Chapter 1
Introduction and Methods of Mechanical Energy Harvesting

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Abstract The harvesting of various forms of mechanical energy, ranging from kinetic and surface strain energy to flow-induced aeroelastic and hydroelastic vibrations, has been investigated extensively over the last decade. The goal of this book is to cover the state-of-the-art research advances in energy harvesting with a focus on different transduction mechanisms and forms of mechanical excitation. The following chapters include various examples of energy scavenging using piezoelectric transduction, electromagnetic induction, electrostatic transduction, as well as electroactive polymer harvesting. The aim of this first chapter is to provide a brief introduction to the literature and fundamentals of energy harvesting methods discussed through this volume along with an outline of the present book.

1.1 Introduction

The goal in energy harvesting is to enable self-powered electronic devices by scavenging ambient energy for various wireless electronic applications ranging from structural health monitoring to medical implants [1–4]. The energy conversion methods that have been used for transforming mechanical (mostly vibrational and kinetic) energy into electrical energy are the piezoelectric [5–7], electromagnetic [8–11], electrostatic [12–15], and magnetostrictive [16] or magnetoelectric [17] composite-based conversion methods as well as the use of electroactive polymers,

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such as dielectric elastomers [18, 19] and ionic polymer-metal composites [20–22]. Low-power electricity generation from kinetic energy and ambient vibrations can be argued to be a relatively well-established field with several review articles having already appeared in the literature [23–27].

It has been argued in several review articles [24, 25, 27] that piezoelectric energy harvesting remains the most widely researched harvesting method due to its ease of application, high voltage output without requiring post-processing for voltage multiplication or bias input, high-power density, as well as relatively mature thin-film and thick-film manufacturing methods [28, 29] that can be used for fabricating devices at different geometric scales. However, other techniques such as electromagnetic induction and electrostatic transduction methods also have specific advantages. For instance, although it remains a challenge to develop and fabricate effective MEMS electromagnetic energy harvesters due to the poor transduction properties of planar magnets and the limited number of induction loops for such small-scale devices [30, 31], electromagnetic induction is very convenient for harvesting kinetic energy with large deflections as long as the geometric scale allows for sufficiently strong electromechanical coupling with a proper coil-magnet arrangement. Likewise, in spite of its bias voltage requirement as a particular downside, electrostatic energy harvesters are very conveniently implemented MEMS fabrication techniques [14, 32]. Consequently, while focusing on various forms of excitation and the multi-physics aspects of power scavenging, throughout this book we intend to cover the advances in energy harvesting methods with examples involving various transduction mechanisms.

The examples of state-of-the-art energy harvesters discussed for different excitation forms (such as deterministic and stochastic) and different physical ambient conditions (such as flow excitation, human gait, and vibrations) in this text predominantly consider piezoelectric transduction, electromagnetic induction, electrostatic transduction, and electroactive polymer techniques. Therefore the following section provides a brief introduction to each of these energy conversion methods along with useful references from the respective literature. As previously mentioned, several review articles [23–27] are available for the reader's reference on the efforts of energy harvesting using these mechanical energy harvesting methods. This chapter ends with an outline of the book along with the motivation for each section.

1.2 Methods and Materials for Energy Conversion

1.2.1 Piezoelectric Transduction

Piezoelectricity is a two-way coupling between the mechanical and the electrical behaviors of materials belonging to certain classes, particularly ceramics and crystals. Piezoelectric materials, such as the ceramic PZT (lead zirconate titanate), the single crystal PMN-PT (lead magnesium niobate-lead titanate), or the semi-crystalline polymer PVDF (polyvinylidene difluoride), exhibit the so-called direct and converse piezoelectric effects. In the simplest terms, these materials produce electric polarization when strained mechanically (direct effect), and they become strained mechanically when subjected to electric polarization (converse effect). The concept of energy harvesting leverages primarily the direct piezoelectric effect to convert mechanical and structural vibrations (i.e., kinetic energy) into electricity. It is useful to note that the converse effect is still exhibited by the material during energy harvesting and manifests itself in the form of shunt damping in strongly coupled energy harvesters [4, 33].

