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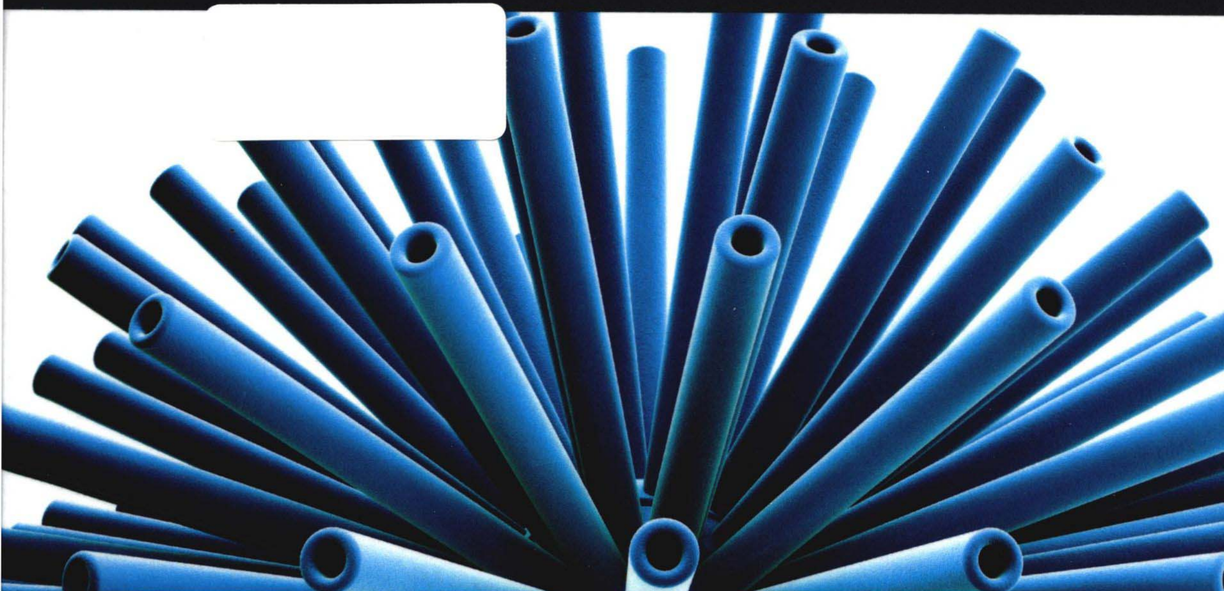

Volume 3

Electrostatic Kinetic Energy Harvesting

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and Dimitri Galayko

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Electrostatic Kinetic Energy Harvesting

Preface

Miniaturization and efficiency are current trends in modern microelectronics. They will most likely continue to be for the next few years as we enter the age of the Internet of Things. Future technologies will rely on energy sources and, for this reason, energy harvesting is an extremely active, versatile and developing area that includes engineers and scientists from the field of electronics, microsystems and material science. While there are many different types of energy harvesting systems, we believe that electrostatic kinetic energy harvesters – devices that generate electricity from mechanical motion employing the capacitive (electrostatic) mechanism – are underrepresented in the literature. Although they are particularly compatible with microtechnology, they are also more complex compared to other kinetic energy harvesters.

This book is the summary of collaboration between three research groups from Université Paris-Sorbonne, University College of Dublin and Université Paris-Est on kinetic energy harvesters carried out between 2007 and 2015. Although this book is focused on energy harvesting employing the electrostatic transduction, we believe that this allowed us to write a complete and self-sufficient study. The book covers all aspects necessary to understand and design an efficient harvester, including linear and nonlinear resonators, electrostatic transaction principles, microfabrication processes and the design of conditioning electronics.

This book is primarily intended for Master's degree and PhD students who wish to discover the field of kinetic energy harvesting. It contains both chapters on fundamentals and chapters that present state-of-the-art results. We believe that some chapters will also be of interest to scientist and engineers involved in the design and development of kinetic energy harvesting.

