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MAGNETIC EFFECTS IN PHYSICAL SENSOR DESIGN AND DEVELOPMENT

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In this paper we present a review on magnetic effects used for physical sensor applications. First, we illustrate the two key parameters affecting the response of any magnetic device, which are the domain wall dynamics and the domain rotation dynamics, introducing the corresponding materials and the required tailoring processes. Then, we illustrate the physical sensors based on magnetic effects and materials such as position, mass, field, security and derivative sensors. Finally, we try to give an algorithm, according to which an engineer is able to develop a magnetic sensor, starting from the requirements of measurement and the material development & tailoring, up to the sensor housing, discussing also the future trends in magnetic sensor design.

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1. Introduction

Sensors and transducers have an increasing interest because of their importance in many technological applications. As an example, all modern vehicles and transport means use a wide variety of sensors and transducers. The operation of all medical instruments is also based on sensors. Industry is also employing more and more transducers for the monitoring and control of production lines.

In the literature one can find many ways of categorizing sensors [1]. We use three principles for such categorization. The first principle concerns what a sensor can measure, the most significant divisions being physical and chemical sensors: physical sensors are detecting position, mass, current, time and relative sizes whereas chemical sensors detect the presence of different gases in a given atmosphere. The second principle is related to the physical phenomenon and materials the operation of the sensor is based on, the main categories being conducting, semiconducting, dielectric, magnetic and superconducting sensors. Finally, the third principle tells where the sensor can be used, the main categories being industrial, transport, automotive, medical, military, domestic and environmental sensors.

In this paper we wish to illustrate the magnetic effects used in physical sensors design and the corresponding applications. Bearing in mind that magnetic effects and materials can be mainly used in physical sensor applications, we firstly provide a rather short introduction to the main magnetic effects, governing the behavior of magnetic devices and sensors, which are the domain wall dynamics and the domain rotation dynamics. Their careful control determines the predictable response of any magnetic sensor. Introducing these mechanisms, we present the corresponding magnetic effects and the required properties of the materials used for each case. One of the key-point in sensors design based on magnetic effects and materials is the hysteresis on their response. Thus, we introduce principles of tailoring the hysteresis loop with respect to applications. We conclude that, in physical sensor design it is important to eliminate hysteresis, while the opposite occurs for read & write process, where a clear hysteresis is required.

Consequently, we illustrate the main families of sensors based on magnetic effects. Taking into consideration that the magnetic effects are by definition used for physical sensors, we present position, mass, field and derivative sensors. Additionally, we describe the security and smart sensors.

Then, we focus on the main applications of sensors based on magnetic effects, mainly on the most important category which is represented by field and position sensors.

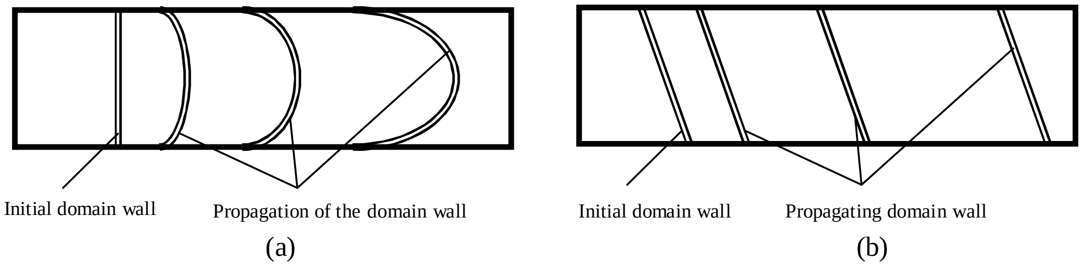
At the end, we try to give a methodology, according to which one can develop step by step a sensing element based on a magnetic effect, starting from the problem determination, concerning the specifications of the measurement, up to the sensor housing techniques. Finally, we discuss the future in magnetic sensors and give our opinion in what is important in the near future.

2. The main magnetic effects

The dynamics of magnetic domains is the main mechanism responsible for magnetic effects able to be used in sensing applications. Any possible use of the dynamic response of this mechanism can result in a sensing element. There are two distinct cases of domain dynamics, one being the domain wall dynamics and the other domain rotation dynamics. There also exist dependent effects derived from these dynamics, both macroscopic and microscopic. In the following we shall present the domain wall dynamics, the domain rotation dynamics as well as the macroscopic and microscopic dependent mechanisms. These effects shall be illustrated bearing in mind that a key parameter in magnetic sensors is the hysteresis in their response. Hysteresis should be negligible in given applications like mechanical and field sensors in order to improve the uncertainty level of the sensors, but it should be heavily present in other applications like security sensors to improve the stability of stored information.

2.1. Domain wall dynamics

The dynamics of domain walls and their corresponding use in sensor applications concern their nucleation and mobility or propagation in the magnetic substance. There are two cases of domain wall propagation [2]: the blowing process and their parallel motion. The mode of propagation depends on the energy stored in these walls. Low energy walls propagate in blowing as shown in Fig. 1(a) - simulating the behavior of a liquid -, while high energy walls propagate parallel as shown in Fig. 1(b).



(a) (b)

Fig. 1. Domain wall dynamics: (a) blowing domain wall motion; (b) rigid domain wall motion.

There are two main reasons for high-energy storage in domain walls: the one is based on the pinning effects of magnetic dipoles and the other on the presence of defects in the material structure. Since defects can occur in both soft and hard magnetic materials, it can be said that the blowing process is more likely to occur in low pinning materials which are the soft magnetic materials, while the parallel motion occurs in the hard ones.

