Advances in magnetic sensors

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***Abstract*-** Magnetic sensors serve not only for the measurement of the magnetic field, but also to measure position, speed, force, torque, electric current and other variables. Magnetic compass is still an important navigation tool in case that GPS signal is not accessible, such as underground or underwater. Advances were made thanks to new materials (e.g. nanocrystalline), new principles (e.g. GMR and SDT) and new design procedures and tools (e.g. FEM simulation packages).

I. Introduction

In this paper we review advances in magnetic sensors since the recent book on this topic [1]. We will make a short overview of the sensor principles, but we concentrate on sensors which are based on magnetic principles, and measure non-magnetic variables such as position or force. The reason is that precise magnetic field sensors and magnetometers were recently reviewed in [2]. We also briefly present several novel application examples.

II. Physical principles

We make an overview of modern principles and new solutions used in magnetic sensors.

A. Hall sensors

Hall sensors are still by far the most popular magnetic sensors on the market. Their principles are described in an excellent book by Popovic [3].
Most of them are made on silicon, but sensitive thin-film sensors are made from InSb, which is 5-times more sensitive than silicon due its higher electron mobility. Another popular material is InAs (twice the silicon sensitivity), which has lower temperature dependence of the Hall voltage compared to Si and InSb. The highest working range of the mentioned materials has InAs: more than -40 to +150°C. Hall sensors based on multilayer GaAs heterostructures achieved very low noise of 100 nT/√Hz @1Hz [4].
The well known week point of Hall sensors is offset and its temperature dependence. Spinning current technique is used to this type of error. The principle is based on electronic commutation of current and voltage electrodes in symmetrical sensor structure with 4 (or 8) contacts. The output voltage is measured for all current directions and averaged. Integrated CMOS small-size Hall sensor with an active area of 2.4 µm × 2.4 µm supplied by the spinning current achieved noise of 300 nT/√Hz @1Hz [5]. Intelligent Hall sensors in CMOS technology allow to add analog elecronics as well digital processor on the same chip as the sensor structure.
Another new trend in the design of Hall sensors is integration of field concentrators. Field concentrators (also called flux concentrators) are made of soft magnetic material, which can be electrodeposited or sputtered on the semiconductor surface. Best field concentrators are made of amorphous tape shaped by etching. The hall sensor is positioned into the airgap between the two pieces of the concentrator. Due to the high magnetic permeability of the concentrator material the field in the airgap is amplified by the gain factor from 2 to 500. The gain is a function of the concentrator geometry and permeability. Permeability as an intrinsic material property is highly dependent on temperature. It is therefore important to keep gain reasonably small so that it is much smaller than the permeability and therefore stable. The other possible problems are remanence and non-linearity especially in the case of sputtered concentrators, which have high coercivity and low saturation magnetisation. 100 pT/√Hz @1Hz is the lowest noise reported in Hall sensor with 20 cm long concentrators – however both the offset and gain stability of such sensor are very poor. Even with flux concenttrators, Hall sensors are not serious competitors of AMR and fluxgate sensors in the low-field region [6].

B. AMR sensors

The principles and design of Anisotropic MagnetoResistors are described in a noticeable book written by Tumanski [7]. These devices were originally developed for magnetic reading heads, but in this function they were fully replaced by GMR (Giant Magnetoresistors) and later by SDT (Spin-dependent Tunnelling) sensors. Functional material in AMR sensors is single-domain soft permalloy magnetic thin film, which has electrical resistivity in the direction of its magnetization by 2 to 3 % higher than in the perpendicular direction. The magnetization is rotated by the measured field and this changes the resistance. In order to linearize the sensor characteristics, a structure of so-called barber poles made by sputtered aluminum is used to deflect the current direction by 450. Full Wheatstone bridge is used to compensate the temperature dependence of the material resistivity and to further linearize the characteristics. The permalloy magnetization without external field has two possible directions. They are defined by so called flipping field pulses, which eventually also recover the single-domain state and thus define the sensor characteristics, which can be distorted by strong external field. Periodical alternating flipping into "SET" and "RESET" states is a good technique to achieve stable sensors with low offset and small temperature offset drift. Modern AMR sensors have integrated flat flipping coil and also integrated compensation coil used in the feedback mode. Feedback improves the sensor linearity and stabilizes its sensitivity. Excellent study comparing noise of various magnetic sensors is [8]. It is not easy to measure AMR noise properly: in some cases the noise of the amplifier should be suppressed by cross-correlation techniques. Realistic resolution of AMR sensor is 10 nT [9].

