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Linear Magnetic Stray Flux Array based on GMR-Gradiometers

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Abstract

A drastic increase in storage density of magnetic media had a strong impact on the development of new sensor concepts for the measurement of weak magnetic fields. Two prerequisites were the miniaturization and the efficiency of the used effect. A number of magnetic field sensors based on various mechanisms have been developed and found their applications in information data-storage technology, mechanical engineering, and automotive industry. The use of such sensors is quite attractive for special nondestructive testing (NDT) applications, e.g. eddy current testing with high penetration and online monitoring capabilities. Compared to most conventional sensors, the sensitivity of giant magneto-resistance (GMR) based sensors is higher; therefore, weaker magnetic fields can be detected. Based on a commercial GMR chip, we have designed an array with 16 gradiometer sensors arranged in a line with a pitch of 4mm. A pre-amplifier and a multiplexer are integrated into the sensor array. A PC data acquisition board digitizes the output signals from the array. The sensor array has been tested on surface and sub-surface defects. This paper presents an overview of the equipment design, including Sensor-On-Chip (SOC) technologies especially suitable for industrial application.

Keywords: magnetic flux leakage, giant magneto-resistance, array

Introduction

Surface and sub-surface inspections of ferromagnetic components are widely required in various industrial applications. Usually, ultrasonic, liquid penetration, and electromagnetic methods or their combinations are applied. Due to the high sensitivity and spatial resolution, magnetic particle (MP) inspection is one of the mostly used NDT methods for this purpose. The magnetic particle method has anyway some disadvantages, such as need of the surface preparation and necessary effort to avoid the environmental pollution. In addition, this method does not allow a reliable automatic evaluation of the inspection results, so that the human factor still affects the inspection reliability.

The magnetic stray flux or magnetic flux leakage (MFL) method is a non-contact electromagnetic method with the capability to detect surface and sub-surface flaws in ferromagnetic materials. Using sensor arrays, MFL inspection can be performed faster and fully automated; thus, high inspection speeds can be achieved. In addition, due to the intelligent signal processing and new magnetic sensors, MFL, in combination with MP method, has the potential to gain access to a large range of applications.

High sensitivity and signal dynamics, negligible temperature and frequency dependence, good integration capability and small aging effects are the most desirable properties of magnetic field sensors for their using for NDT applications. The costs and the power consumption are also relevant for the array setup with a large integration number (Figure 1). The conventional magnetic field sensors, based on the Hall Effect or the induction law do not satisfy all these requirements. Novel magneto-resistive

(MR) sensors can be a good alternative [1]. These sensors have already found their application in nondestructive testing (NDT), e.g., eddy current testing with high penetration and online fatigue monitoring [2, 3].

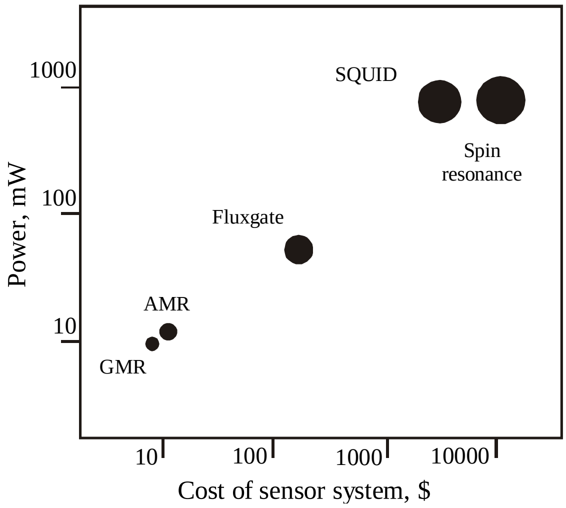


Figure 1: Comparison of low-field magnetic sensors with the same low field limit, $nT/Hz^{1/2}$. Areas represent relative size of sensor systems (after [4]).

Due to the emerging nanotechnology, thin layers down to the nanometer range were achieved, which lead to the discovery of a new class of magneto-resistance effects. In 1988, Grünberg and Fert have found a new MR-effect, called “giant” due to its enormous value in comparison to the well-known anisotropic magneto-resistance (AMR) effect [1].