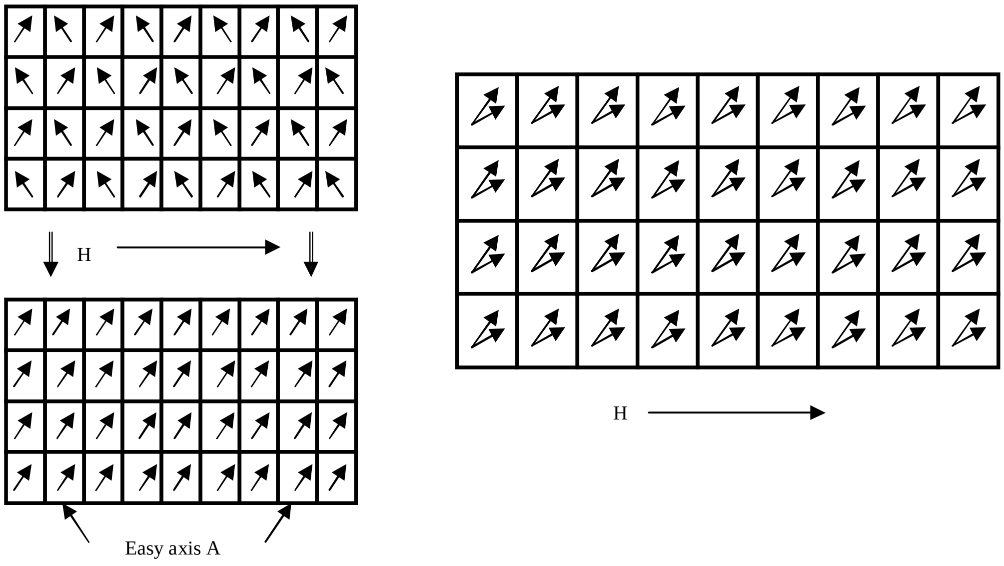
The reversibility of the domain wall propagation defines the presence or not of hysteresis in the sensing element. Such reversible process depends mainly on the defects existing in the magnetic substance as well as on the pinning effect of magnetic dipoles. There are cases where a magnetic device should have negligible hysteresis. As an example we refer to physical sensors where absence of hysteresis improves the uncertainty of the sensor response. But, there are also cases where the magnetic device should have a large hysteresis effect like in recording surfaces used for security sensors. Domain wall dynamics are used for small field measurements as well as for mechanical sensors based on small field measurements.

Therefore, a sensor designer should tailor the magnetic material with respect to the application in request. If the case is a sensor based on domain wall propagation with a hysteresis in the minimum possible amplitude, then, the material should include as less as possible defects and be as soft as possible. This is controllable by the composition of the material targeting coercive fields of the order of 10 mOe, as well as by the annealing process of the material to minimize the internal stresses, which affect the above-mentioned defects. In this case the material should have low magnetostriction and correspondingly low magneto-elastic response to avoid cross-talking effects with probably uncontrollable magneto-elastic waves. One can fulfill both requirements by using FeCoSiB wires with magnetostriction in the range of 0.1 ppm, after thermal annealing and/or magnetic field annealing. The use of the magnetostrictive materials may result in high levels of Barkhausen noise. Typical temperature conditions are in the range 30-60^{o}C/min for rising temperature, steady state conditions of 300-750^{o}C for 10 – 60 minutes and finally natural cooling in Ar atmosphere for about 12-24 hours. Typical field conditions are 800 – 8000 A/m in the easy axis direction. Another technique, which is also used, is the stress – current annealing, with typical values of tensile stress and current of 100 – 500 MPa and 100 – 300 mA, respectively.

In the contrary, in security sensors the pinning defects or the controllable introduction of defects on the surface of the material can result in a significant improvement of the sensor stability.

2.2. Domain rotation dynamics

The domain rotation dynamics have two distinct areas of operation: the irreversible and the reversible area of operation. The irreversible rotation occurs when the magnetic domains, which are oriented on a given easy axis, A, re-orientate to another easy axis, B, closer to the axis of the external field H, due to the presence of this field [3], as shown in Fig. 2(a). The reversible domain rotation occurs after the irreversible rotation process or domain swift. Since the new easy axis B is not in general the same with the axis of the external field H, the magnetic dipoles tend to orientate to the axis of the external field H, as shown in Fig. 2(b). After the removal of the external field, the rotated magnetic domains return back to the easy axis direction B, where they have been initially and irreversibly re-orientated. In general, magnetic domains do not return back to their initial easy axis A.



a) b)

Fig. 2. Magnetic domain dynamics: (a) two distinct axes of anisotropy and consequent irreversible rotation due to the presence of the magnetic field; (b) reversible magnetic domain rotation after the irreversible magnetization process.

Both reversible and irreversible processes are associated with the presence of magnetostriction. The dynamic behavior of these processes can result in elastic waves, propagating along the magnetic material. The irreversible process is additionally responsible for the small or large Barkhausen jumps, introducing magnetic noise in the sensing element. The presence of the irreversible processes in hysteresis result in magnetic rotation as well as in a relatively higher level of noise with respect to the reversible processes. Both hysteresis and noise affect the uncertainty of any possible magnetic device used for sensor application.

Therefore, if the target is the development of a sensor, where the hysteresis and noise should be minimized, only the reversible area of domain rotation should be used. In the contrary if the target exhibits high hysteresis then the irreversible area of the domain rotation should be used, although the Barkhausen noise co-existing in this process would suggest use of domain wall propagation techniques rather than irreversible domain rotation. Domain rotation effect has mainly found applications in the field of mechanical sensors.

Thus, a sensor designer using the effect of domain rotation should tailor the magnetic material in order to minimize the amplitude of the external field responsible for the irreversible rotation process and correspondingly maximize the external field range for reversible rotation. This means that the material is tailored with respect to its magnetostriction function or λ – H loop. The magnetostrictive materials used for this effect can be found in the form of thin films, ribbons and wires. The amorphicity of the used magnetostrictive material helps in the minimization of the irreversible rotation processes, due to the minimization of the coercive field and the field range responsible for the irreversible domain rotations. Probably, the recently developed nanocrystalline materials can further reduce the hysteresis of the irreversible domain rotation, provided that they can exhibit magnetostriction. Annealing techniques can also be used in this case, not only to eliminate the defects existent in the material, like in domain wall dynamics, but also to re-orientate the magnetic easy axis in such direction to eliminate the irreversible swift process of the domain rotation. Elimination of the irreversible process takes place simply due to the absence of easy axis direction close to the external field, H. For this case the magnetic field in the field annealing should be perpendicular to the easy axis of the material. The magnitudes of temperature and field are similar as in the case of domain wall dynamics.

