Chapter 1
Introduction

1.1 Background and Motivation of Vibration Energy Harvesting

In our daily life smart sensors have become an essential part increasing comfort, security and efficiency in many industrial and civilian application areas such as automotive, aircraft and plant industry, industrial and home automation or machine and health monitoring. Going one step further it does not come as a big surprise that there is a steady increase of wireless sensor networks (WSN) following the paradigm of ubiquitous computing. Many of nowadays applications would not be possible without the advance in miniaturizing the size and reducing the power consumption of electronics and the progress in wireless technologies. As a further advance smart sensors and WSN will tend to be even more embedded and mobile in the future. With a higher level of integration numerous new applications become possible.

However, the power supply of the sensor nodes evokes some serious challenges for the widespread implementation of WSN's. Because the sensors need to be wireless, the power is usually provided by primary or secondary batteries. It must be said that as long as the battery survives the life–time of the sensor node, batteries are often an appropriate solution. This is because the energy density of primary and secondary batteries has significantly increased over the last two decades [4]. Nevertheless batteries have some unavoidable drawbacks. The most important one for application in WSN's is that the energy is inherently limited. Thus the battery must be replaced or recharged sooner or later. Especially in difficult to access applications or applications with many sensor nodes this is often not feasible because maintenance becomes too costly. Another characteristic of batteries is the typical operating temperature range of −55°C to +85°C which might be insufficient in some applications. Energy Harvesting opens up new ways to solve these problems. Just as for the alternative energy sources in the power economy the basic idea behind energy harvesting is to convert non–electric ambient

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energy from the sensor environment into electrical energy. The primary goal is to obtain an energy autonomous, maintenance–free sensor system with (at least theoretically) unlimited life time. In contrast to the alternative energy sources in the power economy environmental protection aspects plays a subordinate role in energy harvesting devices.

Commonly used environmental energy sources are heat, light, fluid flow or kinetic energy [53]. This book focuses on the conversion of kinetic energy in form of vibrations which is a very promising approach for industrial applications. For example every machine with rotary parts is forced to vibrate due to imperfection in balancing. So far, existing vibration transducers are commonly based on three different conversion mechanism namely piezoelectric [37], electromagnetic [27] and for micro fabricated devices electrostatic [43]. In rather seldom cases the effect of magnetostriction [49] and magnetic shape memory alloys [39] has been investigated as well. A general approach for the comparison of the different conversion mechanisms has been presented in [70]. Especially for the aimed cubic centimeter range transducers in this book the electromagnetic transduction mechanism based on Faraday's law of induction is expected to be among the most efficient. Another advantage of the electromagnetic conversion is the huge design flexibility. In contrast to this advantage, piezoelectric vibration converters are in most cases based on simple beam and disc elements.

This book considers the design and optimization of electromagnetic vibration energy harvesting devices.

1.2 Literature Review and "State of the Art" in Electromagnetic Vibration Transducers

Since the earliest electromagnetic vibration transducers have been proposed at the end of the 1990s [15, 65] a multiplicity of electromagnetic based vibration transducers have been developed by numerous research facilities. The transducers basically differ in size, electromagnetic coupling architecture, excitation conditions and output performance. Actually electromagnetic resonant vibration transducers are already commercially available [5, 6, 8]. So far commercial vibration transducers are typically add–on solutions, greater than 50 cm^3 and they fulfil standard industrial specifications such as ingress protection (IP code, IEC 60529), operating conditions (like the temperature range, shock limit and so on) or the requirements for electrical equipment in hazardous areas (ATEX/IECEx). Nevertheless, requests from industry show that beyond the existing add–on solutions there is a great demand for application specific solutions. This is because in each application the required output power, the available vibration level and the overall mass and volume will be significantly different. Moreover, it is often necessary that the sensor system needs to be integrated in an existing subassembly. Especially for applications where the volume of the transducer is a critical parameter these facts show that the available output power of a vibration transducer can only be optimally used with application–specific customized developments. In this case it can be guaranteed that the transducer is not under or overdimensioned with respect to the size and the output performance.

