Spatial detection of ferromagnetic wires using GMR sensor and based on shape induced anisotropy

Behrooz REZAEEALAM

Electrical Engineering Department, Lorestan University, P. O. Box: 465,
Khorramabad, Lorestan, IRAN

rezaeealam@gmail.com

Behrooz Rezaeealam (born in 1975) received his PhD degree in Electrical Engineering from the University of Tehran in 2005. Since 2006, he has been working as an assistant professor at the Department of Electrical Engineering, Faculty of Engineering, Lorestan University, Iran. Also, during 2010–2011, he was with Kanazawa University, Japan, where he worked as a part-time researcher working on numerical modeling of magnetostrictive materials and actuators. His research interests are finite element modeling of electrical actuators, electrical motors, and generators.

Spatial detection of ferromagnetic wires using GMR sensor and based on shape induced anisotropy

Abstract: The purpose of this paper is to introduce a new technique for row spacing measurement in a wire array using giant magnetoresistive (GMR) sensor. The self-rectifying property of the GMR-based probes leads to accurately detection of the magnetic field fluctuations caused by surface-breaking cracks in conductive materials, shape-induced magnetic anisotropy, etc. The ability to manufacture probes having small dimensions and high sensitivity (11 mV/mT) to low magnetic fields over a broad frequency range (from dc up to 1 MHz) enhances the spatial resolution of such a probe that is applicable to eddy current testing (ECT) techniques. Here, an AC uniform magnetic field is formed using a Helmholtz coil in which by scanning the probe over an array of acupuncture needles, the distances between them are detected. The results verified the possibility and the performance of the proposed row spacing measurement using GMR sensor.

Keywords: Spacing measurement, GMR sensor.

1. Introduction

Increased research activity on nondestructive testing has been motivated by the need for precise evaluation of cracks and flaws for the assessment of the expected life of mechanical components. Along with a variety of methods that include X-ray, and ultrasonic testing, eddy-current testing (ECT) is also commonly used for detecting defects such as fatigue cracks, inclusions, voids, etc., in conductive materials, and even in inspecting the dimension and alignment of the printed circuit board (PCB) conductors [1].

In recent years, electromagnetic methods for eddy-current inspection have attracted increasing attention. Electromagnetic sensors, based on either Hall effect, anisotropic magnetoresistance (AMR) [2], giant magnetoresistance (GMR) effect [3], or SQUID have been successfully used for the implementation of ECT. Among these, the GMR sensors offer the ease of integration with conventional semiconductor technology and promises smart sensors at reasonable prices with onboard signal conditioning and input regulation [4]. They have small dimensions, high sensitivity over a broad range of frequency (from hertz to megahertz domains), low noise, operate at room temperature.

Although the sensitivities of GMR and AMR sensors are comparable, GMR sensors have better directional property. Both types of sensors detect the component of the magnetic field vector along their sensitive axis. In the case of GMR sensors, fields applied perpendicularly to the sensitive axis have negligible effect on their output. In contrast, the sensitivity of AMR-based probes is lowered by a field perpendicular to the sensitive axis, which, at high values, can even “flip” the sensor response [2].

The directional property of GMR sensor can be used in a difficult problem encountered in NDE, detection of edge cracks [3], contactless angle detection [5], as well as closely spaced arrays of GMR sensors enables one-pass multi-dimensional recording [6].

When a ferromagnetic wire is placed in a uniform magnetic field, the magnetic field is deformed as shown in Fig. 1 due to the corresponding demagnetizing field. The proposed method to determine the distance between wires is to measure the x-component of magnetic flux density around the wires using a GMR sensor that scans in the direction transverse to the wire array.

The proposed row spacing measurement in a wire array using GMR sensor is applicable to the Multi-wire slurry slicing as shown in Fig. 2, that is the leading technique and a main method for large silicon wafer manufacturing [7]. It’s the special processing method that through high speed movement wire carries the grind compound to the process region attrition, finally cuts the silicon anchor into the thin slice.