Chapters 1, 2 and 7 discuss a capacitive energy harvester as a system, with additional chapters devoted to the operation in both the electrical and mechanical domains. Chapters 3 through 6 discuss mechanical aspects of harvesters, and Chapters 8 through 11 are devoted to electronic conditioning circuitry. We have made a choice to present the material at a relatively high level of abstraction, limiting the discussion to the aspects that have the most impact on the global operation of the harvester. While this choice does not allow an extended discussion on some practical aspects of implementation, we are certain that this study provides a deep enough understanding of the role and function of each component in an energy harvester.

We sincerely thank all the PhD students and postdoctoral researchers who have contributed to our collaboration and research under our supervision: Mahmood Ayyaz Paracha, Andrii Dudka, Raphaël Guillemet, Peter Harte, Francesco Cottone, Eoghan O'Riordan, Armine Karami, Mohammed Bedier and Yingxian Lu. In particular, we are grateful to Eoghan O'Riordan, Peter Harte, Armine Karami, Yingxian Lu and Mohamed Bedier for helping prepare this book.

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Introduction: Background and Area of Application

Sensing and data recording is appearing as the new paradigm of the 21st Century: smart cars, smart homes, smart buildings and cities are the objects of very extensive and active research. They all need a large number of communicating sensors (preferably wireless) for installation and operation cost reduction, or reliability improvement. The modern car has a few hundred sensors, and it is expected that the automotive industry will require 22 billion sensors by 2020. Today, most sensors are still powered using wires. Making them autonomous would ease the sensor installation and would, generally, offer a lighter and more reliable system. These ideas about smart environments benefit from the wireless sensor network (WSN) or the Internet of Thing (IoT) concepts. In WSNs, all the sensors are provided with an embedded energy source and an antenna to wirelessly transmit data measurements. This communication system usually takes place in a star network where each sensor communicates with a master node. A better implementation of the network can be arranged if each sensor communicates with the closest node in order to progressively propagate the measured information to reach the base station (Figure I.1). For the IoT, the main idea is that any item of daily life is able to communicate data through such a network.

For both the WSN and the IoT, independent and miniature power sources are usually preferable over wire powering. In the majority of cases, a battery is used, which may last from several days to several years, depending on its size and the application. However, there are applications where a battery is not suitable for some reasons: a harsh environment degrades the battery too fast, an inaccessible location makes the cost of the battery replacement too high, or, for example, a chemical battery may be incompatible with ecological requirements. In these cases, an appropriate solution would be to take energy from the ambient environment of the sensor. This is the modern concept of "energy harvesting".

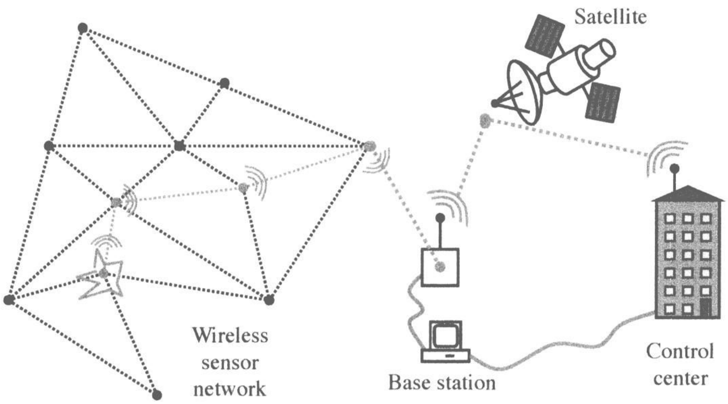

Figure I.1. *Principle of an ideal wireless sensor network (WSN) ecosystem: an event captured by an abandoned sensor node is transmitted through communications with other nodes nearby*

There are many ways to harvest ambient energy. The most mature and efficient technique is the use of photovoltaic cells converting ambient light into electricity. Another useful, but more complex technique, is the use of the Seebeck effect to obtain electrical power from a temperature gradient. However, in some cases where no light or temperature gradient are available in the environment, less conventional energy sources have to be envisaged. Kinetic energy, and more specifically vibrations, can provide great opportunities since these are present in the environment of many applications.

