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# Eddy Current Probes Based on Magnetoresistive Array Sensors as Receivers

Natalia SERGEEVA-CHOLLET<sup>1</sup>, Matthias PELKNER<sup>2</sup>, Thomas ERTNER<sup>2</sup>,  
Marc KREUTZBRUCK<sup>3</sup>, Claude FERMON<sup>4</sup>, Jean-Marc DECITRE<sup>1</sup>, Johannes PAUL<sup>5</sup>,  
Filipe CARDOSO<sup>6</sup>, Susana CARDOSO<sup>6</sup>, Paulo FREITAS<sup>6</sup>, Diogo M. CAETANO<sup>7</sup>,  
Jorge FERNANDES<sup>7</sup>, Moisés PIEDADE<sup>7</sup>

<sup>1</sup> CEA LIST, Gif-sur-Yvette, France

<sup>2</sup> Bundesanstalt für Materialforschung und -prüfung (BAM) Fachbereich 8.4:  
Zerstörungsfreie Prüfung, akustische und elektromagnetische Verfahren, Berlin, Germany

<sup>3</sup> University of Stuttgart, Institut für Kunststofftechnik, Stuttgart, Germany

<sup>4</sup> CEA IRAMIS SPEC, Gif-sur-Yvette, France

<sup>5</sup> Sensitec GmbH, Lahnau, Germany

<sup>6</sup> INESC Microsystems & Nanotechnologies, Lisbon, Portugal

<sup>7</sup> INESC-ID, Lisbon, Portugal

Contact e-mail: natalia.sergeeva-chollet@cea.fr

**Abstract.** Eddy Current (EC) Technique is a powerful method for detection of surface notches and of buried flaws during inspection of metallic parts. This technique is used for inspection at different industrial domains like aeronautics and nuclear one. Classical winding coils are the most commonly used EC sensors. Nevertheless, when the size of flaws decreases or the defect is rather buried deep inside the material, traditional winding coil probes turn out to reach their limits. For this reason, other technologies are investigated to improve this technique.

Magnetoresistive sensors present the advantages of flat frequency response and dimensions at the micron size. These sensors are hence very attractive for the detection of buried defects that require low frequencies because of skin depth effect. Also, they are suitable for small surface defects due to high spatial resolution because of their manufacturing down to one hundred  $\mu\text{m}$  without losing their field sensitivity.

An optimization of such probes based on magnetoresistive sensors (GMR - giant magnetoresistive and MTJ – magnetic tunnel junctions) specially designed to be integrated into an eddy current probe has been experimentally studied. Measurements using MR array probes consisting of 32 GMR- and MTJ-elements, an ASIC, subsequent readout components, and emitters for EC generating inside the material under test are shown. These probes have been developed in the IMAGIC-project<sup>1</sup> for detection and imaging of surface breaking defects and buried flaws. The performances of developed probes have been investigated for several mock-ups.

<sup>1</sup>The IMAGIC-project (“Integrated Magnetic imagery based on spIntronic Components”, 2011 – 2014, project reference: 288381) was funded by the European Commission, Seventh Framework Programme. Further partners involved in the consortium beside BAM and CEA were INESC-ID and INESC-MN (Portugal), Sensitec GmbH (Germany), Tecnatom S.A. (Spain), and Airbus Group (France).



## 1. Introduction

Eddy Current (EC) technique is widespread, ensuring buried or surface-breaking flaws detection in conductive materials. However, when the crack's size decreases or the flaws are rather deep, using of conventional EC winding coil probes becomes rather difficult. Probes with magnetoresistive sensors as receivers are investigated as a solution [1-4]. Magnetoresistive sensors are attractive for EC testing because of their flat frequency response for a large frequency range and high sensitivity. At low frequencies they are more sensitive than conventional winding coils of fixed size. Thus, GMR (Giant Magneto Resistance) sensors are promising for low frequency application, i.e. sub-surface flaws detection, because of the skin depth effect [4-6]. In order to increase the spatial resolution of detection GMR and TMR (Tunnel Magneto Resistance) could be used [7]. These sensors show good field sensitivity and spatial resolution due to the possibility of their miniaturization during fabrication. Moreover arrays of 32 or more elements could be realized in order to decrease inspection time.