The primary purpose of this introduction is to give a basic overview of the recent research achievements in electromagnetic vibration conversion. One suitable way to classify electromagnetic vibration transducers is to use the electromagnetic coupling architecture. An obvious and popular coupling architecture is a cylindrical magnet, which oscillates inside a coil. A silicon micromachined implementation of such an architecture with discrete magnet was reported in 2007 by C. Serre et al. at the University of Barcelona [14] (Fig. 1.1a). The prototype delivered a maximum power output of 55 μW at a voltage level of about 80 mV for excitation with 5.1 μm amplitude at about 300 Hz (18 m/s²). Another silicon bulk micromachined transducer with discrete magnet designed to convert acoustic wave energy was published in 2008 by T. Lai et al. at the Feng Chia University [76]. With a total dimension of 3·3·1 mm³ a maximum open circuit voltage of 0.24 V was obtained for excitation at resonance frequency (470 Hz). A macro scale implementation of this architecture has been used by S. Cheng et al. at the University of Florida in 2007 to verify equivalent circuit models of electromagnetic vibration transducers [68]. With the assembled device an output power of 12.5 mW could be generated at the resonance frequency of about 68 Hz and 30 Ω load resistance. X. Cao et al. at the University of Nanyang assembled another macro scale device [81]. The converter delivered an output power of 35 mW and an output voltage of about 15 V for excitation at the resonance frequency of 43 Hz with 3 mm amplitude. This corresponds to a very high acceleration level of 219 m/s². The output power was processed in an energy harvesting circuit with feedforward and feedback DC-DC PWM Boost converter fabricated in 0.35 μm CMOS technology. A group from the University of Hong Kong presented a PCB integrated solution as well as an AA battery size transducer [59] (Fig. 1.1b). A special feature of this transducer is that beyond the first eigenfrequency (linear oscillation) also higher eigenfrequencies of the system (tilting oscillation) are considered for conversion. The aim was to increase the bandwidth. However due to the large gap between the coil and the magnet the effectiveness of the conversion definitely decreases for the first eigenfrequency. A modification of the previous coupling architecture has been used by G. Naumann at the Dresden University of Technology in 2003 [34]. In this development a linear supported magnet oscillates between two repulsive arranged magnets. The magnetic forces yield a nonlinear spring system. For excitation with stochastic vibrations in an automobile environment a maximum output voltage of 70 mV at a power of 7 μW has been obtained. For harmonic excitation 610 mV and 200 μW are possible with an excitation amplitude of 5 mm at 16 Hz. This corresponds to a rather high acceleration level of about 50 m/s². The same modification has been published by C.S. Saha et al. at the Tyndall National Institute in 2008 [17] (Fig. 1.1c). Beyond harmonic excitation measurements the transducer was placed inside a rucksack. Average load power of 0.95 mW could be obtained during walking and 2.46 mW under slow running conditions. The same architecture