2.3. Dependent mechanisms

Having already described the domain wall and domain rotation dynamics, we can now see the other dependent magnetic effects. These effects can be measured and used as macroscopic properties of the material, namely electrical and magnetic properties, but they are based on microscopic effects.

The most well-known and used effect is the magneto-resistance effect [4], observed mainly in magnetic thin films. According to this effect, the DC electrical resistance of a magnetic film changes about 2-3 %, with respect to the applied magnetic field, due to the magnetic domain rotation and in some cases due to domain wall nucleation. The most significant magneto-resistive effect, named “giant” magneto-resistive effect, appears in some magnetic multi-layers, with resistance changes up to 50-80 % at room temperature, due to the perpendicular anisotropy of the magnetic layers causing perpendicular domain rotations. Recently, the “colossal” magneto-resistive was observed in magnetic oxides, offering even larger changes of resistance, but in cryogenic environments. The magneto-resistance effect is mainly used in field sensors and recording media applications.

Another effect, which has also found applications, is the AC magneto-resistance effect or magneto-impedance effect. According to this effect, the AC resistance or impedance of a magnetic substance varies with the applied field [5]. This effect also exists in non-ferromagnetic materials due to the skin effect, although its amplitude is much smaller than in ferromagnetic materials. In some zero-magnetostrictive wires, which exhibit circumferential magnetic anisotropy, the magneto-impedance changes more than 100 % with respect to the applied external field. Although this effect has recently been studied, it has already been used in industrial and automotive applications due to its great sensitivity with respect to magnetic field.

Recently, another effect attracts the interest of the field sensor domain and more importantly, the recording media market. This is the spin valve effect [6], according to which an especially designed magnetic arrangement exhibit non-monotonic B-H response. This property allows very well localized field measurements with an acceptable accuracy.

Apart from these rather recently observed effects, the classical inductive effects based on the linear variable differential transformer (LVDT) principle, used in fluxgate set-ups [7] for accurate field detection and other mechanical measurements (mainly displacement) are well known for years in the global sensor market. Apart from these magnetic effects, there are other relatively close electromagnetic effects able to detect fields such as the Hall effect, the quantum Hall effect and the SQUID.

From this short presentation of the main magnetic effects used for sensor applications, it can be seen that except magneto-elasticity, which is used for direct detection of mechanical sizes, the main sensing application of magnetic effects and materials is magnetic field detection. Detecting field, one can transfer the measurement in another physical size, like displacement, stress, flow etc. In the next we shall focus our attention on the use of the above-mentioned magnetic effects for the development of sensing elements.

3. Sensor arrangements

The various magnetic effects and materials described in the previous chapter have been used as the core of many sensing elements. These sensing elements are divided into five distinct families of physical sensors and are presented next. As it will be shown, most of them are based on field dependence devices. We start the presentation with the position sensors and the mass sensors, continuing with the field sensors, which cover the largest percentage in the global sensor market. We continue with the read and write sensors, which do not concern recording media only, but also security sensors therefore deserving a short demonstration. Multipurpose sensors are more and more important in applications, especially in the form of smart sensing elements.

3.1. Position sensors

Position sensors have a relatively large percentage in the global sensors market. We can divide the position sensor family in three main subcategories: the terminating switches; the absolute, differential & angular sensors and finally the velocity sensors and accelerometers.

The terminating switches are simple field sensors with a threshold checker operating like on-off switch [8]. Their vast majority are magneto-resistive sensors, since the cost of production of poor quality and mass production elements is small. Their main competitor is the capacitive switch based on capacitance change.

The second subcategory includes absolute, differential & angular sensors. Absolute sensors are able to detect the absolute distance between two points. These two points are usually the exciting and detecting means. Examples of absolute position sensors are the magnetostrictive delay lines (MDL) set-ups [9], which combines time delay detection and voltage modification, the linear variable differential transformer (LVDT) [10] and a linear inductive sensor using closed magnetic paths [11], as shown in Fig. 3(a), (b) and (c), respectively. Their sensitivity and uncertainty can reach 10 μm and 100 μm/m, respectively. Their cost is of the order of 0.1 kEuro/sensor. All of them can be cordless devices. Their competitor is the ultrasonic position sensor which is less expensive but less accurate too.

Differential position sensors are able to detect the traveling distance of the sensing head and not the absolute position. The most important differential position sensor based on magnetic effects materials is the magnetic tape (Fig. 3(d)). A magnetic head reads the flux as it passes on top of a tape [12]. This tape is a corded device and is constructed from a series of hard magnets arranged in up and down orientation of magnetization. The sensitivity and uncertainty of these sensors can be of the order of 1 μm and 10 μm/m, respectively. Their cost is of the order of 1 kEuro/meter. Their competitor is the optic tape, which has similar properties.

Angular sensors can be either absolute or differential. The most classic sensor is the rotating tooth (Fig. 3(e)), which is a differential sensor used in many important applications like ABS in cars. As the disk holding the magnetic teeth is rotating, a magnetic head counts them by means of a series of pulses. Interesting angular sensors based on inductive and magnetic techniques, have also been proposed in the past [13].

Velocity sensors and accelerometers are based either on calculation of the response of absolute or differential position sensors, or detect directly velocity or acceleration. Although most of the velocity sensors or accelerometers are based on calculation process, the development of accelerometers is of interest. A simple velocity meter or accelerometer can be an inductive sensor using an inertia magnetic mass, moving on top of a coil. The motion of the magnetic mass introduces a change in the magnetic flux of the coil. An accelerometer based on the MDL technique has been also proposed in the past, using the change of the flux in the delay line caused by the dynamic motion of a permanent magnet [14].