Figure 1.1 shows various piezoelectric energy harvester configurations. If the poling axis and the mechanical strain axis are perpendicular to one another, the device uses the 31-mode of piezoelectricity (where the 3- and 1- axes are the poling and strain directions respectively). Examples are the bimorph cantilever[1] under base excitation (Fig. 1.1a) or a thickness-poled piezoelectric plate mounted on the surface of a large structure (such as a bridge or a pipe) to harvest strain fluctuations of the host structure (Fig. 1.1b). On the other hand, if the poling and strain axes are coincident, the piezoelectric device is said to be operating in the 33-mode. Typical examples are piezoelectric stacks (made of several thickness-poled piezoelectric layers) as depicted in Fig. 1.1c and monolithic cylindrical or cuboid piezoelectrics such as the thickness-poled annulus shown in Fig. 1.1d. Cantilevered energy harvesters employing interdigitated electrodes [34] also have their strain and electric field directions coincident and exploit the 33-mode in bending. In all cases, the electrode leads are connected to an electrical circuit, which could be as simple as an electrical resistor (which is often used for estimating AC power levels), or more complex circuits such as an AC–DC converter followed by a DC–DC regulator to charge a storage component [35, 36]. Typically, high voltage levels (on the order of volts to tens of volts) are extracted directly from the material itself without needing preconditioning (such as using a voltage multiplication circuit) and piezoelectric transduction does not require a bias voltage. The high voltage output is associated with a low current, which might occasionally be an issue if the leakage current level of the storage component (a battery or a capacitor) or preconditioning circuit is larger than the level of the generated current.

The cantilever configuration shown in Fig. 1.1a has been of particular interest in the energy harvesting community due to its excellent energy harvesting capability when designed to exploit resonance under harmonic excitation. The electrical power generation performance of resonant energy harvesters depend on the level of system's electromechanical coupling[2] (strong or weak) and mechanical damping (high-

[1] A bimorph is a configuration that uses an elastic substructure sandwiched between two thickness-poled piezoelectric layers; a unimorph (not discussed here) is composed of a single thickness-poled piezoelectric layer attached to an elastic substructure.

[2] Electromechanical coupling of a piezoelectric energy harvester depends not only on the amount of the piezoelectric material used but also on the structural design of the harvester (such as the location of the piezoelectric material on the cantilever and the way it is bonded to its substrate).

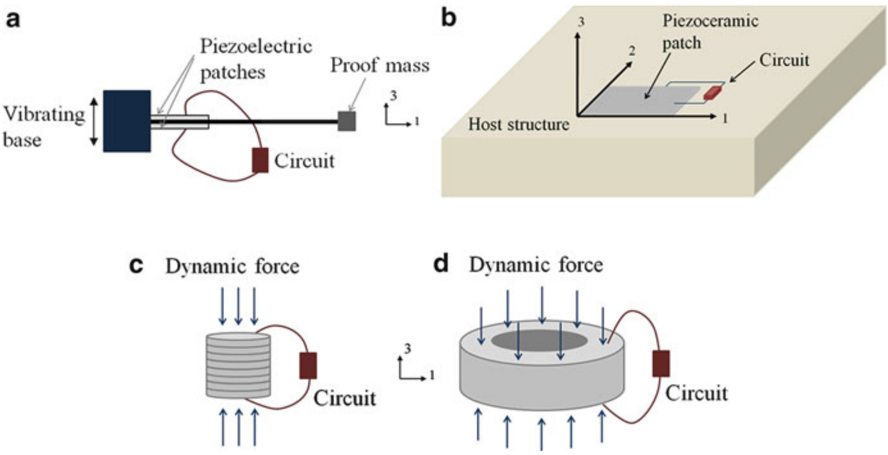

Fig. 1.1 Typical piezoelectric energy harvester configurations: (**a**) bimorph piezoelectric cantilever under base excitation and (**b**) piezoelectric patch harvesting surface strain energy of a large structure using the 31-mode; (**c**) multi-layer piezoelectric stack and (**d**) monolithic annulus under compressive loading using the 33-mode (3-direction is the poling direction in all cases)

or low mechanical quality factor) [4, 6, 37]. Strong electromechanical coupling and light mechanical damping (low-quality factor) are preferred for resonant energy harvesting. In contrast the mechanical quality factor of the harvester has little or no effect on the harvesting performance of a patch attached to a large structure (Fig. 1.1b) or to a compressed stack (Fig. 1.1c) at low frequencies (which are typical of off-resonant conditions that would be found in many applications such as for piezoelectric laminates embedded and strained in a shoe for power scavenging during walking).