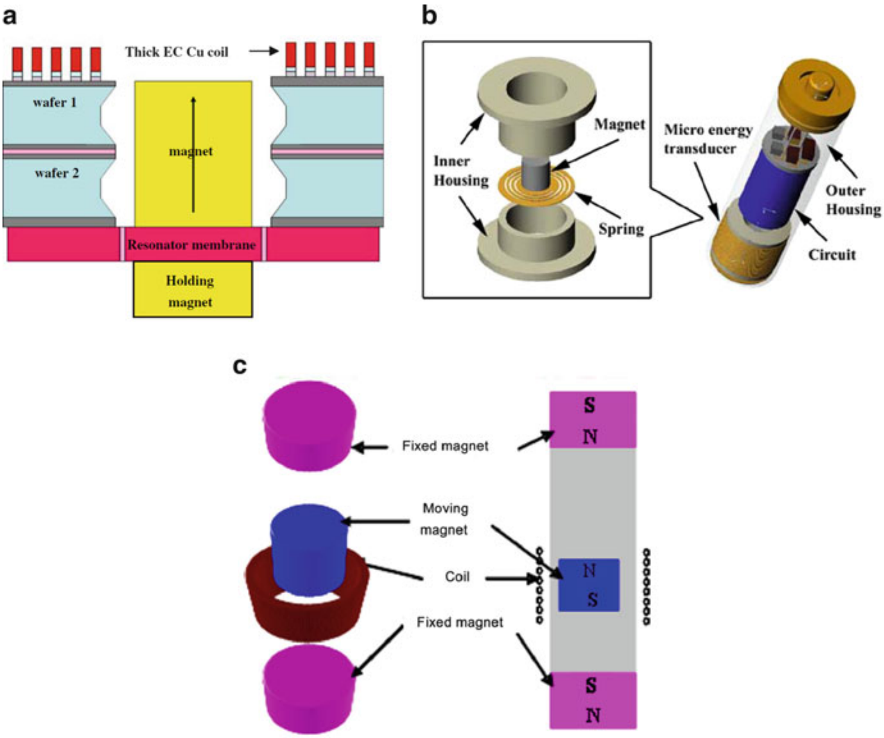

Fig. 1.1 Commonly applied coupling architecture where a magnet oscillates inside a coil. (**a**) Microfabricated implementation [14], (**b**) AA size transducer with multi modal resonating structure [59] and (**c**) with opposite polarized magnets used in a rucksack [17]

has also been considered by D.J. Domme from Virginia Polytechnic Institute in 2008 [26]. With an operating range of 12–24 Hz and an acceleration amplitude of 36.7 m/s² an average output power of 5.5 mW has been obtained. Further examples of this architecture can be found in [33, 57, 69].

Another commonly applied coupling architecture (often used in microfabricated devices) is that of a magnet which oscillates towards a coil without immersion. Based on this architecture P. Wang from the Shanghai Jiao Tong University presented a prototype device in 2009 [61] (Fig. 1.2a). With a not optimized prototype a peak to peak voltage of 18 mV and 0.61 μW could be generated for an excitation of 14.9 m/s² at 55 Hz. The same coupling architecture has also been used in [11] by B. Yang from the National University of Singapore in 2009 (Fig. 1.2b). The transducer is based on a multi–frequency acrylic beam structure. At the first two eigenfrequencies (369, 938 Hz) the maximum output voltage and power are 1.38 mV/0.6 μW and 3.2 mV/3.2 μW for an excitation amplitude of 14 μm. Another development based on this architecture has been used by D. Hoffmann at HSG-IMIT in 2009 [18]. The development is based on micro–machined flexible polyimide films and planar micro–coils (Fig. 1.2c). The assembled device is capable of generating a