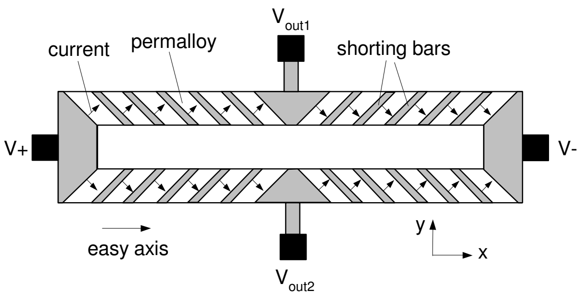

Figure 1. AMR sensor bridge with barber poles. The sensor magnetization after SET flipping pulse is in +x direction, after RESET pulse it is in –x direction. The measured field in y direction causes this magnetization to rotate. From [21].

C. GMR and SDT sensors

Giant magnetoresistors (GMR) and Spin-dependent tunneling magnetoresistors (SDT) are made of magnetic multilayers which have very thin interlayer of either copper (GMR) or insulator (SDT). In GMR sensors the current flows in plane of the multilayer, in SDT the current is tunnelled in a perpendicular direction. In both cases the resistance of the structure depends on the mutual magnetization of the layers nearest to the non-magnetic interface layer. If they are parallel, the resistance is smallest, if they are antiparallel, the resistance is largest due to the spin-dependent effects (scattering for GMR or tunnelling for SDT. The most popular structure is a Spin valve: while one of the layers is freely rotating with the external field, the other layer is fixed by adjacent hard layer (or more often by antiferromagnetic multilayer).

Similarly as AMRs, also GMR and SDT sensors are made as Wheatstone bridges. Unfortunately, there is no simple geometrical trick similar to barber poles for AMR which would allow to achieve bipolar response of the GMR and SDT bridge branches. The sign of the response should be achieved by a DC bias field or, in the case of a spin valve, by changing the orientation of the magnetization of the magnetically hard pinning layer [10].

The most promising industrial application of GMR sensors angular sensor, in which the magnetization is rotated by permanent magnet. If a free layer is single domain (like in AMR), it has saturation magnetization and the sensor output only depends on the angular position of the magnet and not on its distance. The magnetization direction of the free layer of the spin-valve is rotated by the permanent magnet. If the free layer is saturated, the sensor output does not depend on the magnet distance, only on the measured angle.

Recently developed GMR sensors have increased their temperature stability to industrial -40 to +120°C range, with 30 minutes survival at 250°C. However, large magnetic fields—especially at elevated temperatures—can irreversibly destroy some of the multilayer structures.

The main advantage of GMR and especially SDT sensors is their small size. These sensors are therefore conveniently used to detect and measure small objects such as magnetic microbeads for medical applications [11].

D. Fluxgate sensors

Fluxgate sensors are still the most sensitive vectorial magnetic field sensors. Many years several groups tried to miniaturize these devices, but without success: the performance of microfluxgates is still worse than AMR sensor of the same size [12,13].

Printed circuit board (PCB) technology can be used to manufacture low-cost, medium performance fluxgates [14]. These sensors are thin, which can be used in position sensors, magnetic ink reading devices and dBs/dy type gradiometers [15].

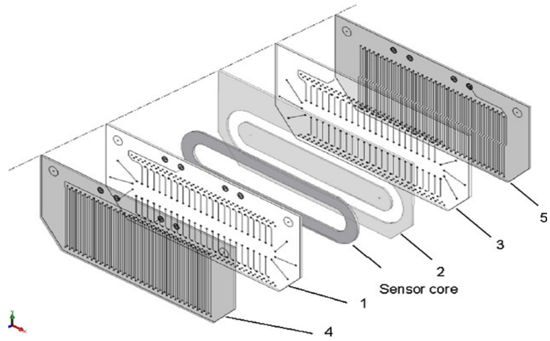

Figure 2. PCB fluxgate sensor: sensor core with its bobbin (2), layers forming excitation coil (1 and 3) and pickup coil layers (4 and 5).From [14].