Giant magneto-resistance (GMR) devices are built from alternating, ultra-thin layers of magnetic and nonmagnetic materials. In the simplest case, a conductive, nonmagnetic interlayer separates two magnetic layers. The maximum relative change of electrical resistance in such systems, with respect to magnetic field, amounts to about 6%, which is twice larger than the AMR-effect. Furthermore, the GMR-effect can be significantly increased through additional layers. The largest effective volume for multilayer systems can reach 100%. The presence of a non-ferromagnetic spacer is not always required, as for example, for thin Fe and Cr layers. In such systems, both layers have different magnetic moments, and by applying a magnetic field, they are aligned in the direction of magnetization, leading to the decrease of electrical resistance. Such systems are produced at the Institute for Metal Physic (IMP) in Russia, using the molecular beam epitaxy (MBE) method [4].

Different scientific groups all over the world intensively explore MR materials, and the number of patents has significantly increased in the last few years [1, 5]. Thus, the MR technology bears a huge potential for practical applications, including NDT.

1. Design of the sensor array

Comparing GMR and Fluxgate gradiometers

A fluxgate gradiometer MDF 9405.30 from Mikroakustika, Russia and GMR gradiometer AB001-00 from Nonvolatile Electronics, USA were selected as magnetic sensors. The gradiometers measure a difference of the magnetic field strength between two points, and the space between these two points is called a base. The GMR gradiometer and the fluxgate had a base of 0.5 mm and 5mm respectively. The GMR gradiometer measured a gradient of a tangential component of the magnetic field whilst the fluxgate gradiometer measured a difference between two normal components. Schematic geometry and simulated output of the used GMR gradiometer are pictured in figure 2.

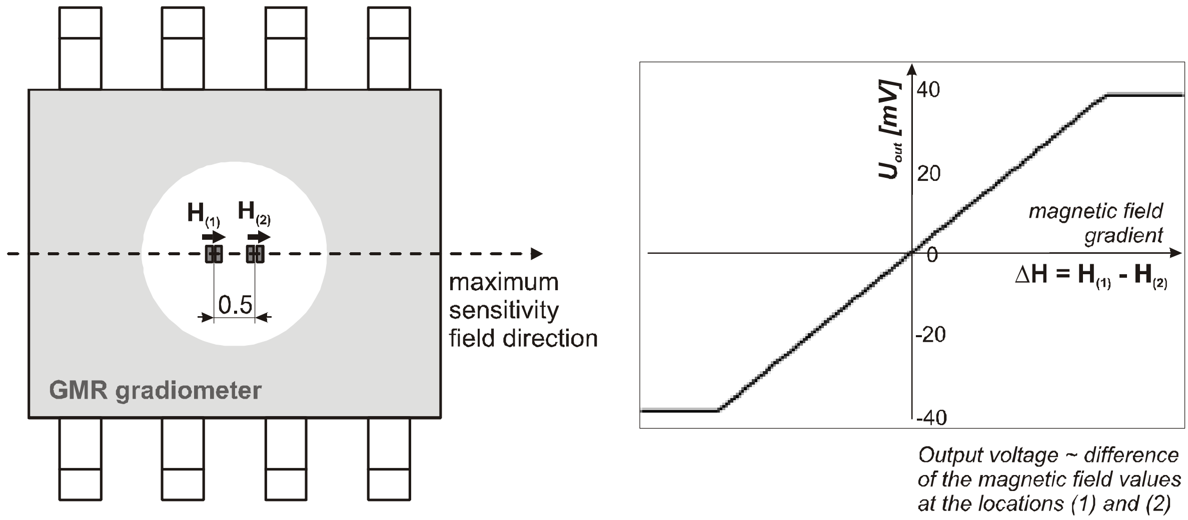


Figure 2: Schematic geometry (left) and simulated output characteristic (right) of the GMR gradiometer.

A number of samples with surface and sub-surface defects have been tested. Both of the sensors showed comparable results in detection of the flaws. The results for surface and sub-surface defects are presented below.