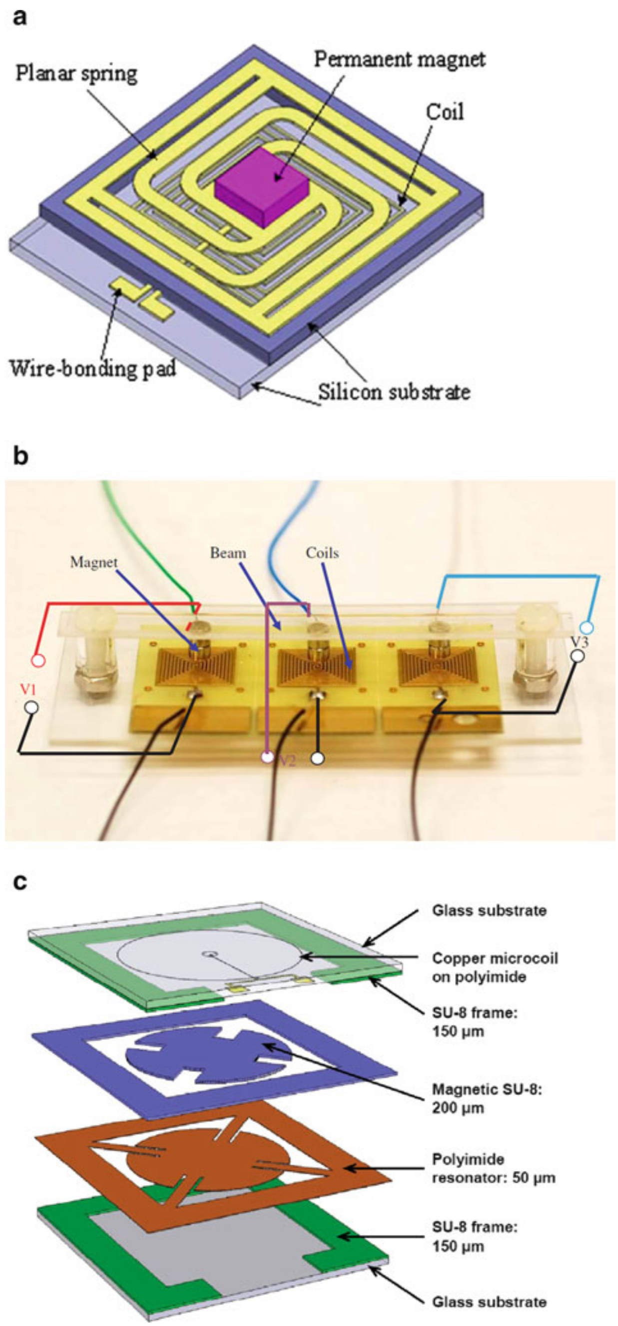

Fig. 1.2 Often favoured coupling architecture in microfabricated transducers where a magnet oscillates towards a coil without immersion. (**a**) Harvester with electroplated copper planar spring and discrete NdFeB magnet [61], (**b**) multi-frequency energy harvester based on acrylic beam [11] and (**c**) transducer based on micro-machined flexible polyimide films and planar coils [18]

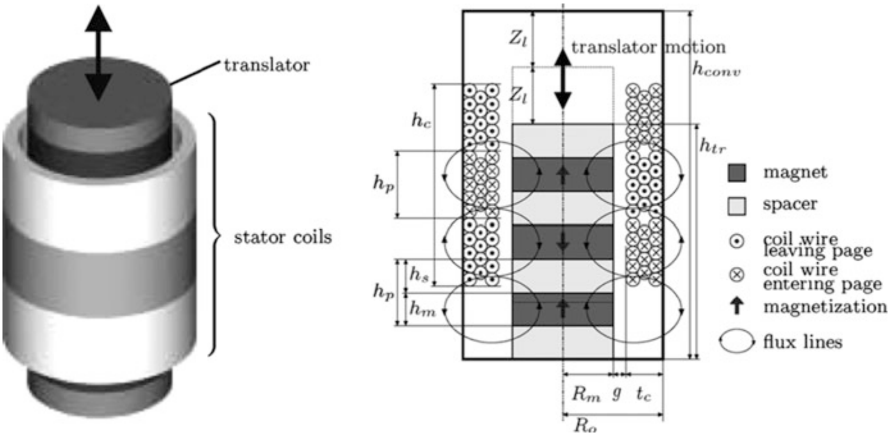

Fig. 1.3 Coupling architecture based on opposite polarized magnets [78]

peak power up to 5 μW (70 mV at 1,000 Ω) from a harmonic excitation with 90 m/s² at the resonance frequency of 390 Hz. Further developments using this architecture have been presented in [15] and [7].

In 2007 T. von Büren and G. Tröster from ETH Zürich developed a multi magnet micro–power transducer. The coupling architecture is based on opposite polarized magnets which provide the oscillating mass [78] (Fig. 1.3). Unlike most of the previous described work extensive finite element analyses (FEA) based optimization calculations have been applied for dimensioning the magnet and the coil. Designed for body worn applications 2–25 μW have been obtained during normal walking depending on the mounting position. Previously, this architecture had also been applied by K. Takahara at the Muroran Institute of Technology in 2004 [46]. This development focuses on the conversion of vehicle vibration. With a prototype 36 mW has been obtained at a voltage level of 1.6 V. For use as a regenerative shock absorber in vehicle suspensions the architecture has also been considered in a development presented by L. Zuo in 2010 [50]. The transducer was capable of generating 16–64 mW at a suspension velocity of 0.25–0.5 m/s. A similar architecture with opposite polarized ring magnets instead of cylindrical magnets and oscillating coil instead of oscillating magnets has been used by M. Ruellan in 2005 [55].

So far the presented architectures had the oscillation direction always in–line with the coil symmetry axis. The resulting geometry is typically cylindrical. However there are also architectures where the oscillation direction is perpendicular to the coil symmetry axis which typically yields a cubic geometry. A silicon micromachined moving coil version of such an architecture has been presented by E. Koukharenko from the university of Southampton in 2006 [31] (Fig. 1.4a). The prototype was capable of generating up to 104 nW for an excitation with 3.9 m/s² at 1,615 Hz. In [74] the same group presented a transducer based on discrete

