Final Publishable JRP Summary for JRP IND08 MetMags
Metrology for Advanced Industrial Magnetics

Overview

Magnetic sensors can be found in a broad range of products in various industrial sectors such as consumer electronics, information and communication technology and automotive. Magnetic sensors are found in, for example, cars, mobile phones, industrial control equipment, medical devices and space instrumentation. The fast product development in these fields creates an on-going need for advanced magnetic sensors with significantly improved specifications in resolution, reliability and operation temperature among others. The MetMags project has delivered tailored metrology for magnetic sensor modelling, characterisation and calibration to underpin the development of future advanced industrial magnetic sensors by the European sensor industry.

Need for the project

The automotive sector is one of the most important European industrial sectors. It is also one of the driving forces for advanced magnetic sensor development; and many sensors are used in today's cars e.g. for motor control or for passenger safety applications like the antilock braking system (ABS) and electronic stability control (ESC). However, many more will be required in the future and at the same time these sensors will be required to meet tighter and tighter specifications, which need to be verified by suitable metrology.

In addition to automotive, there are many other industrial applications of magnetic sensors e.g. in geological exploration, aerospace, biomedical, consumer products, information and communications technology (ITC) and others. All these applications are underpinned by the European sensor manufacturers who need to be able to develop sensors with improved performance to meet changing needs. Future sensors will be ultra-small with high sensitivity and low-noise and, for some applications (geological exploration and space for example), will need to be able to operate at a greater range of temperatures. Manufacturers will need to meet tighter specifications with respect to reliability, operation temperature, device size, field range and calibration uncertainty, etc.

Tighter specifications can only be validated if suitable metrology is in place capable of testing and traceably calibrating the sensor response with improved uncertainties and in relevant environmental conditions such as elevated temperatures. Additionally, future magnetic sensors will rely heavily on optimized or even new material systems and concepts as well as on downscaling of the active sensor elements into the sub-micron range. Here high-resolution characterization tools to characterize ultra-small down-scaled sensor elements are needed. These developments have created the need for an underpinning metrology both for the reliable characterization of laboratory developments and for in-line testing and quality control during the production stage of sensor materials and individual sensor units. Such underpinning metrology for advanced industrial magnetic sensors needs to address the traceable magnetic characterization of new materials and devices (such as spin torque stacks or semiconductor spintronic materials) and the characterization of sub-micron magnetic elements. Furthermore it should address the validation of simulation tools which are used by industry during all stages of development of new magnetic sensor elements. Additionally the manipulation of geometrically constrained magnetic domain walls (DWs) in magnetic strips have become the focus of sensor research with potential applications in biotechnology, chemistry, environmental monitoring and medicine, and traceable metrology for domain wall displacement was not available. Therefore the European sensor industry requires underpinning metrology to develop, produce, test and calibrate advanced industrial magnetic sensor devices to stay competitive in the global market.

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Scientific and technical objectives

The key goals of this project were to:

1. Develop metrological tools and methods for industrial magnetic sensor development.
2. Develop metrological in-line tools and methods for sensor production.
3. Develop metrology for sensor testing and calibration.

Results

Develop metrological tools and methods for industrial magnetic sensor development

- Validated modelling tools for the micromagnetic modelling of micro- and nano-scale magnetic thin film sensors were developed, allowing reliable modelling of the most important magnetic sensor device properties, including magnetic domain structure, magnetisation reversal curves, magneto transport properties and sensitivity. Such reliable modelling is a key factor towards efficient model-based future sensor development.
- A metrology system for the characterisation of key parameters of novel magnetic domain wall sensor devices was established. The system allows for accurate and complete mapping of the domain wall-related change in the anisotropic magnetoresistance as a function of the magnitude and orientation of the applied magnetic field; and is able to identify highly reproducible transitions between domain states, hence to determine the optimal working parameters to underpin the development of specific novel domain wall sensor devices.
- A new micro-Hall-sensor based method for the calibration of the magnetic stray fields of magnetic near field probes for magnetic force microscopy (MFM) was developed, which will allow future MFM based traceable measurements of magnetic stray field on the nano-scale, with strong implications for device testing and materials research.

