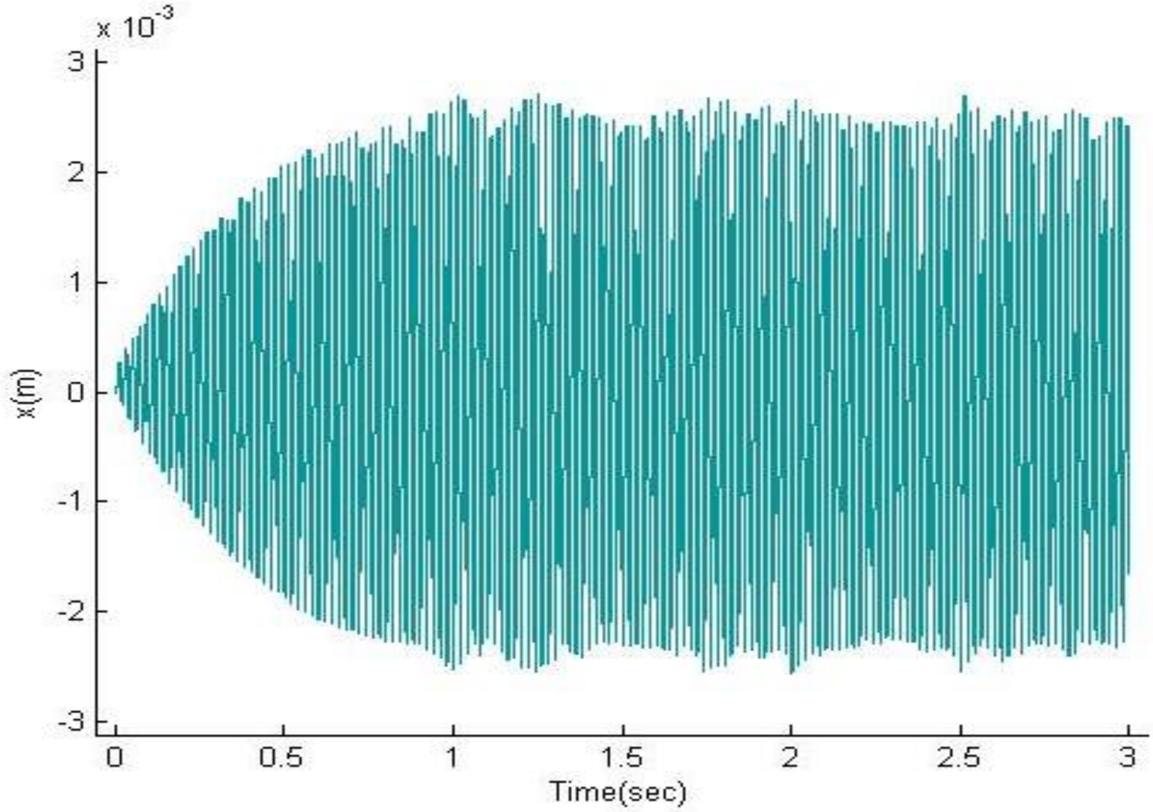


Figure 4.2 (c) Deflection versus time

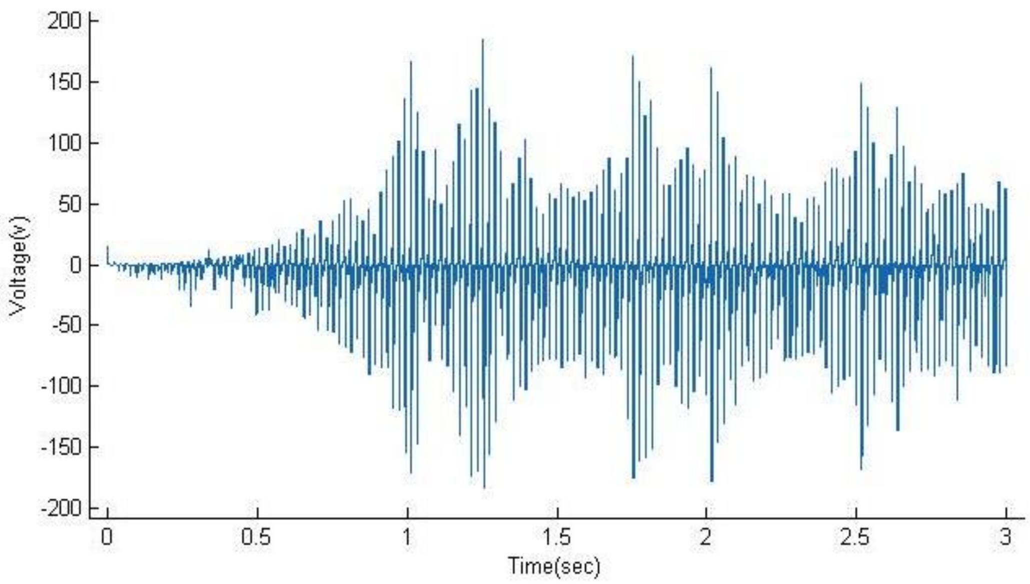


Figure 4.2 (d) Output voltage

4.2 OUTPUT POWER:

Figure 4.2(d) shows that the output voltage of 'cantilever-based electret energy harvesters' can be higher than 150V. This can greatly simplify rectification of the output voltage using diode bridges. Moreover, Figure 4.2(d) shows a particularity of the output voltage of cantilever-based electret energy harvesters: output voltage presents a discontinuity when it passes from its higher value, the capacitance is just before its maximum max (C) to its lower value (the capacitance is just after its maximum max(C) because the current changes direction when the capacitance crosses its maximum. The current also changes direction when the capacitance crosses its minimum min (C*)*. But, since the output voltage equals 0 when the capacitance is minimum, no discontinuity on the output voltage appears.

As a consequence, as the electret-based converter's output powers is linked to the electret's surface voltage Vs and its lifetime to the electret's lifetime, we confirm that Surface Potential Decays (SPDs) are the most appropriate