Non Destructive Testing with GMR Magnetic Sensor Arrays

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Abstract. The inspection of material used in aerospace, nuclear or transport industry is a critical issue for the safety of components exposed to stress or/and corrosion. The industry claims for faster, more sensitive and cost–effective techniques. Technologies based on magnetic sensor with high sensitivity such as giant magneto-resistance (GMR) may be a good solution to improve the performances of the classical probes. The CEA has validated the performances of this technology for two kinds of applications in Eddy Current (EC) Non Destructive Testing. The first application deals with the detection of deeply embedded flaws. An EC probe based on GMR sensor has been developed and evaluated for the inspection of a 316 L stainless pipe section representative of the reactor residual heat removal (RHR) pipes. Cracks induced by thermal fatigue have been successfully detected under a ligament of 7 mm. In the second application, the very small size of the GMR sensitive element (smaller than 100µm) is used to perform a very high-resolution probe. A GMR array probe has been thus specially designed by the CEA to detect small surface breaking flaws (100µm).

Introduction

Inductive sensors are the most commonly used sensors in Eddy Current (EC) Non Destructive Testing (NDT). However their performances are limited by the fact that coils sensitivity decreases with frequency and size. In this context, magnetic sensors with high sensitivity have been investigated for some years to improve the performances of the EC probes. Especially, Giant Magneto-Resistance (GMR) sensors have been used in NDT [1, 2, 3, 4]. These sensors look promising because of their low power consumption, their frequency independent sensitivity and their small size. Moreover, the low cost makes the GMRs attractive for developing commercial probes, and the collective manufacturing process facilitates the making of large array probes.

The CEA has validated the performances of this technology in NDT with two kinds of applications. The first application described in the first part of this paper deals with the detection of embedded flaws. An EC probe based on GMR sensor has been developed and evaluated for the inspection of a 316 L stainless pipe sections representative of the reactor residual heat removal (RHR) pipes. Cracks induced by thermal fatigue have been successfully detected under a ligament of 7 mm. In the second application, the very small size of the GMR sensitive element is used to perform a very high-resolution probe. A GMR array probe has been thus specially designed by the CEA to detect small surface breaking flaws (100µm). The design of the probe has been optimized with the fast semi-analytical models integrated in the CIVA software [5].

Embedded crack detection in Reactor Residual Heat Removal pipe (RHR)

The first development addresses the detection of embedded flaws within a pipe. This work has been done in the framework of a joined R&D program between CEA and the French Institute for Radiological Protection and Nuclear Safety (IRSN). A probe based on a GMR sensor has been developed in this aim. The emitter is made of two square coils, and the receiver is a GMR sensor placed in the middle of the two coils. The interest of this configuration is to cancel the direct coupling between emitter and receiver, and thus to have a null field in the absence of flaw.

This probe has been evaluated for the inspection of the outer face on 316L stainless steel pipe mocks-up representative of the reactor residual heat removal (RHR) pipes and whose thickness is equal to 14mm. Theses pipes have been subjected to heating cycles to create cracking and crazing induced by thermal fatigue. The biggest crack induced by these heating cycles is shown on figure 1 and has a ligament of 7mm.

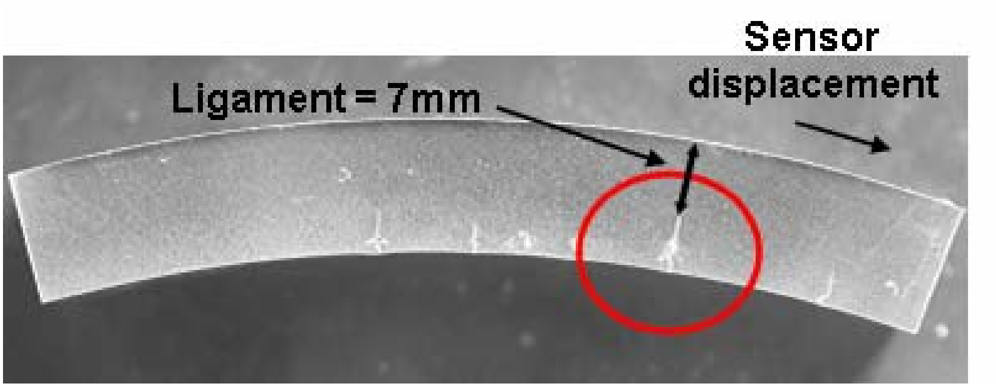

Fig. 1: Transverse section of the 316L pipe affected by cracking and crazing induced by thermal fatigue.