Develop metrological in-line tools and methods for sensor production

- A method for the fast and non-destructive inductive determination of key material parameters for Spin-Torque (ST) materials was developed and tested. It allowed for the first time, the determination of the key material parameter of ST materials - critical current density in a lithography-free process; and will allow more efficient ST material development, as well as fast in-line process control.
- Magnetic force microscopy (MFM) in variable magnetic fields and under variable applied stress was established which enables imaging of the details of the magnetisation reversal process to test and verify the predicted magnetisation reversal in magnetic sensor devices and prototypes. It also allows testing the influence of strain on the magnetisation processes and evaluating the robustness of sensor devices for industrial applications in harsh environments.

Develop metrology for sensor testing and calibration

- A novel calibration procedure for the calibration of tri-axial Helmholtz coil systems was developed. The method is simple and versatile; and allows reliable on-site calibrations of industrial or academic tri-axial coil setups, with low calibration uncertainty. As opposed to other calibration approaches, the calibration does require complex earth's field compensation equipment. The calibration principle was verified at a suburban calibrating facility at the Czech NMI with 5nT p-p noise. An expanded uncertainty of 0.05 degrees was achieved for calibration of the orthogonality. The sensitivity was also calibrated, with a low extended uncertainty of less than 450 ppm.
- A portable three-axis superconducting quantum interference device (SQUID) system was developed and then used for the determination of the magnetic noise vector field behaviour of industrial facilities that produce a nominally zero magnetic environment. In addition SQUID magnetometers with precise calculable SQUID loops were designed, fabricated and characterised for metrological applications. These showed ultra-high field sensitivity of typically of 7.006 nT/Φ_0 ± 0.3 %. These systems are now available for the noise metrology magnetic shielding.
- A low magnetic field facility was equipped with a magnetic shielding and thermal isolation to produce a magnetically and thermally stable environment for noise measurements down to a frequency of 0.1

mHz. The system was also equipped with a temperature forcing system, now enabling precision calibrations of sensitive magnetometers in operational temperatures in the range of -55 °C to 125 °C.

Actual and potential impact

A first stakeholder workshop was organised in the framework of a UK Magnetics Society Seminar "Novel Magnetic Sensors" in January 2011, followed by a second stakeholder workshop in December 2012. A special session on Magnetic Sensor Metrology was organised at the "European Magnetic Sensor and Actuator Forum" (EMSA) in July 2012, with five presentations given by the project consortium. The session allowed dedicated dissemination to the European magnetic sensor R&D experts. An invited talk on "Magnetic Sensor Metrology" was given by the project coordinator at the 12th MR Sensor Symposium in March 2013, allowing high level focussed dissemination of the project results to around 150 stakeholders from the European magneto resistive (MR) sensor R&D and industry.

A *Best Practice Guide for Magnetic Field Measurements* was also published and is available online. The guide is a first step towards future standardisation and copies were sent to various industrial stakeholders.

More than 50 peer reviewed papers on the project results have been published in international scientific journals (see the list of publications). In addition, more than 80 talks and posters have been presented at various relevant scientific conferences to disseminate the output of the project.

Various standardisation committees and scientific bodies have been regularly updated on the outcome of the project, among them the IEC TC 68 "Magnetic alloys and steel", EURAMET TC Electricity and Magnetism, and Deutsche Physikalische Gesellschaft (AK Magnetismus) and routes towards future uptake with respect to standardisation have been discussed.

An international comparison measurement of the earth magnetic field has been successfully completed. It has allowed validation of the novel measurement infrastructure and will lead to improved calibration and measurement capabilities (CMCs) at some of the participating European National Metrology Institutes (NMIs).