1.2.2 Electromagnetic Induction

The conversion of kinetic or vibrational energy into electricity using electromagnetic induction exploits the well-known Faraday's law. That is electricity generation in electromagnetic (inductive) energy harvesting is due to the relative motion between a conductor (such as a coil) and a magnetic field (created by a magnet). Typically, a mechanical oscillator is designed to have a magnet-coil arrangement, which moves relative to each other in response to mechanical excitation. The configuration shown in Fig. 1.2 depicts an electromagnetic energy harvester design that consists of a cantilever combined with a magnet-coil arrangement. The permanent magnet rigidly attached at the tip of an elastic cantilever as an inertial mass (or proof mass) oscillates inside the fixed coil in response to base excitation [10, 11]. The alternative arrangement is to have a moving coil oscillating relative to a fixed

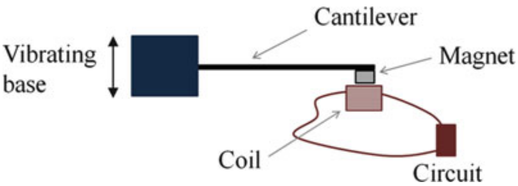

Fig. 1.2 Schematic of a typical electromagnetic energy harvester subjected to base excitation. The permanent magnet that serves as the proof mass of an elastic cantilever oscillates inside a coil due to the ambient base excitation; this relative motion between magnet and coil induced a current that is delivered to the electrical circuit

magnet [10]. The amount of electrical power output depends on the strength of the magnetic field, number of turns of the coil, and the relative velocity between the coil and the magnet. Under resonant operation, the power output is significantly affected by the quality factor of the mechanical oscillator and on the internal resistance of the generator coil.

As for piezoelectric transduction, electromagnetic induction does not require the device to have an initial bias voltage. Similarly, the oscillatory electrical response needs to be rectified and converted to a DC signal in order to charge a storage component. In contrast to piezoelectric transduction, electromagnetic energy harvesting results in low voltage and high current outputs (associated with a much lower optimal circuit resistance as compared to piezoelectric energy harvesters). Consequently, a voltage multiplier circuit is often required to reach the required voltage level of typical off-the-shelf storage components.

1.2.3 Electrostatic Transduction

In electrostatic (capacitive) energy harvesting, ambient mechanical vibrations are used to move the charged capacitor plates (or electrode fingers) of a variable capacitor against the electrostatic forces between the electrodes. These electrodes of the capacitor are separated by air, vacuum, or an insulating dielectric material. Typically a dielectric material is used to both increase the harvested energy and to prevent the capacitor faces from touching under the applied mechanical load [12–14]. The two most common approaches in this method of energy harvesting are charge-constrained and voltage-constrained mechanisms as detailed in [12, 23]. Unlike piezoelectric and electromagnetic energy harvesting methods, electrostatic energy harvesting requires a DC voltage supplied by a battery to oppositely charge the capacitor plates or electrode fingers (i.e. the so-called bias voltage). The oscillatory motion induced by the ambient vibration results in a cyclic variation of the capacitance of the device from a maximum to a minimum value, and the energy transfer per cycle is highly dependent on the ratio of this maximum to minimum capacitance [1].

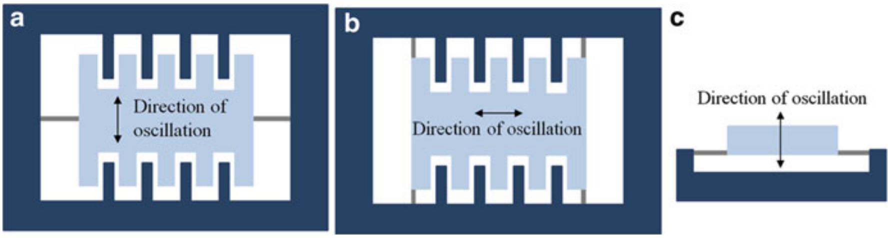

Fig. 1.3 Schematics of electrostatic energy harvesting configurations using in-plane and out-of-plane vibrations: (**a**) in-plane overlap varying; (**b**) in-plane gap closing; and (**c**) out-of-plane gap closing

The basic classification of electrostatic energy harvesters that exploit dynamic capacitance variation in response to mechanical excitation is given in Fig. 1.3 [1, 23]. Two of the configurations (Fig. 1.3b) in this figure employ in-plane vibrations of the electrode fingers while the third approach (Fig. 1.3c) uses the out-of-plane vibrations of the one of the capacitor plate relative to the other. The capacitance variation in Fig. 1.3b is due to the changing overlap area of the fingers and the changing gap between the fingers, respectively, while the gap closing between relatively large electrode plates causes the capacitance variation in Fig. 1.3c. All three configurations are capable of producing roughly the same power output [1]. The in-plane overlap and out-of-plane gap closing mechanisms require high spring deflections to create maximal power output. Particularly in the in-plane overlap mechanism, large deflections may create relative rotation of the oscillating component due to a lack of symmetry in the excitation, thus leading to the touching and possible shorting of the electrode fingers. Roundy et al. [1] suggest that the most favorable architecture is the in-plane gap closing configuration due to its smaller displacement requirement for the same power output, and hence more stable behavior as compared to the in-plane overlap varying mechanism. Furthermore the in-plane gap closing method has a higher power density as compared to the out-of-plane gap closing mechanism. Nevertheless both overlap varying and gap closing mechanisms have been widely researched especially in the MEMS energy harvesting literature [12, 13, 15].

