Chapter 2
From Specifications to Concept

This book is organized in a way that illustrates the full path of development of a real product, which, in its early stage, implies scientific research and the development of a prototype, starting from some requirements. Specifications are typically given by a customer or derived according to the target application. Discussions and agreement on specifications can represent an iterative process which develops in different ways for each case. Even though some specifications can be negotiated and refined, some other parameters, like technology, costs, and time-to-market, are particularly stringent in consumer markets projects. This chapter introduces how to 'translate' product specifications into the definition of a concept with its blocks specifications and proposes a possible flow and methodology for the development of a magnetic field sensor. The proposed case is based on the development of a Z-axis Lorentz force-based MEMS magnetometer but the methodology is meant to be applicable to the development of other types of sensors.

2.1 Development Steps and Methodology

In projects with a relatively short-time development, i.e., projects for consumer market, it is important to have a solid and wide overview of all possible implementations and to target the most suitable one from the beginning, minimizing the risk of changing approach and design strategies half way in the process. Indeed this would cause a delay in the development of the project which is typically not compatible with the time-to-market of consumer products. According to author's experience, as far as the phase "from specifications to concept" is concerned, main steps for a successful and solid development are here listed and they will be discussed in chapters of this book:

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1. Analysis of requirements and specifications.
2. Study of suitable transduction principles.
3. Research about the state of the art.
4. Study and development of theoretical background (if needed).
5. Identification of a feasible concept.
6. System level design based on the chosen concept.
7. Translation of product specifications into block specifications.

System level design is discussed in Chap. 4; subsequently in Chap. 5 the following steps about device design will be shown.

2.2 Specifications for Consumer Applications

Electronic compasses integrated in mobile devices are used for orientation, positioning, and navigation applications. Thus, the measurement of earth magnetic field components along three directions is required to precisely determine magnetic field vector in device operating position. Three axes are important to make the portable device orientation-independent. If the magnetic field lays in the plane of the handheld device, then the compass heading could be computed from the inverse tangent of the ratio of the two horizontal magnetic field components. The third axis avoids that users have to keep the device at a leveled position. Moreover, accelerometers, which are usually integrated in the same IMU with magnetometers, are used to implement a tilt-compensated compass [1, 2].

Main requirements for mentioned portable compasses are

1. Adequate sensitivity and resolution to measure earth magnetic field. Figure 2.1 reports earth field total intensity.
2. Linear full scale range: even though earth maximum magnetic field magnitude can reach about 100 μT, it is important to have a much higher full scale range to cope with local high magnetic field. For example, in presence of vehicles or other ferromagnetic sources in the surroundings of the mobile device, a stronger magnetic field should not saturate the compass to allow a proper detection of earth magnetic field.
3. Low power consumption, a crucial parameter in battery-hungry portable devices.
4. Small package size for the integration in portable devices. The trend is to integrate a compass with other inertial sensors in one single package.
5. Low operating voltage; a typical operating voltage for standard CMOS circuits available in portable devices is 1.6–3.6 V.
6. Compatibility with standard fabrication processes to optimize mass production costs.
7. Audio bandwidth EMC: immunity to disturbers in audio bandwidth to avoid coupling mechanisms and crosstalk from microphones, speakers, and MP3 players. Immunity must be ensured not only for electrical aggressors but also to prevent coupling to propagated mechanical waves.

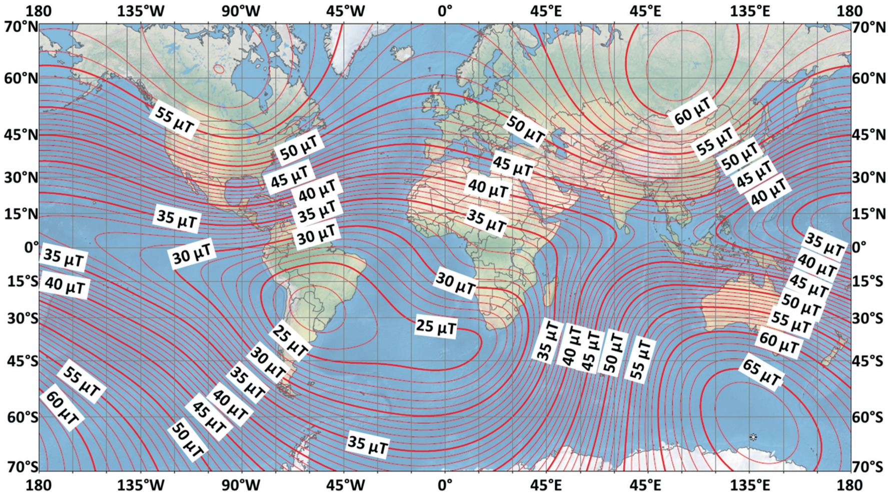

Fig. 2.1 Mercator projection chart showing main field total intensity. Contour interval: 1000 nT. Map developed by NOAA/NGDC & CIRES; http://ngdc.noaa.gov/geomag/WMM; map reviewed by NGA and BGS. Published December 2014. Courtesy of NOAA National Centers for Environmental Information