Another popular development direction is represented by the transverse fluxgate sensors with cores made of wire or planar structure [16]. Some of these sensors use the output at the first harmonics (so called fundamental mode), which is very unusual for fluxgate [17]. Using multilayer wires may reduce perming and improves sensor stability. Using helical anisotropy, such sensor can be made even without coils [18]. This development is at the beginning, far from possible applications.

III. Position and distance sensors

Traditional sensors like Variable reluctance sensors, transformer-based sensors such as LVDT, Inductosyns, Synchros and resolvers, Eddy current sensors and Magnetic encoders are well known and widely used in industry. The gradual improvements of these were mainly made by finding optimum shapes using FEM modelling of magnetic circuits and by using of improved materials such as high-permeability ferrites and amorphous materials.

A. PLCD

A novel type of linear position sensor based on transformer is PLCD sensor. The device has one primary winding and two secondary windings similarly as LVDT, but it has long magnetically soft core, which is not movable. The core is magnetically divided into two parts by a region which is saturated by a permanent magnet attached to the target. The ratio of the secondary voltages depend on the position of this region. Large changes of the magnet distance cause distortion of the sensor characteristics. When the magnet is too far from the core, the dividing region is not properly saturated. When the distance is too small, two saturation zones appear (Fig. 23) [19].

B. Magnetostrictive position sensors

These sensors use acoustic wave in magnetostrictive wire or tube. There are several modifications of these devices, but all are based on pulse excitation and reflection of the wave from saturated region. The time-of-flight of the pulse depends on the position of that region, which is created by movable permanent magnet. These sensors can be up to 6 m long and they may have a resolution of 0.4 µm. The uncorrected nonlinearity can be as low as 0.02% FS. Magnetostrictive delay lines allow to measure also other physical quantities at multiple points [20].

C. Position sensor with permanent magnets

These sensors are very popular for position switches which can achieve 0.1. mm repeatability. They are also used in rotation counters and rotational speed measurement. In order to use this principle for the distance and position measurement, people often use an array of permanent magnets of a magnetic pattern stored in the semi-hard magnetic material. These magnetic rulers or magnetic scales are both either incremental or absolute sensors. Another technique is to use an array of multiple sensors. The configuration in Fig. 3 shows an array of sensors which is used to find the position of the zero-crossing, which is largerely independent of temperature [19].

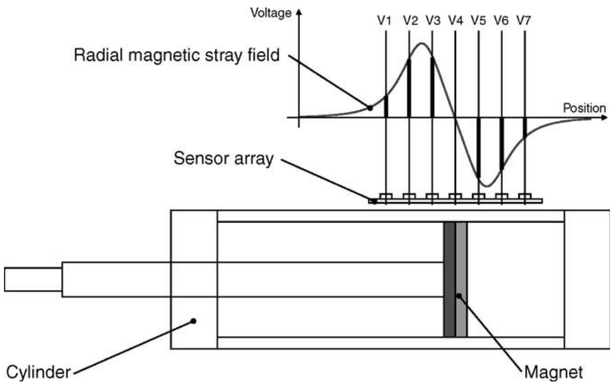

Fig. 3 Method for sensing the absolute position of a permanent magnet with an array of sensors. The exact position of the magnet is calculated using the output signals in the vicinity of the crossover point – from [19].

Contactless potentiometers use a permanent magnet mounted on the end of the rotating shaft. The magnetic field in the direction perpendicular to the shaft is sensed by Hall integrated sensor, AMR or GMR. Hall sensor developed for this aplication by Sentron and Melexix have internal ferromagnetic field guides, which rotate the magnetic field to the direction perpendicular to the chip surface. The integrated circuit provides sin and cos outputs for the complete 3600 of rotation [21].
AMR sensors of this type have only range of 900, which can be extended to 1800 by using another AMRs rotated by 450. The GMR spin valve rotational sensor has 3600 range; once the device is saturated, it is dependent only on the angular position of the magnet, no longer on its distance [22]. Infineon TLE5010 consists of two GMR full bridges giving sin and cos response. From these two signals the digital processor calculates the angular position.