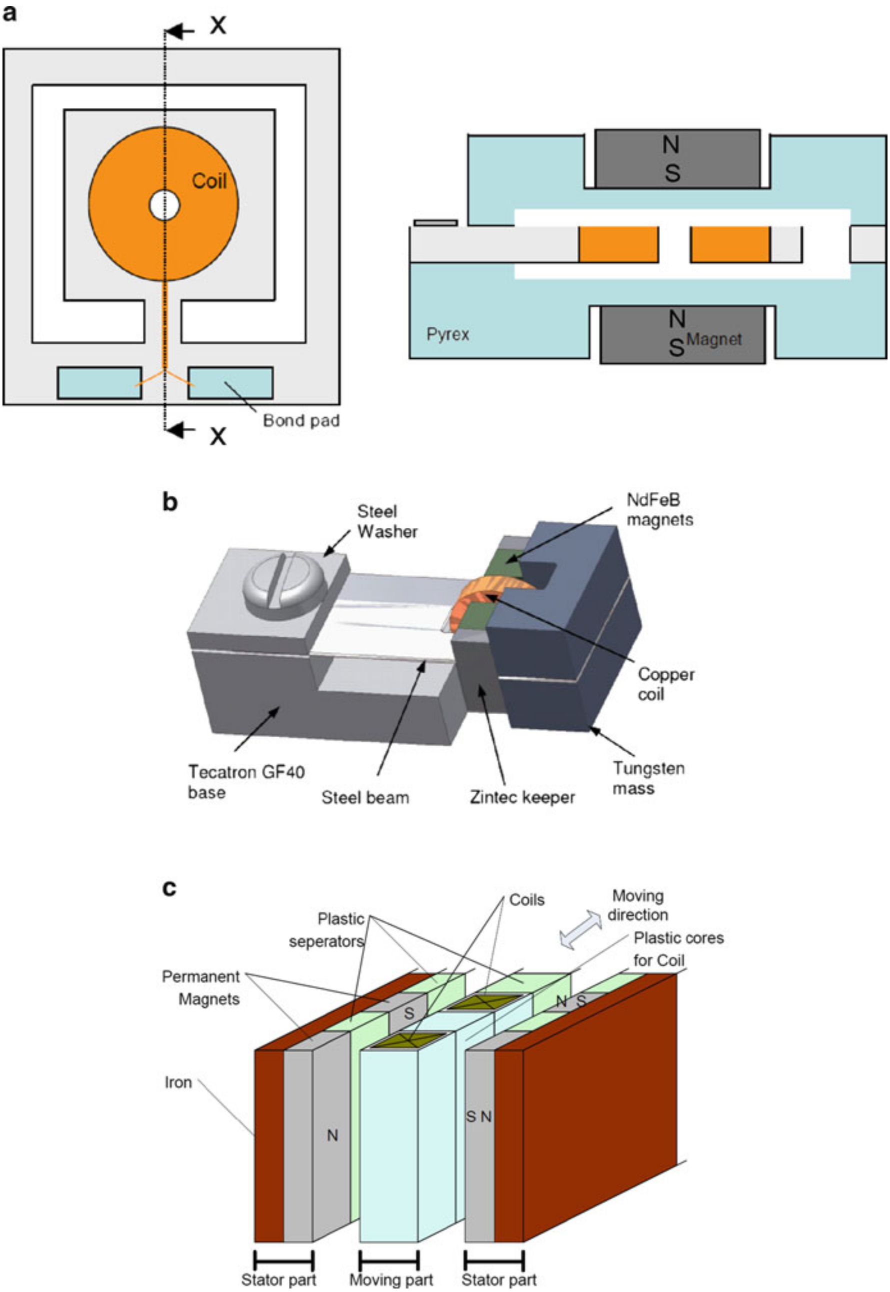

Fig. 1.4 (**a**) Silicon micromachined moving coil version of a magnet across coil arrangement [31]. (**b**) Moving magnet version based on discrete components [74] and (**c**) complete fine–mechanical implementation used to convert human motions [60]