1.2.4 Electroactive Polymers

The two types of electroactive polymers (EAPs) that have been studied for energy harvesting are dielectric elastomers (DEs) [18, 19] and ionic polymer-metal composites (IPMCs) [20–22]. According to the commonly used classification, DEs are *electronic* EAPs whereas IPMCs are *ionic* EAPs. Both electronic and ionic EAPs exhibit coupling between the mechanical stress (or strain) and electrical potential (or charge). The electromechanical coupling in electronic EAPs is due to

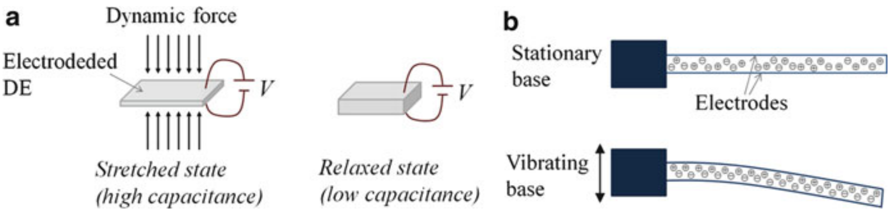

Fig. 1.4 Schematics of basic energy conversion mechanisms in DEs and IPMCs: (**a**) stretched and relaxed states of a DE in the presence of a bias voltage applied to the surface electrodes and (**b**) migration of free cations due to a charge concentration gradient in an IPMC cantilever resulting from bending deformation

polarization-based or electrostatic mechanisms while ionic EAPs exhibit electromechanical coupling due to diffusion or conduction of charged species in the polymer network [38].

A typical DE-based energy harvester is a soft polymer material, such as natural rubber, bracketed between two conductive electrodes (Fig. 1.4a). The mechanism of power generation using dielectric elastomers is analogous to that of electrostatic (capacitive) energy harvesting discussed in the previous section. DEs are elastically deformable insulators that respond to applied mechanical loading and can convert the mechanical work of the resulting deformation into electricity [19]. As in the case of electrostatic energy harvesting, a DC voltage input is required to oppositely charge the electrodes, and a cycle of energy harvesting involves a change of device capacitance from a maximum to a minimum value. A complete energy harvesting cycle consists of the following: (1) charging stage (to a high-charge value) by means of a battery associated with stretching of the DE and therefore increased capacitance, (2) switching to the open-circuit conditions and thickening of the DE at the fixed high-charge state, (3) switching to the output storage device and further thickening associated with loss of tension, hence capacitance reduction until the low-charge state, and (4) switching back to the open-circuit condition at the low-charge state that is associated with increased tension and reduced thickness [18]. In addition to the electromechanical properties of the polymer, various modes of failure (namely electrical breakdown, electromechanical instability, loss of tension, and rupture by overstretching) determine the limits of maximum energy conversion using DEs [18].

IPMCs are composed of ionic polymers, such as Nafion or Flemion, coated by conductive electrodes, which are typically made of gold or platinum. IPMCs exhibit a form of two-way coupling that is analogous to electromechanical coupling in piezoelectric materials. However, the mechanism of electromechanical coupling in IPMCs is based on the motion of ionic species upon application of an electric field or mechanical deformation. An IPMC-based energy harvester relies on the formation of a charge concentration gradient resulting from bending of the ionic polymer (Fig. 1.4b). The free cations within the IPMC migrate from the high-density to low-density region, resulting in an accumulation of charges at the electrode region and a potential difference across the electrodes [21, 39, 40]. Therefore, under dynamic bending of an IPMC cantilever in response to base excitation, an AC output can be generated analogous to piezoelectric energy harvesting. However, power density in IPMC-based energy harvesting is substantially lower (especially as compared to ceramic-based piezoelectrics) with typical power outputs on the order of nanowatts [41, 42].