The CSCAN mapping obtained at 500Hz corresponds to the EC inspection of the outer part of the pipe. This mapping highlights the detection of a deeply embedded flaw located under a ligament of 7mm. The probe shows good detection capabilities, with a signal to noise ratio approximately equal to 30dB.

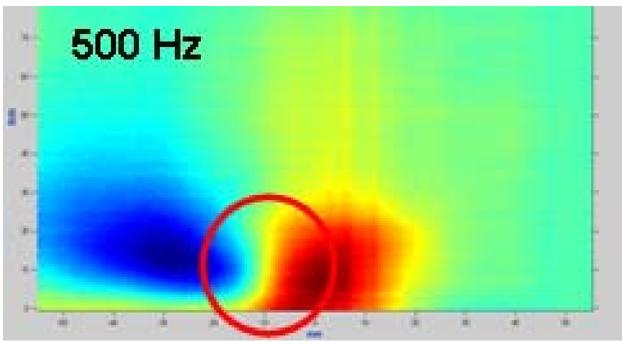

Fig. 2 : CSCAN mapping obtained at 500Hz with a GMR receiver
for the detection of a deeply embedded flaw under a ligament of 7mm.

The experimental results validate the use of GMR technology to detect deeply embedded flaw. Moreover, the performances of the detection are not disturbed by the presence of thermal cracking on the internal face of the pipe.

Small surface breaking flaws detection with a high resolution GMR array probe

This part describes the development and the experimental validations of a high resolution array probe based on GMR sensors. The CEA has developed a GMR array probe prototype for NDT applications. The probe is composed of 11 GMRs, whose sensitive area for each element is a rectangle of 80*9µm. This sensor covers a scanning zone of 1.1 mm with a high resolution of 100 µm.

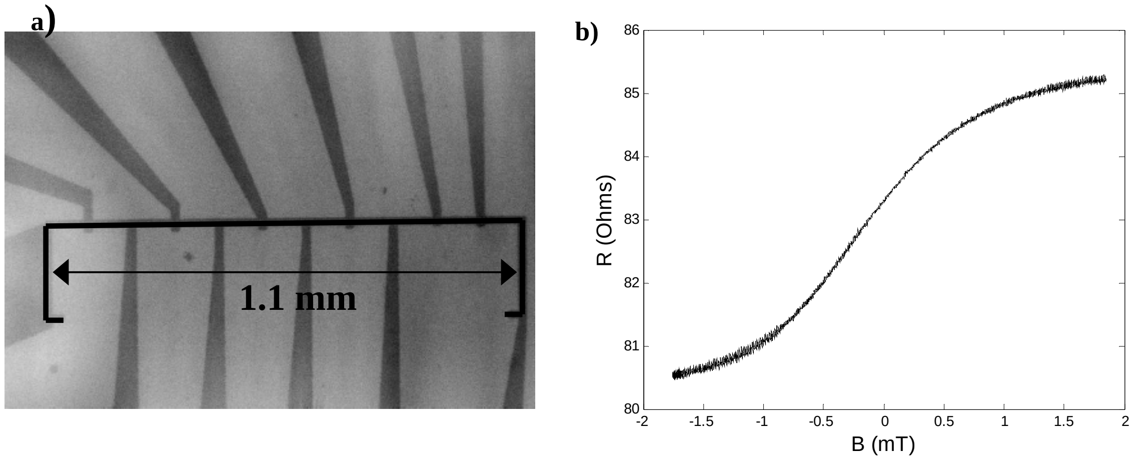

Fig. 3 Description of the GMR sensor: a) Photo of the GMRs array probe. b) GMR characteristics as a function of the applied field.