way to characterize electrets for an application in energy harvesting. This maximum theoretical output power $P_{w\&y}$ can be simply expressed with equation (3.2) mentioned in chapter three**:**

$$P_{W\&Y} = \frac{mY^2{\omega_0}^3Q_m}{8} = \frac{0.005 * (0.000025)^2 * (314.16)^3 * 75}{8} = 9 * 10^{-4}W\ )$$

And the theoretical instantaneous harvested power is given by:

$$p(t) = \frac{U^2}{R} = \frac{1}{R}\left(V - \frac{Q_2}{C(t)}\right)^2$$

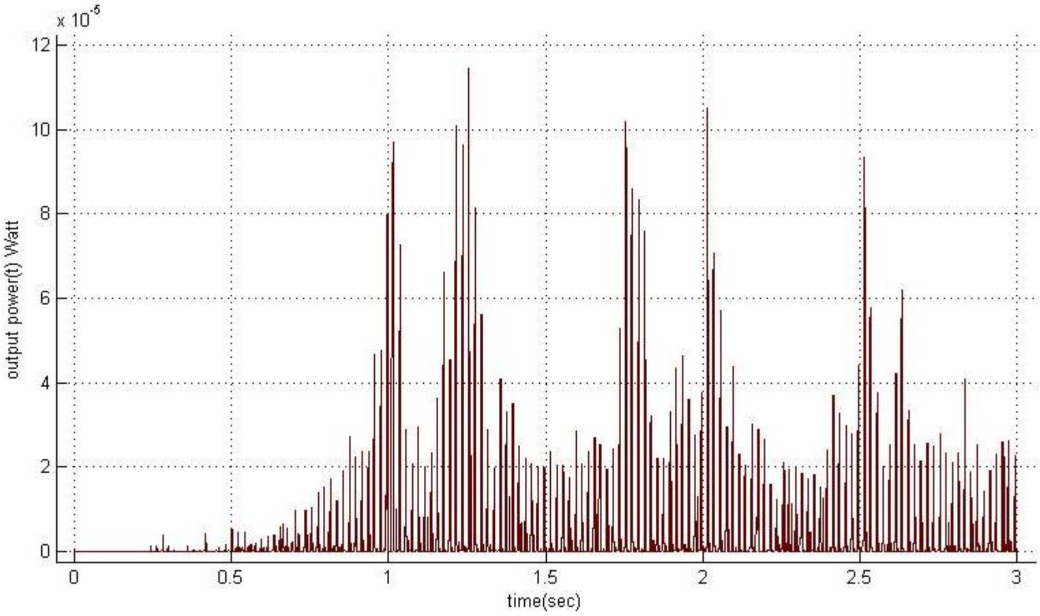


Figure 4.3.the instantaneous harvested power

The resonant system has been optimized and theoretical results have proven that up to 100µW could be reached with low vibrations (25µm@50Hz)≈1ms-2. Actually if we takes parasitic capacitances into account enables to validate design of electret-based vibration energy harvesters that was presented above. Note that output power will decrease and reaches 50µW with a low vibration acceleration of 0.1G@50Hz) [27]

Obviously, it is impossible to power any application, any electronic device with such a supply source. This is the reason why a power converter and an energetic buffer are needed to develop autonomous sensors. All that presented in chapter four.