IV. Torque sensors

Many force sensors based on magnetic effects appeared in research papers, but only one of them become widely used by the industry: magnetoanisotropic force sensor developed by Asea (now ABB). Contrary to that, magnetic torque sensors use two different principles:

A. permeability/anisotropy based torque sensors
Classical sensors of this type Torductor by ABB. The device use two orthogonal U-shaped cores (with excitation and sensing windings) directed towards the shaft. If the permeability of the shaft becomes anisotropic, the symmetry of the circuit is broken and voltage appears on the sensing coil. Improved sensors of this type used multiple coil systems to compensate or measure the shaft imperfections and monitor also the ripple of the torque. A new generation of these sensors use axial coils and grooves on the shaft. The advantage of this configuration is much smaller diameter of the sensor, which allows to integrate the torque sensors into many devices such as hand tools or electrically assisted bikes.

B. polarized band torque sensors
These novel sensors use a thin ring of magnetoelastic material rigidly attached to the shaft or a thick layer of such material. The ring is permanently magnetized in the circumferential direction. The stress induced by the torque rotates the ring magnetization. The magnetization component in axial direction, which is proportional to the measured torque is measured by a DC magnetic field sensor (fluxgate, AMR or Hall). These sensors are manufactured by Magna-Lastic Devices, Inc. (www.mdi-sensor.com), Magnova, Inc. (http://magnova.com) and by Siemens VDO [23]. The Siemens sensor has the shaft spray covered by a 0.5 mm thick magnetostrictive material. The radial magnetic field is sensed by a large fluxgate sensor which also shields the circuit from the external fields. (Fig. 4). This brings about high shielding of external fields. These sensors have error below 0.5% FS in a wide temperature range.

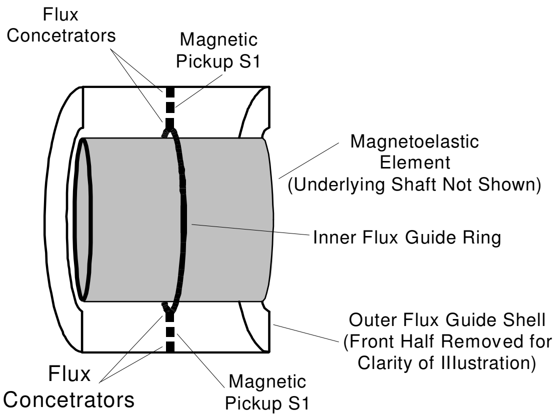

Fig. 4. Siemens torque sensor with polarized rings. The outer fluxgate sensor senses the radial field and shields the bands from external fields [19, 23]

V. Electric current sensors

Electric current sensors will be reviewed in [24].Here we mention only three principles, where the development is the most dynamic:

A. Rogowski coil

The Rogowski coil measures dI/dt, so normally it is used together with an integrator. Single-chip digital integrators are used to process the signal of Rogowski coils (also called dI/dt sensors) for energy meters. Interesting application for metrology is calibration of current transformers.

A. AMR current sensors

AMR sensors measure field in the sensor plane, which prevents them to replace thin Hall sensors in the airgap of magnetic yoke around the current conductor. AMR current sensors are yokeless, gradient bridges. The current conductor is usually integrated with sensors in one device. The measured current is compensated by a feedback current through a compensation conductor. A typical application is galvanically isolated current sensing in a PWM regulated brushless motor. These sensors are manufactured e.g. by Sensitec (also under F.W. Bell label) with ranges from 5 to 220 A. The achieved linearity is 0.1 % , temperature coefficient of sensitivity is 100 ppm/K, offset drift in the (–45 0C to +85 0C) range is 1.4% FS [24].