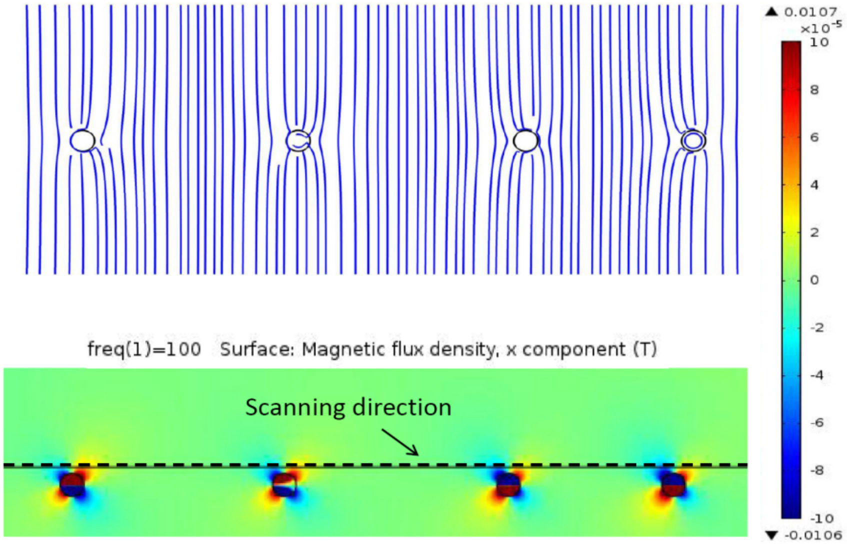

Fig. 1. Parallel wires under an applied external magnetic field.

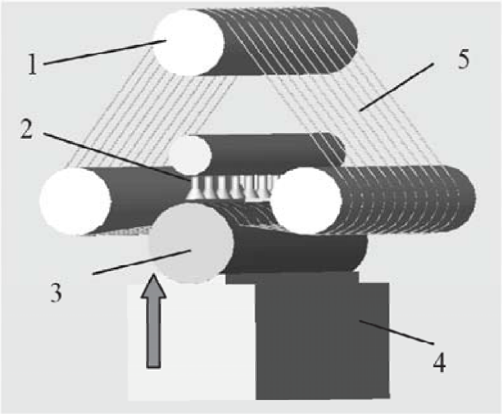

Fig. 2. Schematic of wiresaw
(1-Wire guides. 2- Slurry and abrasive. 3- Si ingot. 4- Workbench. 5- Wire.)