The resistance of each element is about 80 Ohms, and the magnetoresistance ratio is 6 %. As shown in Fig. 3 the sensitivity of the GMR sensor in the range ±1 mT is around 2.5%/mT [6]. The difference of sensitivity between elements is smaller than a few percents.

Optimisation of the probe by simulation

The probe is composed of a current foil emitter and a GMR receiver. The design of the probe has been optimised with the CIVA software. The CIVA software is a powerful multi-technique (ultrasonic, electromagnetic, radiographic) simulation platform dedicated to NDT and composed of simulation, imaging and analysis modules. The software is also associated to a convivial user interface, whose objective is to help the user to easily make some numerical experiments. The developed EC simulation models are mainly based on the volume integral method using the Green's dyadic formalism. The main interest of this method is to quickly predict the signal of the probe due to the presence a 3D flaw [5].

Two kinds of probe configurations have been simulated with CIVA to improve the detection of a 100*100*100 µm flaw, and are explained in this paragraph.

In the first configuration, the current lines of the emitter, oriented along the y axis, produce an uniform magnetic field along the x axis, and the GMR sensor is sensitive to this axis (Fig. 4, part a). In such geometry, the signature of the magnetic field signal produced by the surface breaking flaw consists in one peak, with a maximum magnitude equal to 15 µT (Fig. 4, part b). This configuration is called «Bx configuration».

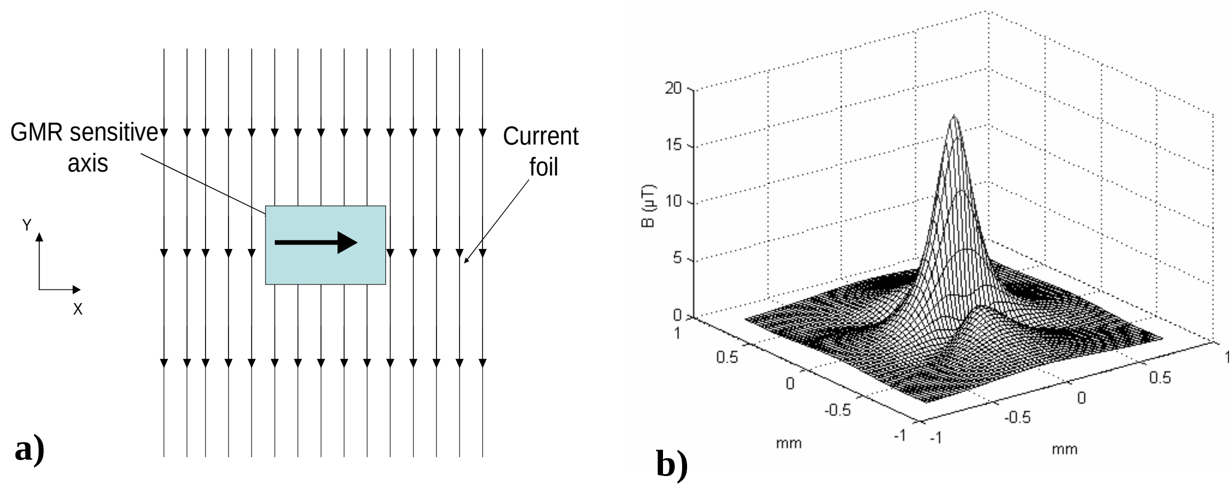

Fig. 4: (a) Description of the «Bx» configuration;
(b) Bx component of the magnetic field due to the presence of a surface breaking flaw (100*100*100 µm).

In the second configuration, the emitter is identical to the second configuration but the sensor is sensitive along the y axis. In this configuration, the signature of the magnetic field signal produced by a flaw of 100*100*100 µm consists in four peaks (Fig. 5, a), with a magnitude equal to 5 µT (Fig. 5, b). This configuration is called «By configuration».