1.3 Outline of the Book

As detailed in the next paragraphs of this introductory chapter, the major sections of this book are organized to include multiple chapters on the following subjects that cover the use of various transduction mechanisms for:

- Broadband energy harvesting and nonlinear dynamics
- Nonharmonic and spectral excitation
- Fluidic energy harvesting
- Advances in electronics
- Materials development and MEMS fabrication

Broadband energy harvesting and nonlinear dynamics: Research efforts toward enabling broadband (or wideband) energy harvesters are motivated by the limitations of well-studied resonant energy harvesters. Resonant energy harvesters (such as cantilevered oscillators) exploit the linear resonance phenomenon under harmonic excitation. A small mismatch between the excitation frequency and the mechanical resonant frequency of the harvester (due to manufacturing tolerances, ambient temperature fluctuations, or varying excitation frequency, among other reasons) results in drastically reduced power output, especially for lightly damped (i.e., high quality factor) harvesters. Exploiting nonlinear dynamic effects has been investigated as a promising way of enabling broadband energy harvesting. The goal is to enhance the frequency bandwidth by introducing nonlinearities through various mechanisms such as magnetoelastic buckling [43–45], purely elastic buckling [46, 47], stoppers [48, 49], and bilinear stiffness [50]. Following an extensive review article on the subject of broadband energy harvesting methods, this section of the book first covers broadband MEMS electrostatic energy harvesting using nonlinear springs and then bistable energy harvesters employing piezoelectric and electromagnetic transduction.

Nonharmonic and spectral excitation: As mentioned in the previous paragraph, the ambient mechanical excitation is often more sophisticated than a simple harmonic input. Therefore, in addition to enabling harvesters that can outperform the conventional designs under nonharmonic excitation, more advanced tools are required to model and analyze the electromechanical response to nonharmonic and arbitrary spectral forms of mechanical energy. Impulse-type excitation has broad frequency content and is most commonly associated with energy harvesting from human gait. Harvesting energy using shoe inserts strained during walking was previously studied in detail [51]. An alternative form covered in this section of the book employs a shoe-mounted cantilever that is exposed to base excitation associated with walking. The resulting excitation form resembles periodic impulse excitation of the energy harvester. Another way of harvesting gait energy disused here is achieved by focusing on the knee joint and employing the rotational excitation of piezoelectric bimorphs through plucking, that is essentially a mechanical frequency-up conversion technique. This section also investigates random excitation of energy harvesters with a special focus on stiffness nonlinearities, in particular bistable energy harvesters studied under harmonic excitation in the previous section.

Fluidic energy harvesting: The motivation in fluidic energy harvesting is to generate low-power electricity in fluidic media (e.g. air, water, etc.) by implementing an appropriate design and transduction mechanism. In-air and underwater flow energy harvesting through aeroelastic [52–54] and hydroelastic [55, 56] vibrations have been extensively researched by several groups. The goal in this research field is to create simple and efficient alternatives to small-scale windmills and wind turbines [57, 58]. The section starts with an investigation of energy harvesting from IPMCs in aquatic media. Two subsequent chapters then focus on harvesting wind energy through bluff body-based and airfoil-based energy harvesters. Finally, acoustic energy harvesting using sonic crystals is discussed as an alternative to well-investigated Helmholtz resonators [59].

Advances in electronics: In most cases, the mechanical energy harvesters discussed in this work require conversion of the alternating output (i.e. AC) to a stable DC signal in order to charge a storage component. Typically, AC–DC conversion is followed by DC–DC regulation to achieve the maximum power transfer to the electrical load [35, 36]. Performance enhancement in weakly coupled piezoelectric energy harvesters using switching circuits has been investigated in great detail in the existing literature [60], and there is currently significant research interest focused on the broad field of energy harvesting circuits. With this in mind, this section starts with an instructive review article on power conditioning circuits used in piezoelectric, electromagnetic, and electrostatic energy harvesting. After this fundamental review chapter, two subsequent chapters focus on novel integrated circuits used in MEMS piezoelectric and electrostatic energy harvesters.

Materials development and MEMS fabrication: Alternative materials and transduction methods are of interest in state-of-the-art energy harvesting research. Although not discussed in this book, the development of lead-free piezoelectric materials [61] with sufficiently strong electromechanical coupling is a present challenge to enable environment-friendly piezoelectric energy harvesters. Likewise, it is essential to enhance the magnetic properties in microscale devices to improve the feasibility of MEMS electromagnetic energy harvesting [30, 31]. We point our attention in this last section first to the relatively less studied yet promising dielectric elastomer-based energy harvesting. After that the focus is placed on materials and devices for MEMS piezoelectric energy harvesting, which is followed by a chapter on performance enhancement in energy harvesting using high permeability magnetic materials.

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