4.3. COMPARISON WITH OTHER DEVICES:

Table 4.1 contained of comparison between most recent electrostatic energy harvesters with this device presented in this research showing good result of theoretical output power.

Author	**Vibrations**	**Active Surface (S)**	**Electret Potential (V)**	**Output Power (P)**	**ref**
Jefimenko	6000rpm	730cm^2	500V	25mW	[21]
Tsutsumino	1.58G@20Hz	4cm^2	1100V	38 Micro W	[29]
Boisseau	0.1G@50Hz	4.16cm^2	1400V	50 micro W	[27]
This work	0.1G@50Hz	4.16cm^2	1400V	$(120microW)_{theoretical}$	

Table 4.1.Comparison to 3 models among the most recent electret energy harvesters

4.4. LIMITS:

Obviously, e VEH has drawbacks and limitations. We present in this subsection the four most important limits of these devices.

i. Integration of devices:

The question of size reduction is common to all VEH. Actually, as the output power is proportional to the mobile mass, it is not necessarily useful to reduce VEH' dimensions at any cost. Moreover, it becomes particularly difficult to design devices with a resonant frequency lower than 50Hz when working with small-scale devices. As a consequence, to have a decent output power (>10µW) and a robust device, it is hard to imagine devices smaller than 1cm^2.

ii. Working frequency and frequency bandwidth:

Ambient vibrations are characterized by a low frequency, generally lower than 100Hz. Moreover, when looking at the vibrations spectra, it appears that they are spread over a wide frequency range. This implies that we need to develop low-frequency broadband devices; this may rise to many problems in the design and the manufacturing of the springs. Indeed, to build low-frequency devices, especially with small-scale devices, thin and long guide beams are needed. They are particularly fragile and are moreover submitted to high strains and stresses.

iii. Gap control:

e VEH output powers are greatly linked to the capacitance variations that must be maximized. Therefore, the air gap must be controlled precisely and minimized to reach high capacitances. Yet, it is also important to take care of pull-in and electrical breakdown problems.

iv. Electret stability:

Electret stability may also be critical. Actually, electret stability is strongly linked to environmental conditions, for example to humidity and temperature. Moreover, contacts between electrets and electrodes must be avoided as they generally lead to breakdown and discharge of electrets.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This research developed an analytical model of 'cantilever-based electret energy harvester' that is in agreement with FEM results. The optimization process has shown that the power harvested by these structures are in the same magnitude as theoretical output powers developed by William and Yates as soon as the surface voltage of the electret is sufficient to absorb the kinetic energy of the mobile mass. The work includes Design, modeling and simulation by SOILDWORK, ANASYS and MATLAB of electro-mechanical and electrical properties of the structure, description of its behavior in operating mode and phases of activity.

Finally, we validated our model with modeling and simulation results which reach up to 10µW per gram of mobile mass for low ambient vibrations of 0.1g (1ms-2), using a resonant system. Cantilever-based energy harvester can be a good low-cost solution to harvest energy when vibrations are constant in frequency and amplitude. The output power meets the magnitude of powers reached by piezoelectric or electromagnetic solutions. In this research the basic concepts and theories of electrostatic converters and electrostatic vibration energy harvesters together with some prototypes from the state of the art, adopting a "global system" vision has been presented. Electrostatic VEH are increasingly studied from the early 2000s. Unfortunately, no commercial solution is on the market today, dedicating these devices to research. We believe that this is a pity because they have undeniable advantages compared to piezoelectric or electromagnetic devices. The first in importance is probably the possibility to manufacture low cost devices (low cost and standard materials). Obviously, the limited frequency bandwidth of vibration energy harvesters does not help the deployment of these devices, even if some solutions are currently under investigation. Yet, with this increasing need to get more information from our surroundings, we can expect that these systems will match industrial needs and find industrial applications.

Anyway, electrostatic converters and electrostatic vibration energy harvesters remain an interesting research topic that gathers material research (electrets), power conversion, low consumption electronics, mechanics and so on. Cantilever-based energy harvester can be a good low-cost solution to harvest energy when vibrations are constant in frequency and amplitude. The output power meets the magnitude of powers reached by piezoelectric or electromagnetic solutions.

5.2 RECOMMENDATION FOR FUTURE WORK

To a chive the high power from electrostatic energy harvester, many other data could be obtained during further studies. The following recommendations could be considered for further research works to enhance the knowledge on emission reduction:

1- The limited frequency bandwidth of vibration energy harvesters does not help the deployment of these devices, so the recommendation is to study how to increase operational bandwidth of this device.

2-To study how to improve the output voltage

3- To study other theories of energy harvesters piezoelectric and electromagnetic devices.

4- Study how to improve power management control circuits' efficiency.

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