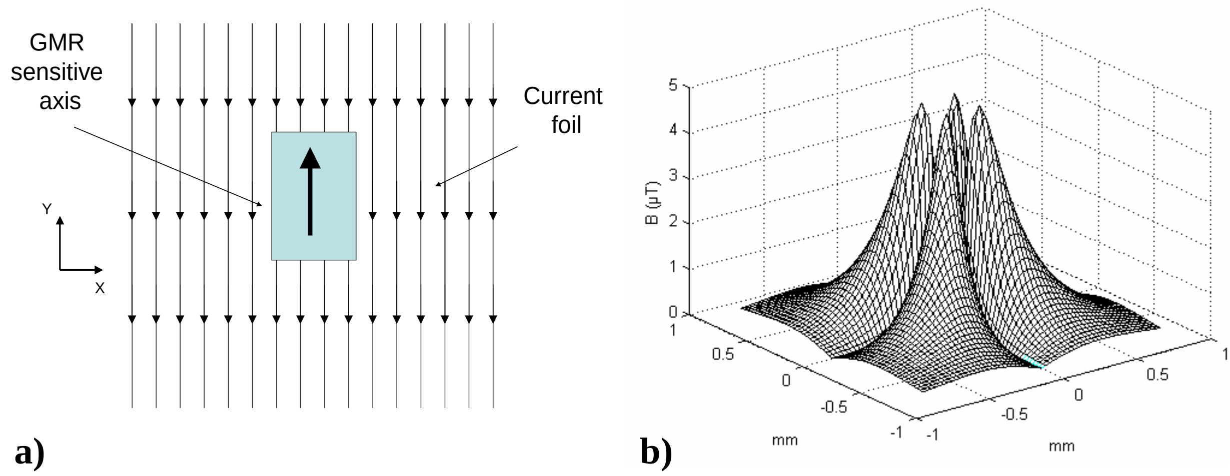

Fig. 5: (a) Description of the «By» configuration; (b) By component of the magnetic field due to the presence of a surface breaking flaw (100*100*100 µm).

The both configurations present the interest to give information concerning the planar magnetic field along the x and y axis. In these cases, the magnetic field due to a surface breaking flaw of 100*100*100 µm is about 10 micro-Teslas and can be easily measured with a GMR sensor. The signatures of the magnetic field in these two configurations are very different and potentially offer supplementary information to characterise flaws.

Experimental validation

A dedicated probe based on a GMR array receiver and two current foils emitters has been realized. The current foils are perpendicular to ensure the measurement of the both components B_x and B_y of the magnetic field. Fig. 6 shows the description of the probe.

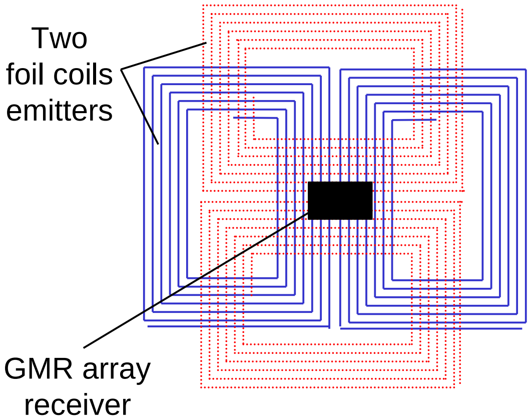

Fig. 6: Description of the probe based on a GMR array receiver and two current foils emitters.

The performances of the GMR probe have been validated in the case of the inspection of an inconel plane mock-up containing small surface breaking flaws. The description of the mock-up is given in Fig. 7. Three notches have been electro-eroded with a size equal to 200*100*200 µm, 100*100*200 µm, 100*100*100 µm. The CSCAN mappings which are shown in this paper are obtained with only one 80 µm long element of the array described above.