The surface defect had a width of 2µm and was machined on a ferromagnetic plate with a size of 300x4x38 mm^3. The crack depth was equal to the thickness of the specimen (4mm) and the length was the same as a specimen width (38mm). The sample was magnetized by DC magnetic field, so that in absence of the defect the tangential component of the magnetic field on its surface was equal to 30 A/cm. The results of the measurement are presented in Figures 3 and 4.

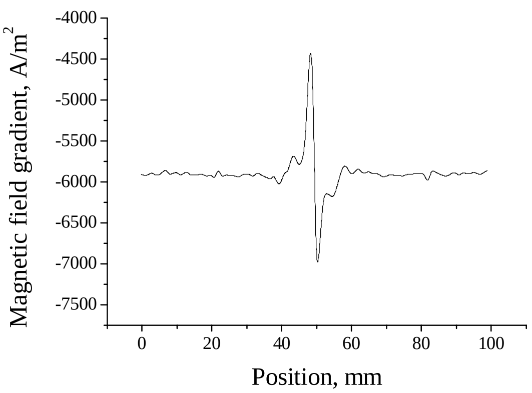


Figure 3: Gradient of the stray field from the surface crack measured by GMR gradiometer.

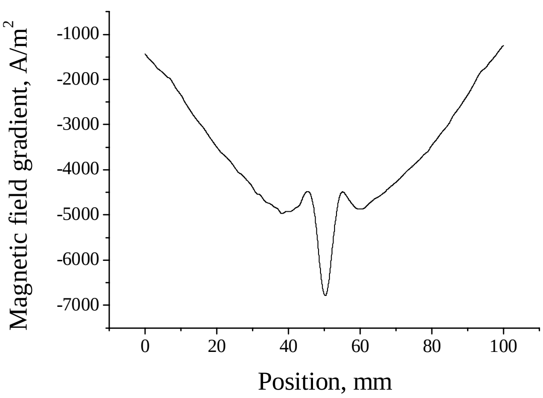


Figure 4: Gradient of the stray field from the surface crack measured by fluxgate gradiometer.

The measurement of the sub-surface defect was carried out on the ferromagnetic block with a size of 200x20x45 mm^3. A crack was machined in the middle of the longest side and was passing through the whole width of the sample (45mm). The crack had a depth of 5mm and a width of about 10µm. The stray field was measured from the opposite to the defect side, so that the crack was 15mm under the surface. The specimen was magnetized in the same way as for the surface defect up to 40 A/cm. The measurement results are shown in Figures 5 and 6.

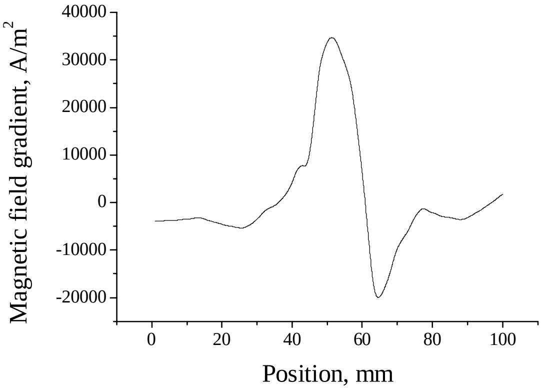


Figure 5: Gradient of the stray field from the sub-surface crack measured by GMR gradiometer.

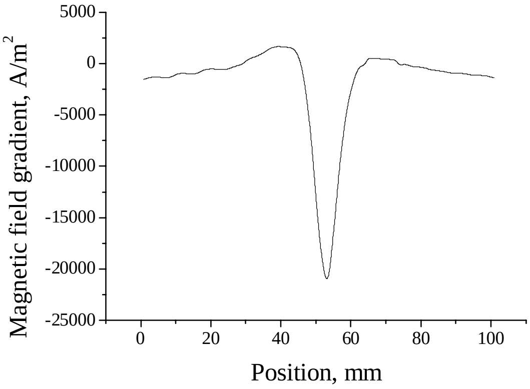


Figure 6: Gradient of the stray field from the sub-surface crack measured by fluxgate gradiometer.