components (Fig. 1.4b). The prototype was capable of generating 46 μW with an excitation amplitude of 0.59 m/s² at a (resonance) frequency of 52 Hz. A pure fine–mechanical transducer using a quite similar coupling architecture has been presented by P. Niu in 2008 [60] (Fig. 1.4c). This transducer was designed to convert human motions like arm swinging, horizontal foot movement or up–down centre of gravity movement during walking. The authors report an average power output of up to 100 mW at a voltage level of greater than 5 V for different body–worn operation conditions. A rotary suspended prototype with magnetic springs has been developed by Z. Hadas in 2010 [83]. When excited with the (nonlinear) resonance frequency of 18 Hz and an acceleration amplitude of 4.9 m/s² 26 mW could be converted at a voltage level of about 9 V. Actually this kind of electromagnetic coupling architecture has also been considered for a tunable device by D. Zhu in 2010 [25]. Even though the tuning mechanism is not self–powered so far, the resonance frequency could already be tuned from 67.6 to 98 Hz. In this range the prototype produced a power of 61.6–156.6 μW when excited at a constant acceleration level of 0.59 m/s². With the intent increasing the bandwidth this kind of coupling architecture has also been used in combination with a piecewise–linear oscillator by M. Soliman in 2008 [56]. Experimental measurements show that the bandwidth could be increased by 240%. However because this increase is based on a nonlinearity the benefit significantly depends on the excitation and the history of the system. In other words, to affirm the benefit in a specific application, the underlying excitation must be taken into account.

So far the reviewed prototype developments are based on commonly used coupling architectures. However a basic characteristic of the electromagnetic conversion mechanism is that the implementation of the electromagnetic coupling can be realized in various kinds. Hence, there are a number of further architectures that have been applied. Some of them are rather specific [52] but on the other hand it surprises that the well known coupling architecture of moving coil loudspeakers has not been considered for vibration transducers as often as might have been expected. Prototype developments of such a "loudspeaker" based coupling architecture, for example, has been presented by H. Töpfer in 2006 [36] and J.K. Ward in 2008 [42] (Fig. 1.5).

Altogether the existing prototype transducers range from 0.1 to 100 cm³ in size and from hundreds of nW to 100 mW in power. It must be said that an absolute comparison is rather difficult. This is because up to now there is no testing standard for vibration energy harvesting devices. Consequently the devices have been tested under different conditions (harmonic vs. impulse vs. stochastic excitation, simple resistive load vs. matched load vs. complex load circuit, . . .). Moreover important parameters for an absolute comparison are often omitted or ambiguous (which components are included in the denoted volume, rms vs. amplitude vs. peak–to–peak values, . . .). Nevertheless an extensive review of electromagnetic vibration transducers has been presented together with the basic scaling laws by D.P. Arnold in [27]. Therein the normalized power density (power related to the volume and the excitation amplitude) of existing prototypes is used as a basis for the comparison. With the normalization the performance of the transducer can be referred to the

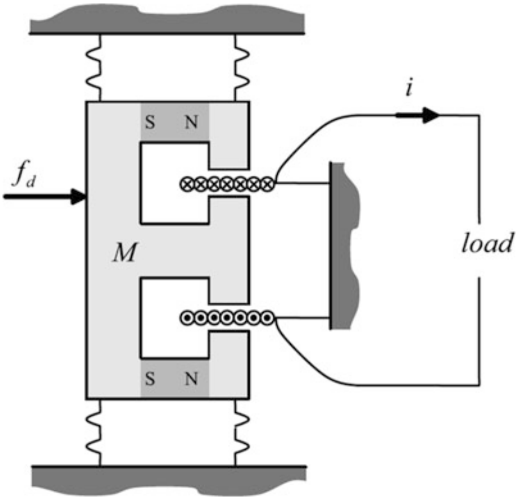

Fig. 1.5 Electromagnetic coupling architecture typically used in moving coil loudspeakers has been considered for vibration transducers in [42]

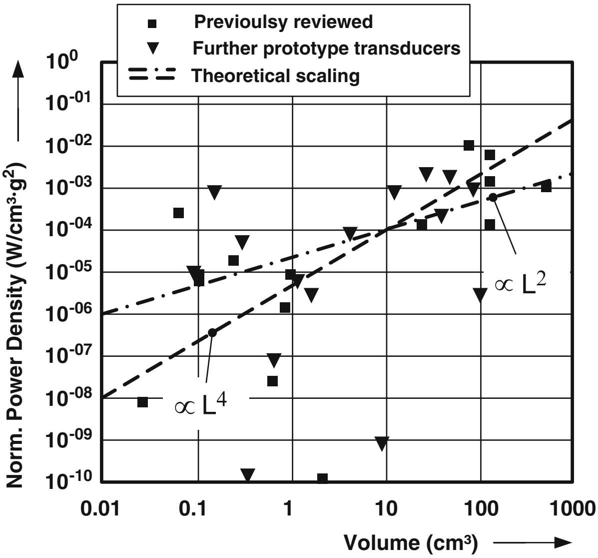

Fig. 1.6 Normalized Power density of previous reviewed vibration transducer prototypes [27] supplemented by transducers reviewed in this book. The *dashed curves* indicate the theoretical scaling