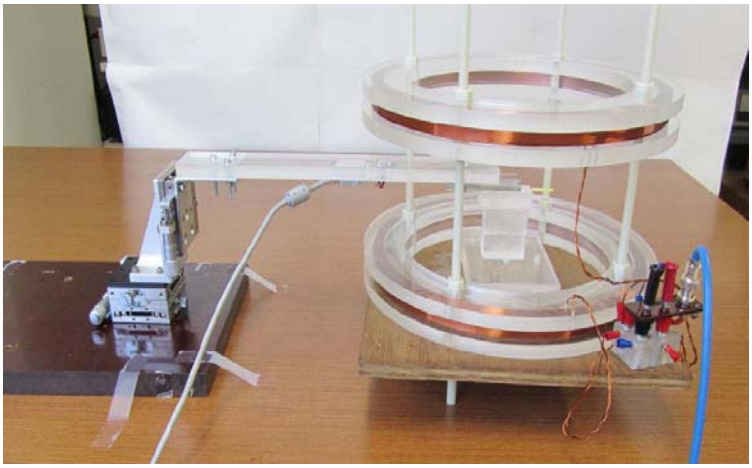

Fig. 3. Helmholtz coil

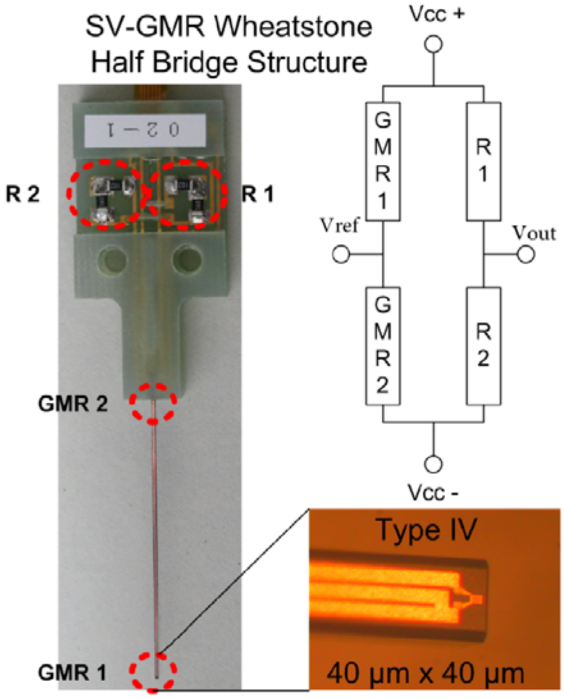

Fig. 4. SV-GMR wheatstone half bridge structure.

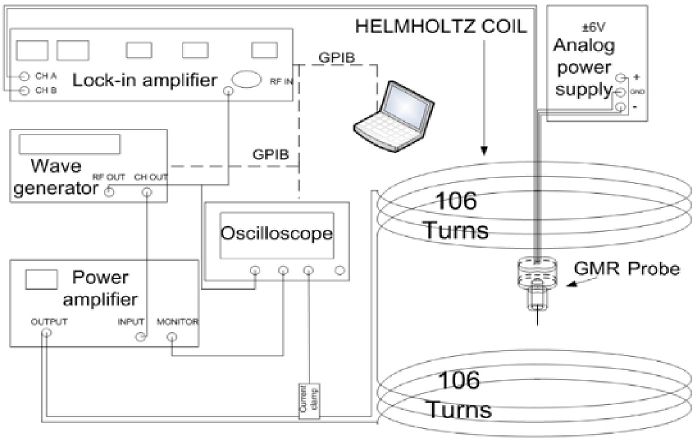

Fig. 5. Schematic illustration of the experimental set up.

2. The experimental setup and the measurements

Helmholtz coil is built in order to produce uniform fields. Typical Helmholtz coil consists of two identical circular coils of 106 turns, that are placed along common axis and separated by the height equal to their radius of 12.5 cm. Uniformity of magnetic field is limited to the second order. It means that it minimizes the non-uniformity in the centre of the coils.

As demonstrated in Fig. 4, the GMR probe has a length equal to 30 mm and the cross-section of the needle equal to 400μm x 400μm. The needle has two GMR elements and two resistors connected into Wheatstone bridge structure. The connection of the elements creates half bridge GMR structure. One sensitive element is at the tip of the needle whereas the second one is distanced 30mm and placed at the opposite end of the needle. This type of connection creates gradient meter which detects difference in fields rather than magnitude. This allows to precisely measure the difference between magnetic flux densities at two locations (tip and opposite side of the needle). The sensitive direction of GMR elements is perpendicular to needle length as shown in Fig. 4 that allows us to detect magnetic flux densities in direction perpendicular to the needle length. This characteristic of the probe enables it to be utilized in detection of the in-phase and out of phase signal components. The designed probe has sensitive elements with the sizes 40μm×40μm that is build from spin valve giant magneto-resistive thin film. The needle shape allows the sensing element to approach the examined materials in a distance of few ten μm.

Fig. 5 shows the schematic illustration of the experimental set up. The Helmholtz coil set was used as the uniform magnetic field generator. The Helmholtz coils were powered by a sinusoidal signal from the wave generator amplified by a power amplifier. The second part of the setup, the GMR probe, was supplied by an analog bipolar DC power supply. The output signal V_{out} - V_{ref} from the bridge of the GMR probe are amplified by the AD524 amplifier and connected to the lock-in amplifier. The amplitude and the phase of the output voltage from the sensor are recorded by the computer connected to the lock-in amplifier by GPIB interface.