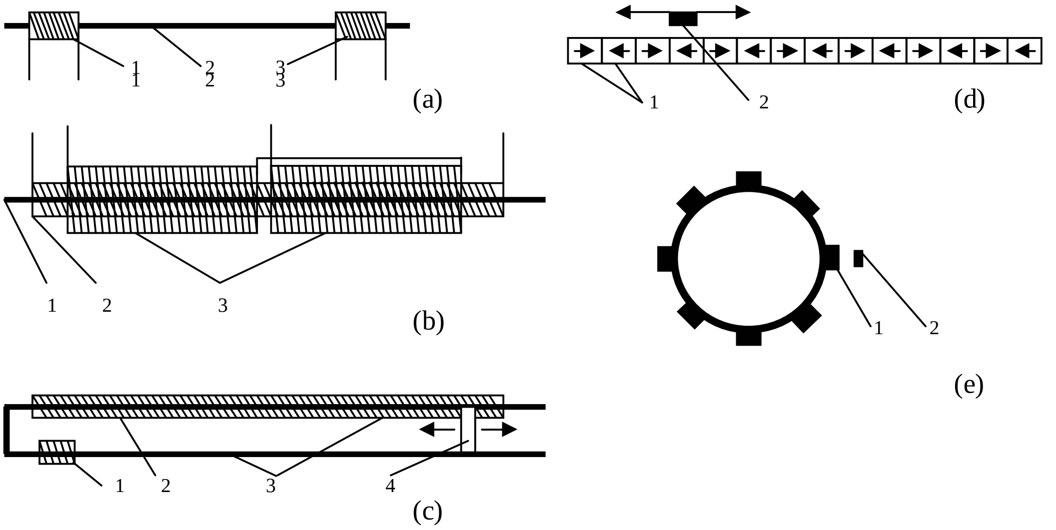


Fig. 3. Position sensors based on magnetic effects: **(a)** Magnetostrictive delay line (MDL) set-up. (1) Movable excitation coil, (2) MDL, (3) Movable search coil; **(b)** Linear variable differential transformer (LVDT) set-up. (1) Soft magnetic material, (2) Excitation coil, (3) In series opposition search coils; **(c)** Inductive set-up. (1) Search coil, (2) Excitation coil, (3) Soft magnetic material, (4) Movable magnetic element, closing the magnetic circuit; **(d)** Permanent magnet type. (1) Permanent magnetic thin films, (2) Searching magnetic head; **(e)** Angular positioning sensor. (1) Radial permanent magnets in tooth arrangement, (2) Searching field sensor.

A special category of position sensors are the dilatometers, which are position sensors with very high sensitivity of the order of tens of nm and very low range of measurement of the order of microns. Typical examples of dilatometers based on magnetic materials are special designs of LVDT's, having as main competitor the capacitive dilatometers. All these devices can be either corded or cordless. Cordless sensors are more preferable for many practical reasons in many applications, the most important being the ease of use and the sensor life time.

3.2. Mass sensors

Mass sensors are divided into three main categories: the load cells, the pressure sensors and the torquemeters, having the flow meters and mass flow meters as a derivative sensing application. All these devices can be based on position or strain sensors detecting indirectly the applied stress. A classical example is the strain gauge. But, there are magnetic materials and corresponding arrangements, which can detect directly the applied stress and therefore the load, pressure and torque on them.

Load cells measuring directly tensile stresses are mainly based on inductive arrangements using as ferromagnetic core a material sensitive to tensile stress [15], as shown in Figure 4(a). Such a core is usually positive magnetostrictive material. The permeability decreases dramatically with stress, so that the output of the coil decreases correspondingly. Accelerometers can also be based on such arrangements. An MDL set-up has also been proposed in the past, using such stressed material coupled with the delay line [16]. Later, an MDL set-up has additionally been proposed, suggesting that direct stress on the MDL offers better levels of sensitivity and uncertainty [17], as shown in Fig. 4(b). Typical values of sensitivity and uncertainty of these devices are 10-100 ppm and 100-300 ppm respectively, with a cost of 1 kEuro/sensor.

Direct measurement of pressure has also been proposed in the past using the MDL set-up, where the pressure was directly measured on the delay line element [18]. The sensitivity and uncertainty of the device is 10 ppm and 100 ppm, respectively, with a cost of 1 kEuro/sensor. The monotonic and un-hysteretic response of this sensor had not found the way to the market, due to the large competition with the piezoelectric materials. Their cost of production is not comparable with the above-mentioned technique, despite the fact that the DC response of the MDL offers a clear advantage with respect to the state of the art.

Torque measurements have been realized by using pre-annealed magnetic materials under torsion. The magneto-impedance effect [19] and the MDL set-up have been proposed in the past as torque meters (Fig. 4(c)), both illustrating very competitive properties. The sensitivity and uncertainty of these devices was comparable and equal to 100 ppm and 1000 ppm, respectively, with a cost of 1 kEuro/sensor.

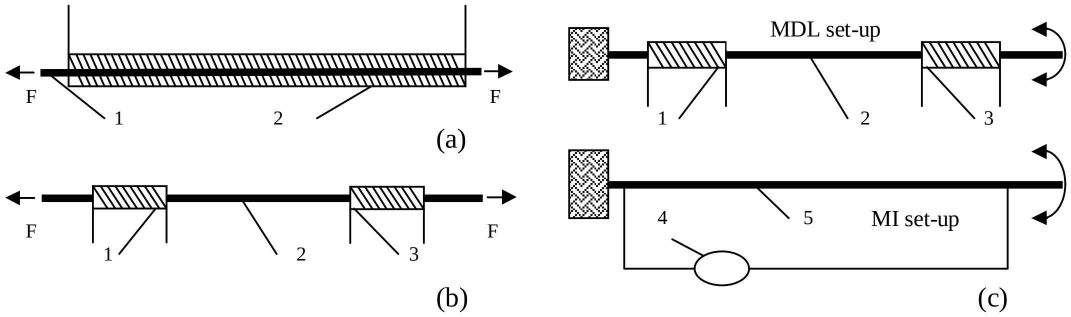


Fig. 4. Stress sensors based on magnetic effects: (a) Inductive sensors. (1) Soft magnetic element, (2) Inductive excitation coil; (b) MDL sensors. (1) Movable excitation coil, (2) MDL, (3) Movable search coil; (c) MDL and MI torque sensors. (1) Movable excitation coil, (2) MDL, (3) Movable search coil, (4) Sinusoidal excitation circuit, (5) MI element.

Flow sensors based on electromagnetic techniques are well known in industry. Recently, flow-meters have also been proposed, using the effect of bending stress on an amorphous wire [20].