As shown in the measurement results, both of the sensors have a capability to detect the stray field of the surface and sub-surface defects, interesting for industrial applications. Since GMR sensor has a number of other advantages relevant for array setup (see Introduction), it has been chosen as a basis for the sensor array.

GMR sensor array

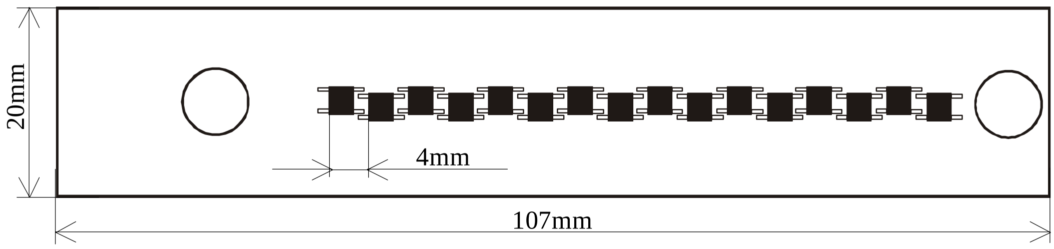


Figure 7: Sketch of the GMR sensor array

An array with 16 GMR gradiometers arranged in a line with a pitch of 4mm was built as shown in Figure 7. Due to the size of the standard TSSOP8 package, the pitch (and therefore low resolution perpendicular to the scan direction) is relatively large, even though the sensor-die itself is only 651x1231μm^2. Consequently, further improvements concerning the resolution by applying a Sensor-On-Chip (SOC) technology for the sensor array setups are possible [6]. Moreover, SOC advantages the integration of the sensors and electronics. They could be placed on the same printed circuit board (PCB) that results in better stability and cost reduction of the entire system.

The circuit board of the sensor array has a size of $20x107mm^2$. The full array length in the direction perpendicular to the scan direction is 64mm. The pre-amplifier and multiplexer are placed on the opposite side of the board.

2. Application examples

Defect detection on a ferromagnetic sleeve

A sketch of the experimental setup for the inspection of a ferromagnetic sleeve is shown in Figure 8. The sample was part of a car steering system having an outer diameter of 50mm, 35mm inner diameter, and a length of 197mm. The specimen had an artificial longitudinal flaw at the outer diameter with width of 1mm and depth of 0.5mm. The defect had the same length as the sample, and was machined by placing a copper wire into the surface notch and by grinding it down to the specimen's surface. The irregular shape of the defect caused a complicated stray field that made the experimental measurement very similar to the real situation.