Table 2.1 Main specifications for a prototype of a *Z*-axis magnetometer for consumer applications

Magnetometer specifications	
Voltage supply	1.6–3.6 V
Total current consumption	300–400 μA
Bandwidth	< 50 Hz
Full scale linear range	± 100 μT
Resolution	< 1 μT ($\sim 2°/3°$)
Resonance frequency	$f_r \geq 20$ kHz
Pressure	Standard industrial packaging
Architecture	Multi-chip
MEMS active area	<1 mm $\times$ 2.5 mm
ASIC size	<2 mm^2

8. Operating bandwidth according to applications: typically in the range of a few tens of Hz.
9. Calibration to compensate for production spread.

Specifications are reported in Table 2.1.

2.3 Choice of Transduction Principle

The development of this prototype is based on Lorentz force transduction principle because of its main advantage, compared to other transduction principles, to detect magnetic field: indeed no specialized magnetic materials are required, being a key factor for an implementation with any standard micromachining technology. Additionally, compared to Hall effect-based sensors, which are commercially available and used in smartphones, they do not suffer from magnetic hysteresis and do not need flux-concentrator.

2.3.1 Lorentz Force Transduction Principle

Several works on MEMS magnetometers based on Lorentz force transduction principle are presented in scientific literature (see Sect. 2.4). In all these devices, in presence of a magnetic field B, a driving current I, flowing in a suspended structure orthogonally to the direction of B, determines a force in a direction orthogonal to the plane of both B and I: $\mathbf{F_L} = i\mathbf{l} \wedge \mathbf{B}$. The magnitude of the resulting force on a suspended mass is given by:

$$F_L(t) = I(t) \cdot l \cdot B(t) \;, \tag{2.1}$$

l being the effective length where the Lorentz force acts. Figure 2.2 shows a clamped–clamped beam, the simplest suspended element to have a flow of current. If a current flows through this suspended structure and an external magnetic field is present, this beam moves according to arrows reported in Fig. 2.2.

2.3.2 Position Sensing Techniques

Though the induced motion can be sensed in different ways (e.g., through the change of resistance in piezoresistors [3, 4], using optical techniques based on microlasers

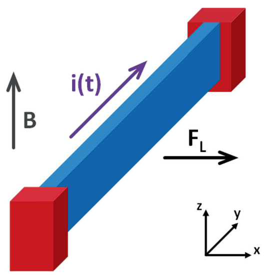

Fig. 2.2 Schematic view of the Lorentz force principle acting on a suspended clamped–clamped beam

[5, 6] or through the change in the resonance frequency of suitably designed resonators [7]), a very popular position interface is represented by capacitive readout [8]. Piezoresistive sensing allows a very high level of miniaturization with good sensitivity but they suffer from noise of piezoresistors and, at least, a dedicated lithography step is needed. Optical sensing is good for out-of-plane measurements, allows measurements with high resolution but it requires the integration of an optical source (typically a laser), a photodetector, and the deposition of some dedicated materials. Therefore this readout technique results in a more expensive and complex system. On the other hand, capacitive readout is easy to be integrated with a standard process because a basic cell can be built simply by facing two structures of polysilicon, either in a vertical or a horizontal orientation. Among other advantages of capacitive readout are its stability over temperature and process corners and no intrinsic sources of noise. Yet, the main drawback is given by electrostatic forces and their dependencies on biasing conditions; more details are given in Sect. 3.1.2.

Additional details about magnetometers working principle and capacitive readout focusing on the specific device architecture developed during this project are reported in Sect. 3.2.

2.4 State of the Art

Many reports and reviews about magnetic sensors and their applications are available in the scientific literature [9, 10]: the purpose of these papers is mainly to provide readers with an introduction to all existing and more common magnetic field transduction techniques together with some technological aspects and applications they are intended for. A more specific overview of resonant magnetic field sensors based on MEMS technology is given by Herrera-May et al. [11].

In this section some recent[1] and/or significant scientific works are reported focusing on papers dealing with Z-axis magnetometers. The purpose of this brief scientific literary review is to identify some solutions which are already available at the time when the development of a new prototype begins. Both mechanical element and circuitry are considered and it is a good practice to compare their performance with given specifications. After a short introduction to each work, highlighting its main characteristics, a table sums up more important parameters to consider as a reference for this project. Works are introduced following chronological order of publication.