3.3. Field sensors

This is probably the largest percentage in the magnetic sensors market. The most frequently used field sensors are the ones used for small field variations or field gradient or magnetic anomaly detection (MAD) [21]. The most important techniques and effects used to develop such field sensors based on magnetic materials are the magneto-resistance effect, the magneto-impedance effect and the inductive techniques like fluxgates. Magnetostriction has also been used in field sensing but only in special applications, as it will be seen later.

Historically, the inductive sensors based on magnetic materials, named fluxgates have been the state of the art in low field sensing and gradient field measurements [22]. Their principle of operation is based on differential inductive response of coils connected in series-opposition, obtaining levels of sensitivity and uncertainty of the order of 0.1 pT and 1 pT, respectively.

Magneto-resistance field sensors as described in the previous chapter, employ the multi-layer structure exhibiting vertical magnetic anisotropy of the ferromagnetic layers. These sensors are manufactured in mass production, facilitating thin film techniques, thus allowing low cost of manufacturing of the order of 10-100 Euro/sensor. Their sensitivity and uncertainty is of the order of 1 nT and 10 nT respectively, being better than the Hall effect sensors.

The recently discovered magneto-impedance (MI) effect in amorphous and nanocrystalline wires [23] allows much better levels of sensitivity and uncertainty, of the order of 1-10 pT and 100 pT, respectively. The cost of such device is of the order of 100 – 300 Euro/sensor. These good specifications allow the use of MI sensors in industrial and automotive applications, although their cost is relatively high in comparison to magneto-resistance sensors. Recently, a couple of research teams try to develop durable MI sensors on thin films for mass production reasons [24]. Generally, the problem in many magnetic thin film sensors is that the sensor characteristics become less attractive in comparison to the bulk sensing elements. Recently, an interesting combination of MI and fluxgate effect in thin film structure has shown promising results in two dimensional field measurements, by using amplitude and pulse width modulation techniques, offering sensitivity in the level of 1 pT [25]. Another magnetic technique takes advantage of the magnetostriction effect and the generated magneto-elastic waves in order to realize a distribution field sensor for non-destructive evaluation of magnetic surfaces [26].

All these sensors based on magnetic effects and materials have a major competition with respect to their performance. The SQUID sensors based on the Josephson effect, allowing single magnetic quantum measurement, is the today's absolute state of the art with sensitivity of the order of 1 fT.

3.4. Security sensors

The read & write sensors are split in two main categories: the recording media and the security sensors. The recording media, including both writing surfaces and reading heads is rather out of the scope of this article, despite the fact that the reading heads based on magnetic effects mainly employ giant MR sensors.

The security sensors are based on the combination of different magnetic properties, for example different B-H loops, in order to generate a code based on a series of magnetic signatures, which allows the recognition of an object without direct optical observation. This family of sensors can be used in applications where optical bar coding is impossible for practical reasons.

3.5. Multipurpose sensors

These sensors determine the so-called smart sensor family, which includes three different subcategories, the multi-parameter sensors, the self-learning sensors and the reacting sensors. The multi-parameter sensors are able to detect more than one physical size. An example is a magneto-elastic arrangement, based on negative magnetostrictive ribbons, which is able to detect field and stress at the same time. This occurs due to the fact that the pulsed output of the sensor is modulated only by amplitude due to the ambient field, while the pulse width is modulated only by the tensile stress. The self-learning sensors are related to their ability of self-calibration ability and the auto-scaling of the range of measurement. The reacting sensors are complete electromechanical systems, which are able to sense and consequently react with respect to the measurement. An example is a missile-driving sensor, which includes a precise field navigation sensor, which measures the direction of motion of the missile and a reacting system, changing the direction of the missile with respect to a pre-loaded order.

4. Sensor applications

The above-described sensing elements are used in a vast variety of applications. We are briefly introducing the main categories of such applications with respect to the used sensors.

4.1. Industrial applications

The main field in industrial applications is the non-destructive testing and evaluation (NDT&E) [27]. When magnetic materials are used as sensing elements they are mainly dedicated for eddy current technique (ECT) or magnetic anomaly detection (MAD) testing. Both sensing techniques require the use of small field sensors. The most commonly used sensors for this purpose are the Hall sensors, offering sensitivity of the order of 0.1 mT. The giant magneto-resistive (GMR) elements, offer an improved sensitivity of the order of 1 μT. Furthermore, the recently developed MI elements, offer a sensitivity of 10 –100 pT. The value of sensitivity reflects the ability of sensor to detect small field variations, which corresponds to the size of existing crack or defect. MDL sensing elements have also been proposed, being able to perform distribution measurements, despite their current disadvantage of poor sensitivity. The second more frequent field of industrial applications is the position, velocity and acceleration/vibration controllers. The vast majority of these sensors are position switches based on the GMR effect, with a repeatability better than 10^{12} and cost ~1 Euro/sensor. Other kinds of position sensors are also used, dependent on the required sensitivity. For good sensitivity of the order of 1 μm, differential position sensors are used based on the magnetic permanent magnet tape arrangement, with a cost ~1 kEuro/sensor. For sensitivity of the order of 10 μm, the MDL technique is employed, with a cost ~0.1 kEuro/sensor. Recently, a new MDL arrangement has been proposed, according to which the sensitivity is of the order of 1 μm, offering the additional advantage of performing static position measurements. Another important kind of industrial applications is the mass sensors, like load cells, torque meters and pressure gauges. Up to this moment the vast majority of such industrial sensors are based on conducting or semiconducting materials. Strain gauges are the most commonly used sensors for load measurements. Today’s load sensors are based on miniaturized elements fabricated by lithography techniques, thus allowing a drastic reduction of their cost. But, recently the MI and MDL techniques have been used for some interesting applications of load and derivative sizes measurements, with sensitivity better than strain gauge arrangement as mentioned in the previous chapter. Their problem at the moment is their short lifetime, which is ~10^8 in comparison to strain gauges with ~10^{12}.