A. Magnetooptical current sensors

Magnetooptical current sensors are ideal for high-voltage high-current applications. They are based on the Faraday Effect - either in bulk material or in an optical fibre. The Verdet constant of optical fibers is smaller than that of bulk glass, but the sensitivity can be increased by using multiple turns of the fiber. Sensor made of low-birefringent flint fibre with a very low photo elastic constant, achieved the accuracy required for the 0.1% class of current transformers in the range of 1 kA [25].

VI. Metal detectors

All modern metal detectors still rely on two basic principles: eddy currents (for every metal) and DC field gradiometers (for ferromagnetic metals). Even the plastic antipersonnel mines contain tiny metal parts such as spring and needle; modern eddy-current metal detectors are able to detect these small parts even in the presence of magnetic soil [26]. The current problem is poor discrimination ability of these devices. There are two devopment paths: (i) dual metal detectors which employ ground penetrating radar to recognize the plastic part of the mine and (ii) mapping systems which create image of detector signal distribution and use image processing methods tio recognize the target.

Magnetometers can detect large bombs as deep as 6 m. They either measure the vertical gradient dBz/dz using two fluxgates (Foerster), or the scalar vertical gradient using two Overhauser or Cesium magnetometers. A third approach is to use tri-axial fluxgate gradiometer as described in [27]. Vectorial sensors give more information about the target, but they are sensitive to angular mismatch and positioning errors [28].

VII. Applications

A. Compass

The precise electronic magnetic compasses based on fluxgate sensors have 0.1 deg accuracy. Keeping sensors in the horizontal plane is not practical especially for fast moving platforms. In this case it is necessary to use tri-axial magnetic sensors and two inclinometers and recalculate the correct azimuth from the known pitch and roll angles.
AMR compass is less precise than fluxgate compass. The main source of error of AMR compass is so called crossfield effect [29]. After all corrections, a 1 deg azimuth error is typical for an AMR compass [30].

B. Detection of magnetic particles

Ferromagnetic particles in the human lungs can be measured by fluxgate gradiometer using their remanence. There are several approaches to the solution of the reverse problem of the magnetometry, i.e. to estimate the source from the measured field map [31]. When the size of the particles is decreasing, they become superparamagnetic and loose the remanence. In such case we should use pulse or gradiometric methods to detect them under AC excitation.

C. Medical distance and position sensors

Magnetic trackers are used to measure the position of the inside the body: 1 mm precision is achievable for sensors of 2 mm diameter. The small 3-axial induction coil in the catheter measures the low-frequency field from the external coil system. A simple system measuring the distance between two coils was used to monitor the movements and size of the stomach [32]. Magnetic biscuits for monitoring of the digestion tract are usually pasive devices, which are monitored by external sensors. The magnetic marker may be a hard magnet, magnetically soft magnetic material, Wiegand wire, an LC resonator [33] or an RF transponder.

D. Space research and geophysics

The instruments and methods to observe the Earth's field from surface stations and from satellites are described in [34]. Space DC magnetometers use three orthogonally mounted fluxgate sensors together with a resonant magnetometer [35]. Similar instruments mounted on stable pillars are used in the Earth's field variation network.
AC fields are usually measured by iron-cored induction coils. Geophysical and archeological prospecting methods include DC magnetometry and measurement of magnetic properties of samples. Instrumentation for DC magnetometry is similar as that used for bomb location.
Measurement on samples includes evaluation of the tensor of susceptibility and remanence. These methods are also use in archeology to find burried objects and date pottery and bricks.

VIII. Conclusions

In 1980 many people considered magnetic sensors outdated. Their design was very conservative and the development was very slow. That was the time, when optical fibre sensors were the preferred path for the future. Than the revolutionary discoveries came: amorphous and nanocrystalline soft magnetic materials, NdFeB permanent magnets, room-temperature AMR in ferromagnetic thin layer, GMR, SDT, GMI and other new effects. New software design tools allowed to substantially optimize the geometry of magnetic circuits. New magnetic sensors penetrated the market and found their applications. Most of these fascinating advances were triggered by magnetic storage industry with its large market volumes and hunger for new technologies. Magnetic sensor industry is presently very dynamic and innovative.

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