The idea of using kinetic energy to power a system is well known, such as with the dynamo invented in the late 19th Century. However, recent developments in material science and microelectronics allow us to envisage miniaturized systems combining a source of ambient mechanical energy and a sensor supplied by this source, possibly without any battery. Three families are generally distinguished for this conversion of mechanical energy into electricity, depending on the mode of transduction used: electromagnetic, piezoelectric and electrostatic. Each family has its advantages and drawbacks. In principle, we can say that electromagnetic transduction is the most effective in theory, but its performance drops as the device dimensions are scaled down. The piezoelectric transduction is efficient at all scales but requires constant stressing of an electroactive material, which raises reliability issues. Finally, the electrostatic transduction may be more complex to implement but is particularly suitable for miniaturized systems.

There are numerous applications for kinetic energy harvesting, even if there are few commercial products so far. For instance, mechanical structure health monitoring includes the monitoring of bridge oscillations, cracks in plane wings or changes in train rail fixtures with the aim to avoid deadly accidents. Other common examples include mechanical vibrations of the heart (can power an implanted pacemaker) or tire pressure monitoring systems (can be fed with mechanical energy of a rotating wheel).

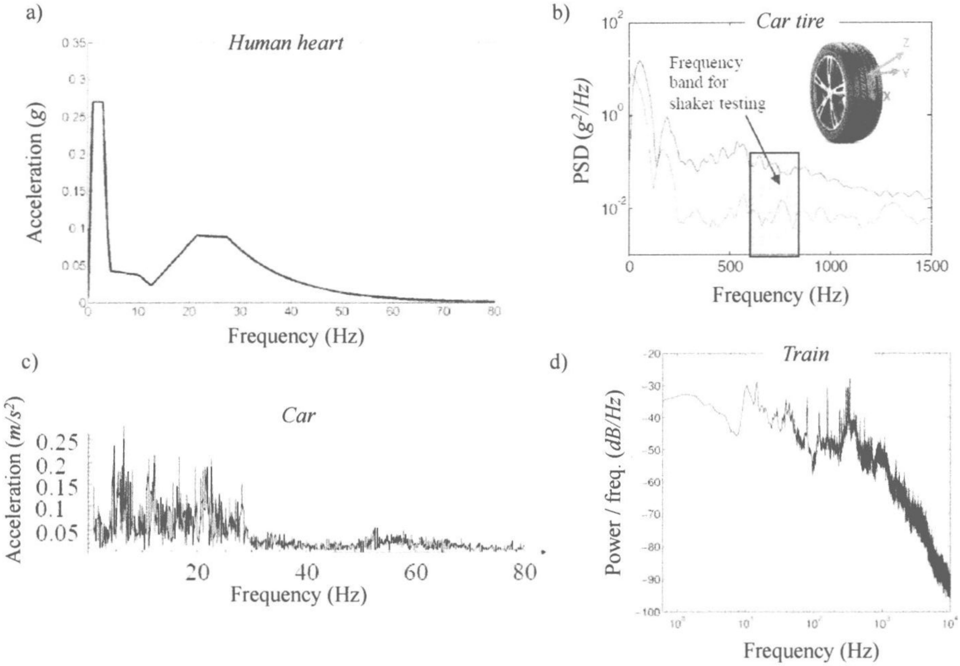

Figure I.2. *Examples of different vibration spectra published in the scientific literature: a) typical shape of the acceleration spectrum in the right atrium of a human heart [DET 11], b) power spectral density of the acceleration measured on the inner surface of a car tire driving at 60 km/h [REN 13], c) acceleration spectrum of a car [DES 05b] and d) acceleration of a train [VOC 14]*

Vibrations suitable for the generation of electricity can be of various forms. They can be periodic or non-periodic, harmonic or non-harmonic, regular or irregular, spread over a large frequency range or occurring at a single frequency. As shown in Figure I.2, each environment has a specific vibration frequency spectrum and it is very difficult, if not impossible, to design a generic KEH: each application needs a dedicated device in order to optimize the power yield.