The new calibration facilities and metrology tools and methods delivered in this project will enable the European magnetic sensor industry to develop, produce and calibrate more reliable magnetic sensors to stay competitive in the global market.

Intermediate impacts

A world leading anisotropic magneto resistance (AMR) sensor producer has optimised their magnetic thin film deposition and fabrication process using the MFM in variable magnetic fields capability developed at the German NMI. The new metrology system has enabled the manufacturer to pinpoint the generation of thin film point defects occurring during the production process. The manufacturing process was subsequently optimised and the defect generation was overcome.

The low magnetic field facility developed at the UK NMI has been used to measure the magnetic moment of components for the European Space Agency (ESA) EarthCARE mission. The total magnetic moment of the spacecraft is required to meet a certain value in order to deliver the science quality of the mission objectives. If this is not achieved, the science quality will be deteriorated and the full potential of the mission will not be delivered, at great expense to the ESA members. To date the low magnetic field facility has also been used for industrial magnetic sensor calibrations by six European sensor producers.

The new 3D magnetic field calibration systems developed at the Czech Republic NMI have been used for industrial precision calibrations by a company for geological exploration applications; and the ESA has expressed a strong interest in the best practice guide for magnetic field measurements (see above) for their critical magnetic cleanliness work for future space missions.

Longer-term impacts

Impact on European industry and economy: The fast development of magnetic sensors as a key technology for wide spread future applications and high-tech products is highly beneficial for the advancement of the European high-technology industry and hence for future employment in this sector. Europe traditionally has a strong industrial sensor branch and two of the three world leading vendors of AMR and giant magneto resistance (GMR) sensors are European based. However, the EU MR sensor industry faces strong international competition, as well as fast product development, which requires underpinning metrology to enable sustained innovation in the EU. Direct access to the new high level metrology infrastructure at the European NMIs for EU magnetic sensor manufacturers gives a competitive edge to the European MR sensor industry in global competition.

Impact on consumer safety: Road accidents are a major cause of death in industrial countries. However automotive safety systems like ABS and ESC drastically reduce the likelihood of accidents. According to eIMPACT (2020 high scenario) ESC is expected to prevent by far the most fatalities and injuries: about 3,000 fatalities (-14 %), and about 50,000 injuries (-6 %) per year. Therefore, EC regulation No 661/2009 requires ESC systems on all vehicles from 01 November 2014. Both ABS and ESC systems heavily rely on multiple magnetic sensor input (e.g. speed, rotation, acceleration and steering wheel position). Furthermore, magnetic sensors are nowadays used to monitor tyre pressure, to control airbags or to detect whether seats are occupied and safety belts are in use. Therefore by providing enabling metrology for the development of improved magnetic sensors, the project underpins the development of improved magnetic sensors with direct impact on traffic safety in Europe and worldwide.

Impact on health: In bio-technology, monitoring the kinetics of protein interactions on a high-density sensor array is vital to drug development and clinical diagnostics. The current gold standard for these applications is based on surface plasmons, but the detection threshold and the throughput are limited. Here, advanced and highly sensitive magneto-resistance (MR) nano-sensor arrays, based on MR sensor devices, have prospects for high throughput and the highest sensitivity to enable faster drug development and fast, cheap and reliable clinical diagnostics. Other health relevant applications of MR sensors are cardiac pacemakers and magnetic nanoparticle detection for cancer diagnosis and treatment. Again, the new metrology infrastructure at the European NMIs, as well as the improved measurement guidelines provided by this project, allows better sensor calibration for improved bio-tech and health applications.

Impact on science and innovation in the EU: The project has carried out excellent, cutting edge research at European NMIs in collaboration with European industry and European universities in a highly competitive field. It has thus generated expertise and practical know how in an industrially relevant field at the European NMIs to the sustainable benefit of the European magnetic sensor stakeholders.

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