A first example of a Lorentz force magnetometer based on MEMS technology with capacitive sensing was presented by Emmerich and Schöfthaler [12], Emmerich et al. [13] of the Sensor Technology Center (STZ) of Robert Bosch GmbH, Reutlingen, Germany in 1999. The proposed mechanical element, operating at resonance to exploit Q-amplification, consists of a central beam with parallel-

[1] At the time research activity behind this book began.

plates electrodes, suspended by four folded spring. A thin layer of aluminum is deposited on top of moving structure to reduce electrical resistance and to provide a constant voltage across all movable fingers minimizing attractive forces which arise from electrical potential difference between fixed and movable electrodes. The device has an area of 1300 μm × 500 μm with 32 electrode fingers and it is implemented using Bosch standard surface micromachining [14] and packaged with a nominal pressure of 1 mbar. Experimental results are provided using discrete components electronics for capacitance to voltage conversion and device driving. There are not any specific details about power consumption of the overall system (even though current flowing in mechanical element is known).

This work represents a significant reference since the used technology is very similar to one available for the development of prototypes shown in this work (details are given in Sect. 5.2.1); Bosch technology has the main advantage of metal deposition on top of released structures. Resonance frequency of this prototype, about 1.3 kHz, is definitely lower than specifications given for this project.

A second prototype of magnetometer was published in [15] by Izham et al. of University of Birmingham in 2003. Even though resonance frequency of about 9 kHz is not so lower than the specification for this project, intrinsic current consumption of 29 mA per spring is by far out of specifications. Moreover, the paper does not give any details about electronics and so no overall system considerations are provided in this paper.

A third example concerning both out-of-plane and in-plane Lorentz force magnetometers was proposed by Kyynäräinen et al. [16] of the Technical Research Centre of Finland, in 2008. They integrate micromechanical sensing elements for all three axes in one silicon chip using a process which allows metal deposition on top of moving structures. The specific element proposed for out-of-plane field detection is based on a double-ended tuning fork architecture, working at resonance with high quality factor (about 10,000 for pressure in the range 10–100 μbar). The peculiarity for this implementation is the use of multi-turn excitation coils: on top of one single released element many metal paths (either 5 or 10 for Z-axis sensitive element) for current are deposited enhancing the sensitivity without increasing power dissipation. Resonance frequencies for these devices are around 50 kHz, satisfying the requirement to work out of the audio bandwidth. On the other hand, such a high Q-factor limits mechanical bandwidth to about 5 Hz with a consequent longer settling time when the device is switched on.

A fourth paradigmatic example of a parallel-plates magnetometer was proposed by Thompson and Horsley [17] working at Mechanical and Aerospace Engineering at University of California, Davis in 2009. Their first prototype, fabricated using SOIMUMPS foundry process (MEMSCAP Inc.), operates at resonance frequency ($f_r = 8468$ Hz) at ambient pressure. The architecture of the device is close to the first introduced and folded springs are chosen to allow for longitudinal expansion without stress accumulation. The main drawback of using folded flexures results in reduction of effective Lorentz force. A larger occupied area of about 2200 μm × 700 μm could also be explained because the used process does not have an interconnect layer to route differential capacitors cells.

Table 2.2 List of more recent and/or significant scientific works about *Z*-axis magnetometers

Z-axis Lorentz force magnetometers								
Work	Area (μm × μm)	I (mA)	Noise ($\mu T/\sqrt{Hz}$)	BW (Hz)	Mass (μg)	Q (–)	f_r (kHz)	k (N/m)
Emmerich and Schöfthaler [12]	1300 × 500	0.93	0.20	10[a]	3.6	37	1.3	0.24[a]
Kyynäräinen et al. [16]	2000 × 400	0.1	0.07	2[a]	12[b]	10,000[c]	50	250[b]
Thompson and Horsley [17]	2200 × 700	2.6	1.01	87[a]	6.8	48.8	8.5	19.5
Li et al. [21]	1000 × 200[d]	0.4	0.14	7	0.82[a]	1400	20.55	13.7

For each work many parameters are reported, particularly the noise density performance with respect to the active area of the sensing element, the dissipated current, and the maximum signal bandwidth

[a]Deduced from other parameters given in the paper

[b]Kindly provided by the authors

[c]At a pressure ~ 0.01 mbar

[d]Full size for a 2D sensing element

The same authors also proposed an external solution to boost quality factor, known as *parametric amplification*. It consists of a modulation of the elastic stiffness at twice the natural frequency [18]. As a consequence, there is an increase of the oscillation amplitude at the device resonance frequency and thus an increase of Q. A MEMS resolution is limited by a mix of electronic and mechanical noise and the reduction of electronics noise can be achieved at the cost of increasing the biasing current of the preamplifier and so the power consumption. When micromechanical sensors performance is limited by electronic noise, parametric amplification can improve the system signal to noise ratio because the equivalent noise force resulting from electronic noise is inversely proportional to the force sensitivity. The main drawback is that it requires additional circuitry to drive the spring stiffness [19].