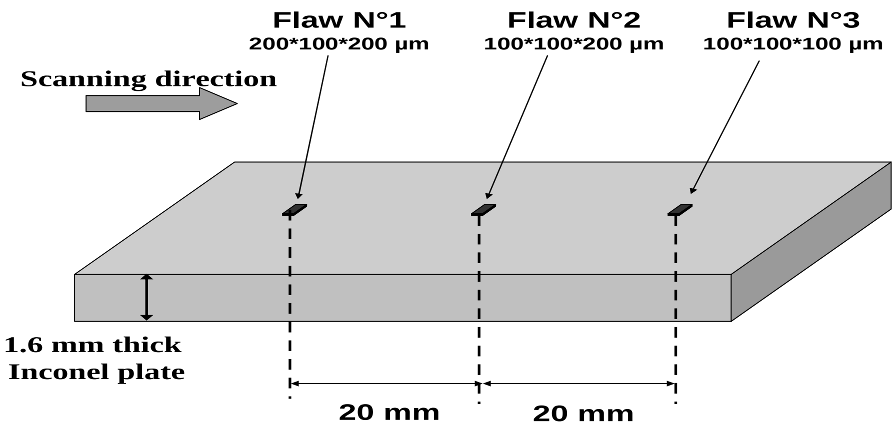

Fig. 7: Description of the experimental mock-up.

Fig. 8 shows the CSCAN mappings obtained for the inspection of the 200*100*200µm flaw, in the case of the Bx field measurement (Fig. 4, a).

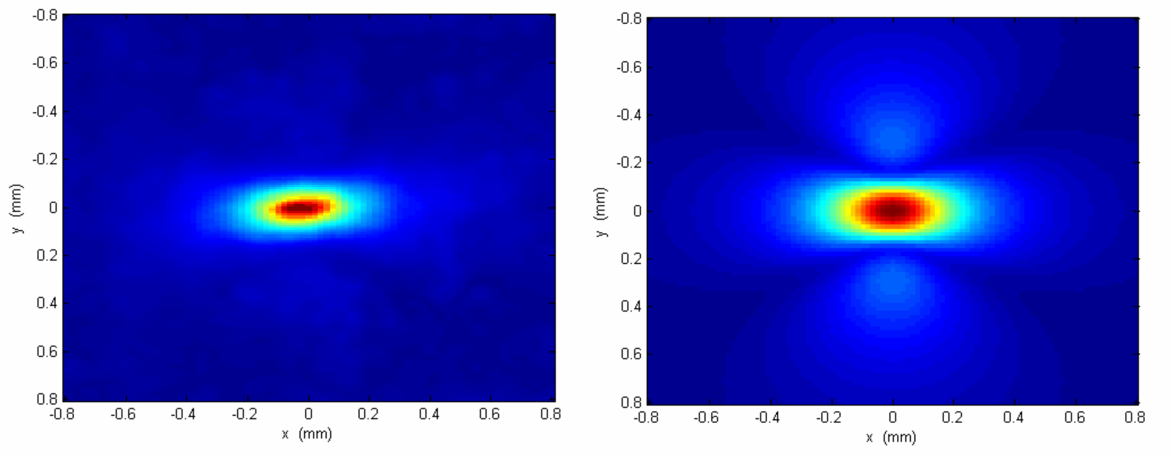

Fig. 8: Experimental CSCAN mapping of the 200*100*200 µm flaw (left part), and comparison with the simulated results (right part) in the case of Bx measurement.

Fig. 9 shows the CSCAN mappings obtained for the inspection of the 200*100*200µm flaw, in the case of the of the By field measurement (Fig. 5, a). The four lobes signature corresponding to the 4 edges of the flaw are good detected.
These both mapping have been compared with simulated results (Fig.8 b, Fig.9 b), and the obtained results show the good agreement between experiments and simulation.