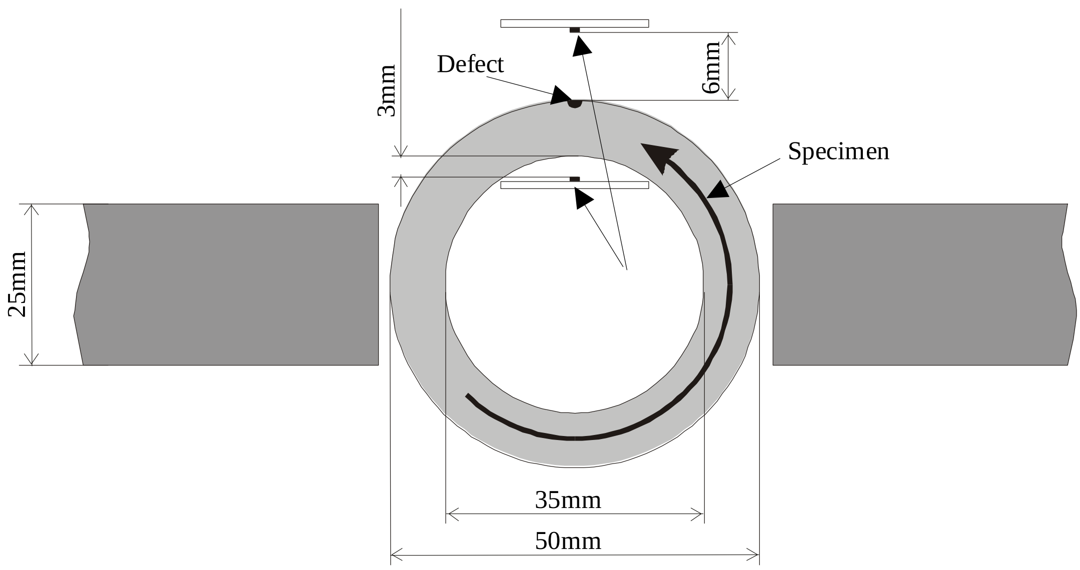
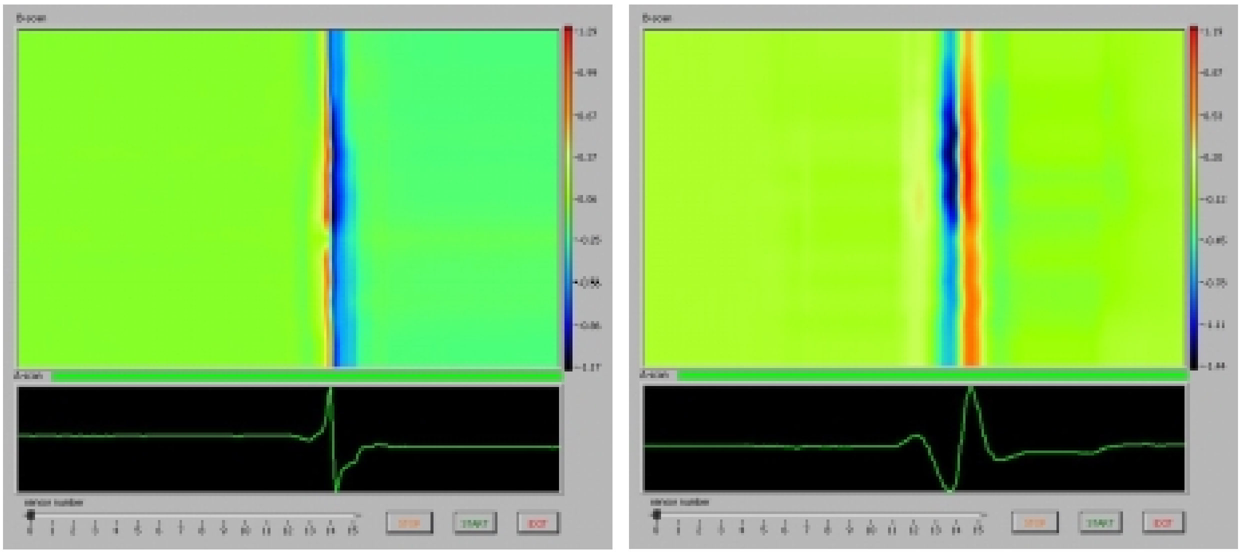


Figure 8: Experimental setup: defect detection on a ferromagnetic sleeve using MFL technique

The specimen was magnetized by DC magnetic field so that its tangential component (in the absence of the flaw) was equal to 20 A/cm at the lift off of 0.5mm. The scanning process was performed by rotating the sample in the stationary magnetic field. In order to investigate surface and sub-surface defect detection using the same specimen, the sensor arrays have been placed outside and inside the sleeve with sensor-to-specimen lift off 6mm and 3mm, respectively (see Figure 8).



a **b**

Figure 9: Magnetic field scanning results for the ferromagnetic sleeve with an artificial flaw on the outside: **a** – scanned from outside the sleeve; **b** – scanned from inside the sleeve. The upper part in the figure represents the B-scan, with axis X corresponding to the scan direction and axis Y corresponding to the length direction of the sensor array. The lower part shows the A-scan of a selected sensor.

The scanning results from the outside and inside scans are presented in Figures 9a and 9b. The scanning process takes about 5 seconds while the specimen passes through the angular positions from 0° to 360°. The sampled signals contain 512 points for each sensor and can be observed in the A-scan mode by choosing the corresponding sensor number (Figure 9, lower part).