The same research group presented a second generation of devices in [20] and in [21], whose resonance frequency is pushed to higher frequency outside audio bandwidth.

A summary of main parameters and features of considered papers about Lorentz force magnetometers is reported in Table 2.2.

References

1. STMicroelectronics, *AN3192 Application Note. Using LSM303DLH for a Tilt Compensated Electronic Compass* (2010)
2. T. Ozyagcilar, *AN4248 Application Note. Implementing a Tilt-Compensated eCompass using Accelerometer and Magnetometer Sensors*. Freescale Semiconductor (2012)
3. V. Beroulle, Y. Bertrand, L. Latorre, P. Nouet, Sens. Actuators, A **103**(1–2), 23 (2003). doi:10.1016/S0924-4247(02)00317-5. http://www.sciencedirect.com/science/article/pii/S0924424702003175

4. P. Robert, V. Nguyen, S. Hentz, L. Duraffourg, G. Jourdan, J. Arcamone, S. Harrisson, in *2009 IEEE Sensors* (2009), pp. 963–966. doi:10.1109/ICSENS.2009.5398195
5. F. Keplinger, S. Kvasnica, H. Hauser, R. Grossinger, IEEE Trans. Magn. **39**(5), 3304 (2003). doi:10.1109/TMAG.2003.816753
6. F. Keplinger, S. Kvasnica, A. Jachimowicz, F. Kohl, J. Steurer, H. Hauser, Sens. Actuators, A **110**, 112 (2004). doi:10.1016/j.sna.2003.10.025
7. A. Tocchio, A. Caspani, G. Langfelder, IEEE Sensors J. **12**(6), 1719 (2012). doi:10.1109/JSEN.2011.2177657
8. G. Langfelder, T. Frizzi, A. Longoni, A. Tocchio, D. Manelli, E. Lasalandra, Sens. Actuators, A **167**(2), 374 (2011). doi:10.1016/j.sna.2011.02.003
9. J. Lenz, S. Edelstein, IEEE Sensors J. **6**(3), 631 (2006). doi:10.1109/JSEN.2006.874493
10. D. Robbes, Sens. Actuators, A **129**(1–2), 86 (2006)
11. A.L. Herrera-May, L.A. Aguilera-Cortés, P.J. García-Ramírez, E. Manjarrez, Sensors **9**(10), 7785 (2009)
12. H. Emmerich, M. Schöfthaler, IEEE Trans. Electron Devices **47**(5), 972 (2000). doi:10.1109/16.841228
13. H. Emmerich, M. Schöfthaler, U. Knauss, in *MEMS'99. Twelfth IEEE International Conference on Micro Electro Mechanical Systems, 1999* (1999), pp. 94–99. doi:10.1109/MEMSYS.1999.746759
14. M. Offenberg, F. Larmer, B. Elsner, H. Munzel, W. Riethmuller, in *The 8th International Conference on Solid-State Sensors and Actuators, 1995 and Eurosensors IX. Transducers'95*, vol. 1 (1995), pp. 589–592. doi:10.1109/SENSOR.1995.717293
15. Z. Izham, M. Ward, K. Brusnon, P. Stevens, in *Nanotech 2003*, vol. 1 (2003)
16. J. Kyynäräinen, J. Saarilahti, H. Kattelus, A. Kärkkäinen, T. Meinander, A. Oja, P. Pekko, H. Seppä, M. Suhonen, H. Kuisma, S. Ruotsalainen, M. Tilli, Sens. Actuators, A **142**(2), 561 (2008). doi:10.1016/j.sna.2007.08.025
17. M. Thompson, D. Horsley, in *2009 IEEE Sensors* (2009), pp. 992–995. doi:10.1109/ICSENS.2009.5398216
18. M. Thompson, D. Horsley, in *TRANSDUCERS 2009. International Solid-State Sensors, Actuators and Microsystems Conference, 2009* (2009), pp. 1194–1197
19. L. Grasser, H. Mathias, F. Parrain, X.L. Roux, J. Gilles, in *Design, Test, Integration & Packaging of MEMS/MOEMS* (2007)
20. M. Thompson, M. Li, D. Horsley, in *2011 IEEE 24th International Conference on Micro Electro Mechanical Systems (MEMS)* (2011), pp. 593–596. doi:10.1109/MEMSYS.2011.5734494
21. M. Li, V. Rouf, M. Thompson, D. Horsley, J. Microelectromech. Syst. **21**(4), 1002 (2012). doi:10.1109/JMEMS.2012.2196493

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