4.2. Biomedical applications

Another significant application of sensors based on magnetic materials and effects are the biomedical applications [28]. The most traditional sensing systems are the encephalographs. These are field sensor arrays able to detect fields in the range of 0.1 – 1 μT. The most widely used sensor array is the SQUID system, with a sensitivity of 1 – 10 fT and a cost of 1 MEuro/sensor. Recently MI sensors have started being used in such applications, having the disadvantage of lower sensitivity of the order of 10 – 100 pT but a cost of the order of 10 kEuro/sensor. Apart from that, another family of biomedical sensors based on magnetic effects is a new type of cardiograph, which is simpler in operation and less expensive than the classic electrocardiographs, although it does not perform all measurements obtained with the latter. It requires only two sensors based on the MI effect which are set at the two hands and costs ~1 kEuro/sensor. Very recently and due to the evolution in DNA evaluation, some micromachined field array sensors have been developed [29], having a spatial resolution of the order of 1 mm and a cost of the order of 100 Euro/sensor. These devices are mainly based on the GMR effect, while MI sensors are currently tested for the same application.

4.3. Military applications

Although not very popular, the military applications of sensors including sensors based on magnetic materials, covers a large sector of the global sensors market, in terms of budget and importance. One significant application is the anti-mining control system. Up to now, the low field or field gradient or magnetic anomaly detection systems are the only existing devices able to detect mines. The more sophisticated the mines become the less iron is use and therefore the more sensitive and accurate field sensors are required. Many types of sensors have been used for this purpose from fluxgates to MI and MR sensors. Their sensitivity in today’s sensors is of the order 10 – 100 pT. It is said that the budget of anti-mining control process in Balkans in the next decade is to be of the order of 300 million Euros. Another military application used also for domestic applications is the magnetic signature. According to this, the military and not only vehicles are equipped with coils supplied by a given, usually coded, current waveform. Detection of the field produced by such current results in recognition of the given type of vehicle. Applications of this system mainly refer to boats. Another application is the missile navigation. At this moment, the state of the art of this application is based on gyroscopes based on inertia mass control or global positioning systems (GPS), but research is under way in order to employ field sensors. The principle of operation is based on the field variation measurement and corresponding corrective action due to the earth’s field. GMR and GMI sensors have been employed for this purpose.

4.4. Environmental applications

In the last decades, the environmental protection becomes more and more vital for the whole globe. Therefore, the measurement of many parameters affecting the environmental status is by definition important. The monitoring of the electromagnetic radiation is a significant part of this process. The method of detecting such radiation is the field monitoring. The range of measurement with respect to frequency extends from DC up to 30 GHz fields. An easily understandable example is the mobile telecommunication electromagnetic pollution, where the measurement of the radiation in the range of 1-2 GHz determines the correct control and use of antennas and cellar phones. The sensitivity of all these measurements ranges from a few pT up to a few mT. Sensors based on magnetic materials govern mainly the low frequency market of these sensors, being a unique method for the measurement of the DC field pollution. Fluxgates have been extensively used for such purpose, while GMI field sensors are currently under test for the same reason. Apart from that, they have started being used in higher frequencies using the GMI effect. A distinct environmental application of DC field sensors is the space field monitoring. Each satellite is equipped with field sensors, in order to perform meteorological measurements apart from craft navigation. The most traditional kind of sensor used for such application is the fluxgate, while recently GMR and GMI field sensors have been employed to compete the performance, the cost and the operational difficulties rising from the size of fluxgates, offering promising results. Another environmental application is the counting process in domestic areas. Counting of vehicles in traffic with corresponding corrective actions in traffic signaling is an important issue in all big cities.

4.5. Automotive applications

Automotive applications of sensing elements are more and more significant in our days probably due to marketing reasons apart from their significance in passive or active safety process. Car or road accidents have unfortunately a large percentage of vital accidents per day. It should be noted that in many countries which are at the boundary between developed and under-developed, the number of mortal accidents in the weekends is larger than the number of killed persons in the civil war of Yugoslavia. Therefore, it can be understandable the fact that more and more sensors are used in modern cars. More than 1,500 sensors are used in most cars, produced today. Sensors based on magnetic materials govern some of these sensing applications. The most classical and well-known sensor is probably the angular positioning magnetic sensor used to activate the ABS systems in the brakes of the cars. A rotating ring with teeth of permanent magnetic material is rotating with the wheel motion. Any sudden and unexpected blockage of the wheels during braking energizes the anti-block system (ABS) thus relieving the braking pressure for some friction of the second. Many thousands of human lives have been saved due to this system. Another trial in applying magnetic effects in vehicles is the torque sensors used in wheel steering and shaft operation monitoring. These sensors are up to this moment in laboratory development stage, but it is expected that they will soon be installed in industrial production. Very recently, a GMI field sensor has been used in controlling the position of a car [30]. Toyota, the Japanese car company has employed field sensors in monitoring the parking process. Such positioning sensors are also under test to assist the driving process by means of informing the driver for the status of the car path and even react to an incorrect decision of the driver.

4.6. Laboratory sensors

In the field of laboratory sensors the science of metrology governs the applications of sensors and systems based on magnetic materials. The most widely used application is the field calibration secondary standards based on accurate field sensors. Fluxgates is the most widely used family of magnetic sensors for this reason. Another application is in the atomic force (AFM), magnetic force (MFM) and scanning tunneling (STM) microscopy, according to which a detailed topography of a flat surface can be determined with atomic resolution. An interrogating stylus is vibrated on top of the surface generating forces (Van der Waals for the AFM, magnetic forces for the MFM and electric forces for the STM) with respect to the topography of the under test surface. Recently, a new MFM system has been introduced, having a very narrow magnetic, promising sensitivity of the order of 0.1 nm [31]. Apart from these sensing instruments, in the metrology related to Current & Mass primary standard experiments, a new technique based on magnetic materials is experimentally tested, aiming to occupy the artifact of the kilogram. Using the Lorenz and Ampere’s Law, an experimental facility, using Quantum Hall Effect realization of the Volt and Ohm, is implemented to determine the kilogram and vice versa [32]. At the moment, three National Metrological Bodies are employed in such application.

4.7. Domestic applications

The domestic applications of sensors based on magnetic materials mainly include navigation sensors, security sensors [33], as well as recording media for CD and DVD reproduction. Recording media are a separate engineering sector, so that we will ignore it in this review. Apart from the electronic compass (a small field vector sensor), which is the state of the art in modern navigation aids, the security sensor market attracts significant attention from research groups. Magnetic security sensors are used when optical bar coding systems cannot be used due to harsh environmental operation or disability of optical observation. These sensors consist of a combination of a series of magnetic substances in a given order, which have distinct magnetic properties, so that the non-optical reading of these properties results in a binary or decimal word, which is the magnetic signature of the subject on which the sensor is attached.