In order to assure that hysteresis of the GMR material does not influence the measurements, the experiment with the Helmholtz coil in small AC fields was performed. Helmholtz coil was producing 0.1 mT of alternating magnetic field with the frequency

100 Hz. The tip of the needle type probe was placed in the geometrical center of the coils. The resulting output signal of the GMR element at the tip of the needle, was supplied to the oscilloscope and transferred by GPIB interface to a computer. The data collected by a measurement in X, Y, and Z axes are presented in Fig. 6. It can be noticed that in X and Y axes the sensor do not react on externally applied field. In Z axis sensor linearly changes it's amplitude with the magnetic field. Hence, the sensor bridge presents high sensitivity in Z axis.

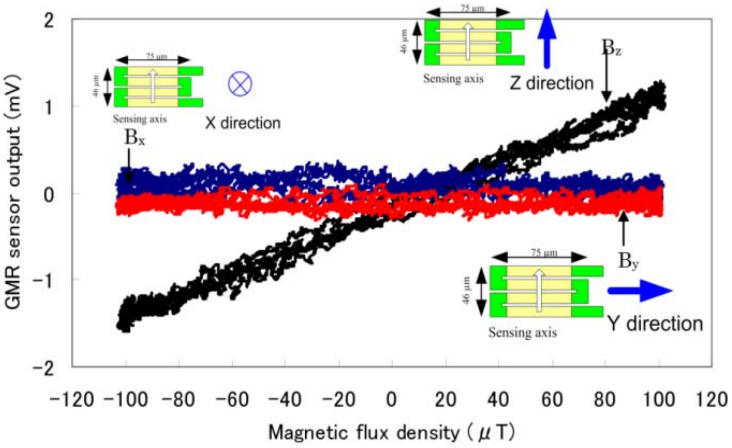

Fig. 6. Small AC characteristic of the GMR sensor.

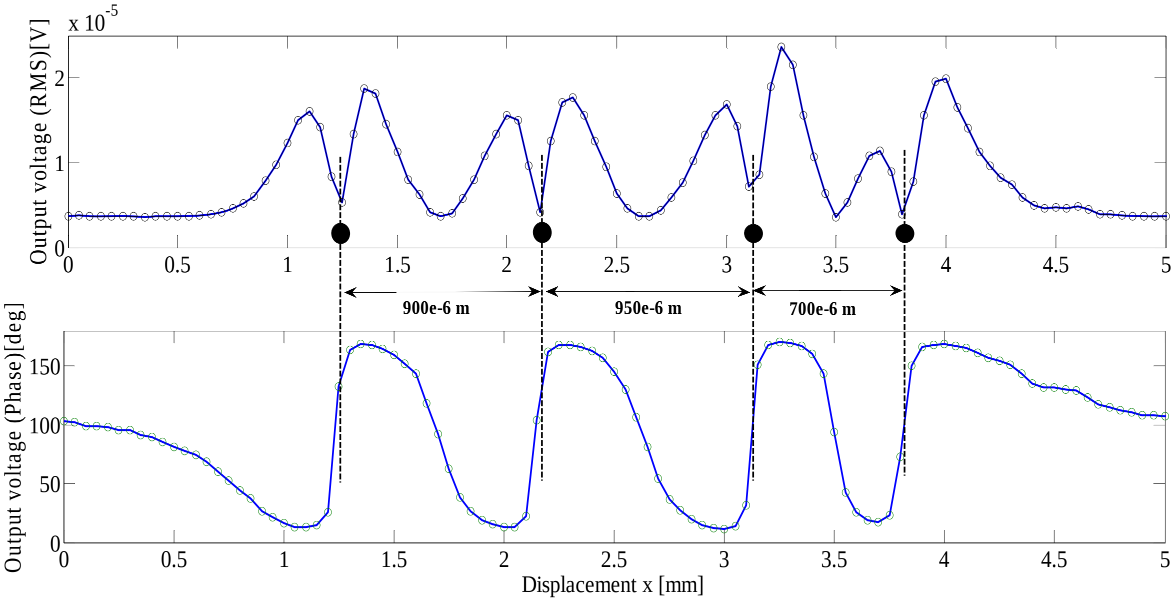

Fig. 7. The amplitudes and phases of the signal at the corresponding distances from the acupuncture needles.