input energy which opens up the possibility for absolute comparison (Fig. 1.6). Even though there are orders of magnitudes between the absolute values of the normalized power density the theoretical scaling law is evident. The diagram has been supplemented with some of the prototype developments reviewed in this book (Table 1.1). At very small dimensions electromagnetic vibration transducers scale

Table 1.1 Comparison of vibration transducer prototypes from the literature review

References	Volume (cm^3)	Resonance frequency (Hz)	Amplitude (g)	Power (W)	Power density (W/cm^3)	Normalized power density ($W/cm^3 g^2$)
U. Barcelona [14]	1,8[a]	385	2.98	$5.5 \cdot 10^{-5}$	$3.1 \cdot 10^{-5}$	$3.4 \cdot 10^{-6}$
U. Florida [67]	42[a]	66.7	1	$1.3 \cdot 10^{-2}$	$3.0 \cdot 10^{-4}$	$5.5 \cdot 10^{-4}$
U. Hong Kong [81]	85	42	21	$3.5 \cdot 10^{-2}$	$4.1 \cdot 10^{-1}$	$9.3 \cdot 10^{-4}$
TU. Dresden [34]	1.17	16	5.14	$2.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$6.5 \cdot 10^{-6}$
U. Cork [17]	12.5	8	0.039	$1.5 \cdot 10^{-5}$	$1.2 \cdot 10^{-6}$	$7.7 \cdot 10^{-4}$
U. Freiburg [29]	4.4[a]	98	1	$3.6 \cdot 10^{-4}$	$8.1 \cdot 10^{-5}$	$8.1 \cdot 10^{-5}$
U. Virginia [26]	112	16	3.74	$5.5 \cdot 10^{-3}$	$4.9 \cdot 10^{-5}$	$3.5 \cdot 10^{-6}$
U. Shanghai [62]	0.31	280	1	$1.7 \cdot 10^{-5}$	$5.6 \cdot 10^{-5}$	$5.6 \cdot 10^{-5}$
U. Singapore [11]	10	369	7.67	$6.0 \cdot 10^{-7}$	$6.0 \cdot 10^{-8}$	$1.0 \cdot 10^{-9}$
HSG-IMIT [18]	0.68	390	9	$5.0 \cdot 10^{-6}$	$7.4 \cdot 10^{-6}$	$9.1 \cdot 10^{-8}$
Lumedyne [7]	27	57	0.24	$4.1 \cdot 10^{-3}$	$1.5 \cdot 10^{-4}$	$2.6 \cdot 10^{-3}$
U. Southampton [31]	0.1	1,615	0.4	$1.0 \cdot 10^{-7}$	$1.0 \cdot 10^{-6}$	$6.5 \cdot 10^{-6}$
U. Southampton [74]	0.1	52	0.59	$4.6 \cdot 10^{-5}$	$4.6 \cdot 10^{-4}$	$1.3 \cdot 10^{-3}$
U. Brno [83]	50[a]	18	0.5	$2.6 \cdot 10^{-2}$	$5.2 \cdot 10^{-4}$	$2.1 \cdot 10^{-3}$
U. Ankara [41]	0.38	5,135	74.23	$2.2 \cdot 10^{-7}$	$5.8 \cdot 10^{-7}$	$1.1 \cdot 10^{-10}$

[a] Volume estimated

with L^4 and large dimensions with L^2 ($L =$ linear dimension). The reason for this is that at small dimensions the unwanted parasitic (viscous) damping dominates the electromagnetic damping and vice versa.

A possible reason why the published prototype transducers have a significantly different output performance is due to the fact that many different electromagnetic coupling architectures have been applied. The different architectures may inherently have a different output performance capability. Moreover the dimensioning of the electromagnetic coupling architecture components is often based on simplified assumptions, experience, if not intuition. Hence, it may be assumed that many devices operate still well below their maximum possible output performance.