5. Developing a sensor

Developing a sensor is a science and an art by itself, combining knowledge of material science, engineering design and metrology. A relatively generic procedure is given next, which can be followed to properly develop a sensor. This procedure is also illustrated in Fig. 5.

5.1. Facing up the under measuring size

The very first action is the definition of the under measurement physical size or property. It includes three certain steps, which must be investigated from the beginning. Although they do not include much of science and engineering, they do play a decisive role in the final sensor development.

At first, one should define the under measurement size. Such problem is faced up in two ways. The one refers to sensor designers, who perform such definition by a market research and the other to manufacturers or service engineers who need a sensing element as a solution in a given problem of their production or service. In both cases, the clear definition of the problem refers at first to the determination of the problem and consequently the physical size under measurement. This can be position, mass, field, time, electrical sizes, temperature and their derivatives.

Then, the definition of the characteristics/parameters of the under measurement physical properties takes place, which directly reflects the characteristics of the sensor under development. The most important properties are the range, the sensitivity, the uncertainty and the sensor response dependence on parametric effects.

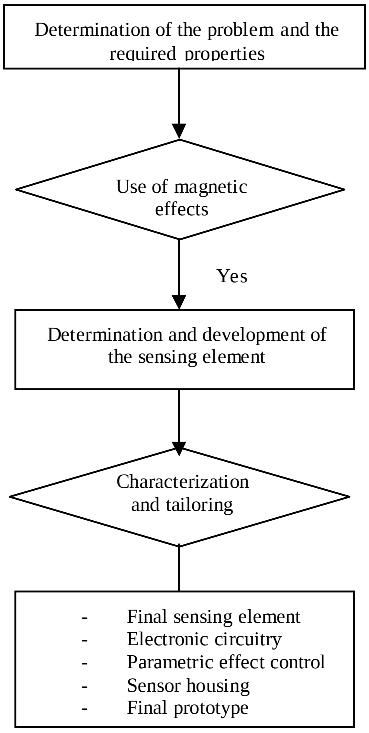


Fig. 5. Flow chart of the sensor development process.

The sensitivity is the ratio of the change of the sensor response under the least possible induced input and this induced input. The sensitivity reflects how easily a sensor can measure a physical size. The uncertainty of the sensor is the deviation of the measurement from the true value of the physical size at the time of measurement. As mentioned in Introduction, the uncertainty of sensors based on magnetic materials and effects includes mainly the hysteresis caused by the magnetic response of the used material. Usually, sensitivity and uncertainty are determined during the calibration process. The sensor response dependence in magnetic materials mainly includes dependence on ambient field, but also on temperature & humidity as well as on time.

5.2. Choice of the sensing principle

Having finalized the determination of the required characteristics of the sensor under development the next step is the definition of the criterion or criteria for selection of the magnetic effect and material to be used. The criteria reflect the importance of the above-mentioned parameters and their priority in selecting the proper effect and material. As an example there are cases where the dependence on ambient field is more important than the sensor uncertainty or cases where the temperature dependence does now allow the use of sensors having outstanding uncertainty performance. Generally, the sensitivity, uncertainty, ambient field, temperature & humidity dependence as well as temporal effects are the most important key-parameters in magnetic effect and material selection for sensor applications. Then, a table including the effect characteristics and required properties helps in deciding on the closest effect to satisfy the set criteria. At this point it is important to notice that the experience of the sensor designer in material science in general is important to recognize the superiority or not of magnetic effects and materials with other effects, like conducting, semiconducting, superconducting, optoelectronic etc. Choice of a magnetic material and effect in a given application, where it is not more acceptable than other effects and materials like the above-mentioned ones, may results in complete project failure.

5.3. Development of the sensing device

Having defined the magnetic effect to be used for the given sensor, the essential matter is the development and characterization of the sensing device, as well as the proper tailoring of the magnetic material. The development of the sensing device includes the design and manufacture of the magnetic material and consequently the development of the device. The design and manufacture of the material can be realized following three main ways, dependent on material. One is the thin film process, realized by thermal evaporation including electron gun evaporation, DC and AC sputtering, molecular beam epitaxy and chemical vapor deposition. By using these techniques many magnetic effects can be achieved, although the most proper one is to design multi-layers exhibiting giant magneto-resistance (GMR). Apart from that, magnetostrictive (MX) and magneto-impedance (MI) thin films layers have recently been developed for miniaturization purposes, with relatively promising results. The second technique concerns the various rapid quenching techniques having as final results ribbons, wires and glass covered wires. The major application of this technique concerns MI and MX materials. Finally, another technique is the thick film manufacturing process mainly dedicated to magnetic oxide films.

The characterization of the device includes structural and magnetic characterization and sensing element calibration. Magnetic characterization mainly implies B-H and λ-H loop determination in one or more axes of anisotropy, but also magneto-optic and electrical characterization. There are two important parameters, which should be taken into account when these loops are measured: one is the loop dependence on the frequency and the other is the spatial uniformity of the loops along the length of the produced material. The frequency dependence is necessary for the operation of many magnetic sensors while the spatial uniformity of these loops warrantees the repeatability of the sensor response. Structural characterization mainly implies surface characterization using scanning microscopes like scanning electron microscopy (SEM), transmission electron microscopy (TEM) and scanning tunneling techniques (AFM, MFM & STM), X-ray diffraction and differential temperature analysis (DTA) for phase transformation analysis. Structural characterization is required for explaining and understanding the macroscopic and mainly magnetic properties of the material as well as for deciding on the tailoring process of the material. Sensing element calibration implies the use of the classic primary, secondary or working-standard sensor calibration techniques. The decision concerning the calibration technique to be used depends on the uncertainty level requirements, set by the previous steps of the sensor development process.