Detection of non-metallic inclusions in cold rolled strips

For the on-line high-speed detection of inclusions in cold rolled steel strip (thickness 0.8 mm) the MFL technique using GMR gradiometer has been used (see Figure 10 for the sensor-to-specimen arrangement). The optimization objective has been to maximize the sensor lift-off. As the results presented in Figure 11 show, the defined artificial smallest detectable defect (drilled hole with a diameter of 0.2 mm and depth 0.2 mm) can be reliably detected with the GMR sensor lift-off of 1.5 mm [7].

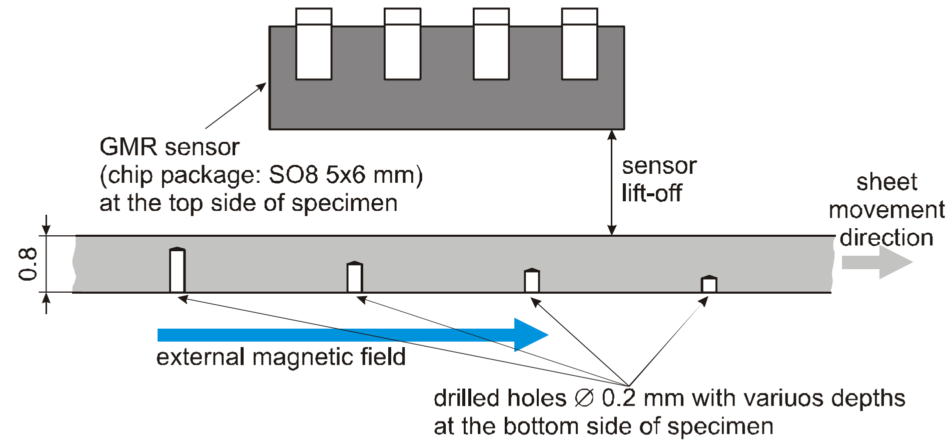


Figure 10: Arrangement of the sensor and the test specimen: detection of non-metallic inclusions (here: drilled holes as artificial defects) in cold rolled strips.

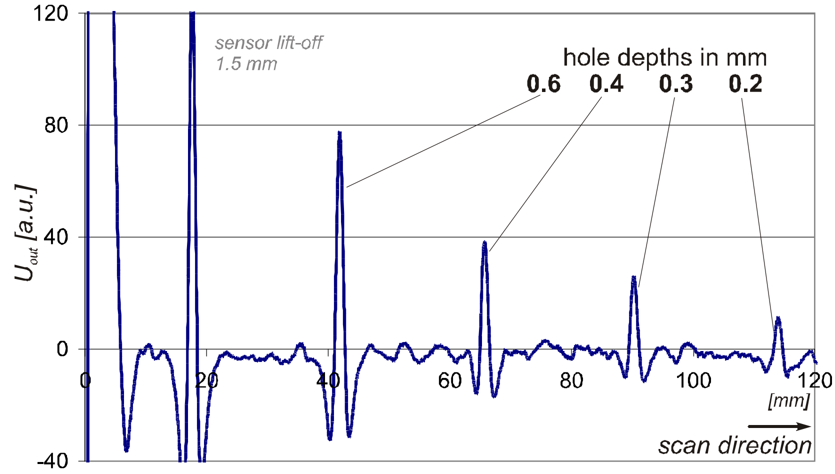


Figure 11: GMR sensor signal versus location along the test specimen with artificial defects at the sensor lift-off 1.5 mm.

3. Conclusions

A linear magnetic stray flux array, based on GMR-gradiometers, for the detection and analysis of defects in ferromagnetic materials was developed, and specimens of different shape and with different types of flaws have been inspected. A program for data acquisition and analysis has been written. The test results demonstrated that an array setup, based on GMR gradiometers, can be successfully applied to NDT applications, and in combination with MP offer an efficient solution for the nondestructive testing of ferromagnetic components. A further improvement of the spatial resolution of the sensor array is possible through the application of SOC technology and through the increase of the integration number.

4. Acknowledgment

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