1.3 Conclusions from the Literature Review

Section 1.2 gives an overview on existing work that has been done in the field of electromagnetic vibration transducers. For this reason over 200 papers have been reviewed. The following conclusions can be drawn from this review:

- The existing transducers range from 0.1 to 100 cm^3 in size and from hundreds of nW to 100 mW in output power.
- Nearly all vibration transducers (commercial as well as research work) are based on the resonance phenomenon.
- The resonant vibration conversion is inherently limited to narrow band operation.

- The basic analytical theory is commonly known and it is applied to understand the influence of the most important system parameters on the output performance and to reproduce experimental data.
- The analytical theory has barely been involved in the design process where magnetic field calculations and nonlinear effects such as flux leakage, inner displacement limit, or stochastic excitation conditions must also be taken into account.
- Especially for micro scale devices the output voltage is often not sufficient for rectification based on standard techniques [13].
- There is a great interest to increase the operation frequency range using tunable devices [12]. The challenge is to power the actuators, control and application circuit at the same time. So far this could not be demonstrated.
- Many different electromagnetic coupling architectures have been applied. In the majority of cases the reason why a particular architecture has been chosen is not explained.
- The applied coupling architectures have yet not been compared and the question which of them performs best remains unanswered.
- The dimensioning of the most important components of the coupling architecture (magnet, coil and if existent back iron components) is often based on rough simplified assumptions, experience if not intuition.
- The comparison of the results presented in literature is rather difficult because a characterization standard does not exist. Consequently the devices are tested under different conditions (impulse excitation vs. harmonic frequency sweep vs. stochastic excitation, simple ohmic load resistor vs. matched load condition vs. complex load circuit, ...). Moreover important parameters are sometimes omitted (power respectively voltage response without the corresponding load resistance, plots in logarithmic scale where it is difficult to extract maximum values, volume is not denoted or it is not stated which components are encompassed, ...).
- In the research work the adjustment of the resonance frequency to an application specific vibration profile is often secondary. Usually the approach is to first build up the transducer and afterwards adjust the vibration to the resonance frequency of the transducer for experimental characterization. In application oriented developments one needs to go the other way round, which definitely brings further challenges in the design process.
- The applied interface circuits for electromagnetic vibration transducers are rather inefficient (typically a simple full wave rectifier with capacitor as storage element).

1.4 Book Objectives

Beside the limitation to narrow band operation (Appendix D) another basic challenge for electromagnetic vibration conversion is the fact that most of the existing vibration transducers operate well below their physically possible

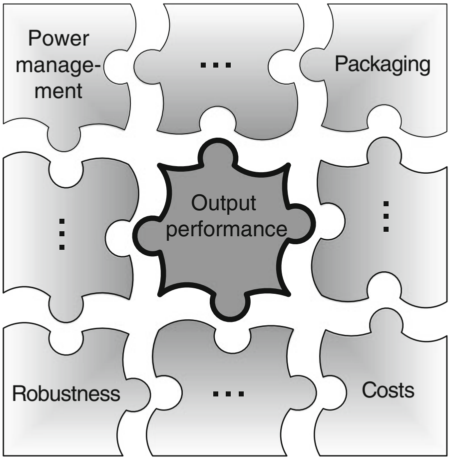

Fig. 1.7 As a vital key role in the design of vibration transducers this book focuses the optimization of the output performance

maximum power. This is because the applied coupling architectures have not yet been classified with respect to their maximum performance capability. Moreover the dimensioning of the most important coupling components (magnet, coil and if present back iron components) is neglected in the majority of cases. Consequently the objectives of this book are:

1. Develop a general optimization approach for the dimensioning of the electromagnetic coupling architecture components.
2. Apply the optimization approach to commonly used coupling architectures and determine the dimensions which maximize their output performance based on overall boundary conditions.
3. Compare and classify the maximum output performance of the electromagnetic coupling architectures.
4. Confirm the integration of the optimization approach in the design flow of an application oriented prototype development of a resonant electromagnetic vibration transducer.

Note that in general different objectives may be taken into account in the optimization process of vibration transducers (Fig. 1.7). However, this book focuses on the optimization of the output performance in terms of the output power and the output voltage. Other aspects like the complexity of the construction or the costs are not considered. They may be taken into account after the technical optimization.