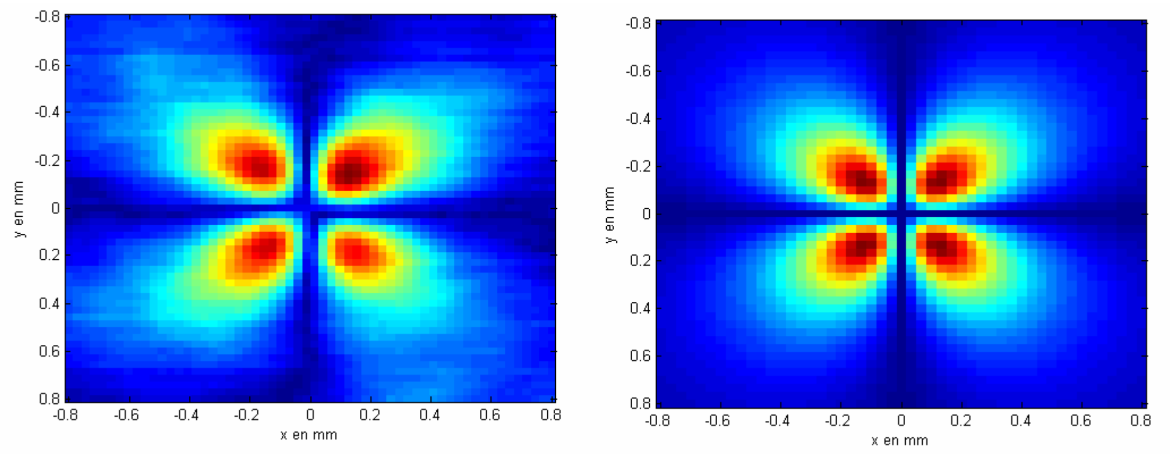

Fig. 9 Experimental CSCAN mapping of the 200*100*200 µm flaw (left part), and comparison with the simulated results (right part) in the case of By measurement.

The probe shows excellent detection capabilities. Fig. 10 shows the EC signal corresponding to the detection of the three flaws of the mock-up in the case of the By measurement: the flaws are well detected, with very good signal to noise ratio (SNR) (Fig. 11). In the case of the 200*100*200µm flaw, the SNR is 25 dB. In the case of the Bx measurement, the values of signal to noise ratio are in the same range of values.

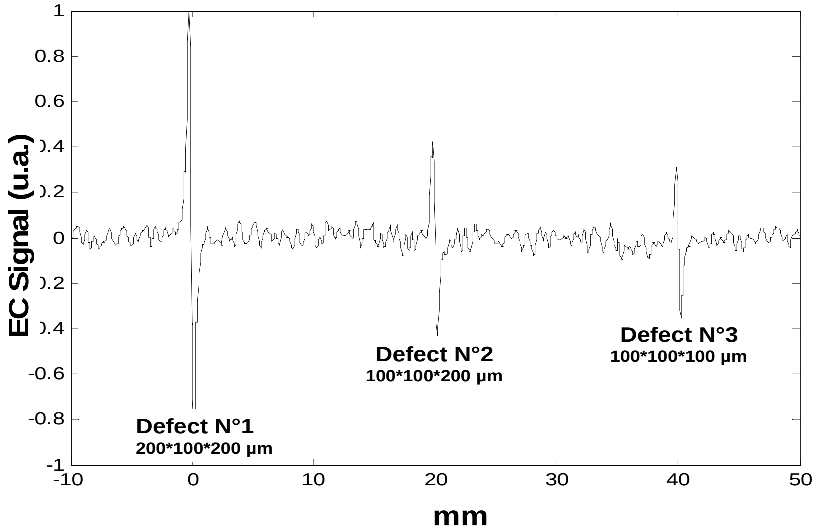

Fig. 10: EC signal obtained for the detection of small surface breaking flaws by the GMR probe in the case of the By field measurement.

	Length (µm)	Width (µm)	Thickness (µm)	**SNR (dB)**
Flaw N°1	200	100	200	**25**
Flaw N°2	100	100	200	**17**
Flaw N°3	100	100	100	**14**

Fig. 11: Signal to noise ratio values corresponding to the detection of small surface breaking flaws by the GMR probe in the case of the By field measurement.

The GMR array probe prototype offers great capabilities to detect small surface breaking flaws (100*100*100µm) with a very high resolution of 80 µm,
The probe configuration ensures the measurement of the both components of the planar fields Bx and By. These complementary data could be used to optimize flaw sizing.

Conclusion

This paper describes the interest of GMR magnetic sensor to non destructive testing.
In the first described application, the high sensitivity of GMR sensors at low frequency is used to detect embedded cracks in a nuclear pipe. In the second application, the small size of the GMRs sensors is used to design a very high resolution probe. This probe shows good detection of very small breaking flaws (100µm) with a high resolution of 100 µm.

References

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