Four acupuncture needles with diameter 100 µm were placed in the center of the Helmholtz coil in which a current of 100 mA produces a uniform magnetic flux density of 100 µT at the frequency of 100 Hz, as the GMR element is only sensitive to AC magnetic field.

As well as, the acupuncture needles are ferromagnetic and their relatively high value of permeability causes more nonuniformity in the magnetic field due to the shape induced anisotropy in the direction transverse to the acupuncture array as shown in Fig. 1. In other words, the variation in x-component of magnetic field at the vicinity of the acupuncture needles would be higher due to the higher demagnetization field and actually this provides a direct measurement of the anisotropy caused by the acupuncture array. As a result, in this case of ferromagnetic needles, the experiments are done under the magnetic field with the low frequency of 100 Hz despite the majority of ECT techniques that employ high frequencies applied to the conducting materials. It is noteworthy that increasing the frequency demands a more powerful power supply to maintain the current of coil at 100 mA.

The tip of the needle type probe scans in the direction transverse to the acupuncture array as shown in Fig. 1. The liftoff distance was not measured and by eye it can be said it is about 300-500 µm. The bridge output signal V_{out}-V_{ref} was supplied to the amplifier and then to the lock-in amplifier as depicted in Fig. 5. The lock-in amplifier derives the amplitude and phase of the signal that are shown in Fig. 7 versus the distance. It is observed that the phase signal changes 180^{o} rapidly as the tip of sensor passes an acupuncture needle and its corresponding location is detected.

3. Conclusions

The proposed method for the row spacing measurement was successfully tested using an array of acupuncture needles that is based on the shape induced anisotropy and measuring the corresponding changes in the magnetic field using a GMR sensor. It was observed that the phase signal provided by the lock-in amplifier, changes 180^o rapidly as the tip of GMR sensor passes an acupuncture needle by which the distances between the wires in a wiresaw can be measured.

Acknowledgements

The author would like to thank Professor S. Yamada for providing equipments and Dr R. Haraszczuk for assisting in the measurements.

References

[1] K. Chomsuwan, S. Yamada and M. Iwahara, "Bare PCB inspection system with SV-GMR sensor eddy-current testing probe" *IEEE Sensors J.*, vol. 7, pp. 890-896, 2007.

[2] B. Lebrun, Y. Jayet and J. C. Baboux, "Pulsed eddy current application to the detection of deep cracks", *Mater. Eval.*, vol. 53, pp. 1296-1300, 1995.

[3] T. Dogaru and S. T. Smith, "Edge crack detection using a giant magnetoresistance based eddy current sensor", *Non-Destruct. Test. Eval.*, vol. 16, pp. 31-53, 2000.

[4] C. H. Smith and R. W. Schneider, "Magnetic field sensing utilizing GMR materials", *Sensor Review*, vol. 18, pp. 230-236, 1998.

[5]. A. J. Lopez-Martin and A. Carlosena, "Performance tradeoffs of three novel GMR contactless angle detectors", *IEEE Sensors J.*, vol. 9, pp. 191-198, 2009.

[6] M. M. Maqableh, T. Liwen, H. Xiaobo, R. Cobian, G. Norby, R. H. Victora and B. J. H. Stadler, "CPP GMR through nanowires", *IEEE Trans. Magnetics*, vol. 48, pp. 1744-1750, 2012.

[7] Z.-H. CHENG, C.-K. XU and R.-Q. PEI, "The vibration and control of multi-wire saw", Proc. Sixth *Int. Conf. Machine Learning and Cybernetics*, Hong Kong, pp. 735-738, 2007.