Tailoring process depends on the results of the characterization procedure. The most significant tailoring process is the annealing of the material. Annealing is realized by thermal treatment, with parametric control of field, stress and current applied during annealing. This process mainly controls the microstructure of the magnetic material allowing proper tailoring of the magnetic domain and magnetic domain wall structure and dynamic behavior. Another tailoring process is the doping of the magnetic material with other substances, using diffusion or ion implantation techniques, which is mainly used for hardening the magnetic materials by pinning the magnetic dipoles in given orientations.

5.4. Development of the sensor electronics

After the development of the sensing element, which is finalized by the characterization and tailoring process, the development of sensor electronics is next by means of development of the excitation circuit, the output signal conditioning circuit and the auto-calibration circuit. These circuits are developed with respect to the power consumption for the excitation circuit and the required specifications for the signal conditioning and the auto-calibration circuit.

The excitation circuit is usually either DC, sinusoidal, triangular or pulsed current acting either on a coil or on the magnetic element itself. The power consumption of this circuit is from 1nW to 1mW. MOSFET amplifiers or embedded circuits are the most used elements in design of these circuits.

The signal conditioning and the auto-calibration circuits are usually high frequency bandwidth amplifiers with microprocessor-controlled analog to digital converters for the auto-calibration procedure, if it exists on board.

Feeding the excitation circuit as well the signal conditioning and auto-calibration circuits is realized by either power supply from the mains if possible, or by batteries and solar cells if applicable.

5.5. Parametric effects and sensor housing

After developing the sensing element and the sensor electronics, the most important activity is the determination and action against the parametric effects. As above-mentioned, the main parametric effects are the ambient field interference, the temperature and the time dependence.

The time dependence is usually faced up using aging process. This process can be achieved by using combination of oxidation and chemical etching of the magnetic sample itself. The magnetic response of the sensing element is stabilized after some treatment and is considered as the rather permanent response of the device.

The temperature dependence problem is solved by some practical negotiations. One has to stabilize the magnetic response of interest, which is either the magnetization or the magnetostriction, with minimum and maximum temperature limits, which are considered as the lower and upper thresholds of the thermal behavior of the sensor. Stabilization of temperature dependence is achieved by annealing techniques. Usually such lower temperature can be tailored down to cryogenic temperatures, while the upper temperature limit is some tens of ^{0}C, but in any case lower than the Curie temperature.

The ambient field interference is the most severe problem of parametric effect dependence. If field sensor is under development, then there is no problem for such parametric control consideration, because it is the physical size under measurement. If not, then there are two solutions: one is the classical magnetic shielding to minimize such effect and the other is the cancellation of the ambient field by in series-opposition arrangements, wherever this can be applicable.

The housing of the sensor if not the parametric effect control arrangements is the protection against the environmental conditions. This mainly refers to the IP numbers of the electrical insulation, as specified by the International Electrotechnical Committee (IEC). This is the sensor protection against environmental conditions such as raining, moisture and high temperature.

After all these arrangements, including material development and optimization, parametric effect facing–up and housing, the sensor is finally calibrated as a complete system and the determination of the final stage corrective actions is to be considered. After performing corrective actions if any, the final design, sensor and its technical envelope are prepared.

6. Designing the future

The successful process in the sensor market depends on the correct prediction for the near future trends [34, 35]. In this chapter we aim to give some hints for the targets and future trends in this engineering market.

Miniaturization is the most significant keyword in all research trials supported by governments and the European Commission. In many cases, miniaturization helps in a significant decrease of the production cost due to thin film mass production lines. Sometimes, the quality of the produced devices increases with the decrease of the size of the devices. An example for that are the semi-conducting miniatures like VLSI or ULSI ships. But, sometimes miniaturization can be a disaster in the properties of a device. For example miniaturized fluxgates offer sensitivity close to Hall effect field sensors, or miniaturized MI thin films do not have the repeatability found in the bulk structures of magnetic wires. In many cases miniaturization improves the properties of semiconductors but not the properties of magnetic materials up to a limit. We believe that the key-point in miniaturization is that it is absolutely necessary provided that the properties are kept at the required levels. This means that in designing magnetic materials, it is correct to design atomic scale effects. Practically, this is in agreement with the recent trends in nanocrystalline magnetic materials for sensor and actuator applications, where the magnetic properties and domains are found in the size of nanometers. This way, the sensing devices, which are at the bottom of the metrological scale, will be able to reach the accuracy and sensitivity of the secondary standards, i.e. of the order of 1 ppm.

Another important characteristic of sensors based on magnetic materials is their properties dependence on ambient field. It is a main reason that mechanical sensors based on magnetic materials have not properly found their way to the market. It is also a main reason of the fact that the vast majority of field sensors are based on magnetic effects and materials. Improvement of the magnetic sensors in the global sensor market strongly depends on their ability in being independent from the ambient field. One method to do it is the cancellation of the ambient field presence by using a kind of in-series-opposition magnetic circuit, wherever this is applicable. Another way is the development of smart sensors which are to detect the ambient field as well as the under measurement physical size and then to perform calculation of the detected size by using microprocessor based embedded circuits.

Integration ability of sensors is another key-point of their successful operation and properties. If the sensor is integrated with the electronic circuits on board, the sensitivity and uncertainty of the sensing element is improved. Recent advances in arranging magnetic materials on integrated electronic circuits indicate that such integration can be achieved by metal bonding process.

Concerning some future targets in sensor design, one can conclude that, position sensors with sub-micron uncertainty are of great interest provided that the problem of ambient field interference is overcome. This can probably achieved by obtaining acceptable MI response on thin film structures or MDL response in nanocrystalline materials. Another significant target is the development of field sensors reaching the sensitivity of SQUID. This could probably be achieved by further tailoring of MI effect and related materials.

Apart from that, nanostructured materials can be used to develop high resolution security sensors which can be used in many domestic applications.

Finally, development of sensors based on magnetic materials for harsh environment use can probably be an advantage in some given applications.

7. Conclusions

In conclusion we may say that magnetic effects play an important role in physical sensors. We have emphasized that the key point in designing the sensing element is the magnetic hysteresis, while solving the ambient field interference can result in a break-through in the sensors market. We finally emphasized on the fact that use of atomic scale effects can result in improvement of the properties of the sensor and we also gave some targets for future sensor development related to position and field sensors.

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