Contents

1

Introduction to Electrostatic Kinetic Energy Harvesting

As a truly modern and complex system, the electrostatic kinetic energy harvester has several blocks, each performing its own function in the electrical or mechanical domains (Figure 1.1). We will briefly overview the role of the blocks in this introduction.

A large amount of energy can be produced by motion or vibrations in the mechanical domain. However it is not possible to use it directly in the electrical domain. Therefore, one would need a mechanism or a device that will transfer one form of energy (mechanical) to another (electrical). Such a device is called a *transducer*.

By definition, the transducer is a mechanism or a device that takes energy (power) in one form and converts it into another form. An electromechanical transducer is a very common and important type of transducers in modern microelectronics and microsystems: it converts mechanical energy into electrical form (and in some applications, vice versa, from the electrical to the mechanical domain). Thus, if one wishes to build a system that charges a storage capacitor in the electrical domain using the kinetic energy of some external motion in the mechanical domain, we should include an electromechanical transducer in such a system.

In the scheme of electrostatic kinetic energy harvesting shown in Figure 1.1, we use a variable capacitor as an electromechanical transducer. Let us consider a very simple case to understand its operation. Suppose that we have a parallel plate capacitor (Figure 1.2), with one of its two plates fixed and the other one movable. The distance

d between the plates is allowed to vary (due to any reason). The capacitance C_t of this capacitor depends on the distance d as follows:

$$C_t = \frac{\varepsilon_0 \varepsilon_r A}{d} \qquad [1.1]$$

where ε_0 is the permittivity of free space, ε_r is the relative permittivity of the medium between the plates (usually air and so $\varepsilon_d \approx 1$) and A is the area of plates.

If the capacitor is charged to Q_t, the energy of the electric field stored in it is

$$W_t = \frac{Q_t^2}{2C_t} \qquad [1.2]$$

Suppose now that we will manually move the movable plate farther from the fixed plate, keeping the charge Q_t constant. The new distance d_1 is greater than the original distance d: $d_1 > d$. The capacitance, according to equation [1.1], decreases and the stored energy, according to [1.2], increases.

In this example, we changed the energy stored in the electrical domain by manipulating a mechanical parameter (the distance d) of the transducer. This type of the electromechanical transducer is called *capacitive* (since it employs a capacitor) or *electrostatic*. There are other types of electromechanical transducers. Notably, electromagnetic and piezoelectric transducers are commonly used in kinetic energy harvesters, but they are out of the scope of this book.

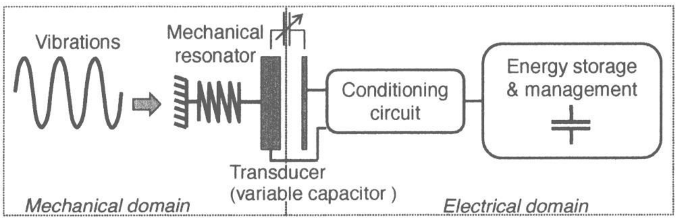

Figure 1.1. *Generic high-level structure of an electrostatic kinetic energy harvester (KEH) that includes a resonator, a capacitive transducer and a conditioning circuit (the transducer couples the mechanical and the electrical domain)*

We can reasonably assume that if we manage to attach one plate of such a capacitor to a vibrating or moving object, the external vibration will move the plate and change the distance d between the plates. This will affect the capacitance C_t and,