In this paper testing results of GMR/TMR based probes for buried flaws and surface cracks are shown. These probes have been developed in the IMAGIC-project ("Integrated Magnetic imagery based on spIntronic Components", 2011 – 2014, EU-project reference: 288381) [6, 8, 9]. In the developed probes ASICs (application-specified integrated circuit) for processing of 32 MR-elements sensor signals are placed on board of the PCBs (Printed circuit board) [10]. Steel, Aluminum and Titanium samples have been investigated. In case of Aluminum and Steel buried flaws detection has been studied. In case of Titanium, a material with lower conductivity, surface defects in micron range have been tested [11].

## 2. MR probe design

During IMAGIC-project two different types of GMR/TMR EC probes for buried flaws and small surface breaking cracks detection have been developed. Several geometries of excitation coils have been investigated for these two applications [6, 8]. Simulations of eddy current distribution in materials of interest have been made. These simulations are made using two different simulation tools: semi-analytical model of CIVA software developed in CEA LIST and commercial FEM-software OPERA. Parametric studies for EC probes optimization are made using CIVA. OPERA is employed for magnetic and current distribution.

First, optimization of emitter has been made. Different coil geometries had been investigated: single wire coil in planar alignment, double coil in planar alignment and single wire coil in perpendicular alignment (see Fig.1). Figure 1 shows the general lay-out of different geometries, current density distribution within the material and current distribution for different frequencies from 100Hz to 8000Hz illustrating the penetration depth.

Based on this study double coil geometry of the emitter has been chosen for buried flaws and sub-surface flaws detection because of the larger penetration depth. The optimal distance between the coils has been found by simulations.

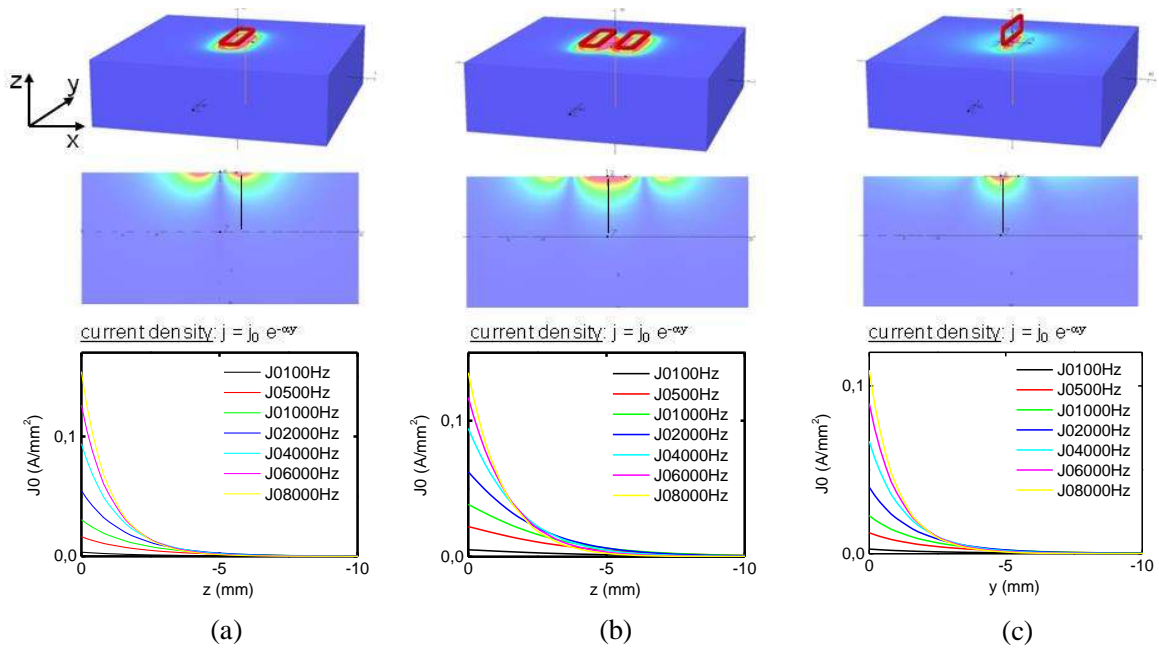
For surface cracks' detections one wire excitation coil has been selected. This arrangement has shown to be most advantageous for high excitation frequencies.

For both applications the emitter frequency has been adapted. In case of small surface breaking defects the frequency should be in the order of some MHz. For buried flaws low frequencies have to be used to generate a sufficiently high eddy current density to detect buried flaws, the simulations have been made for frequency optimization for different depth according to the application cases.

Vertical detection has been proposed after analyzing of receiver/emitter coupling, signature of flaws and signal answer obtained by CIVA and OPERA for both high frequency and low frequency applications.

During the project, the consortium has developed receivers of GMR and TMR sensors arrays for buried flaws and for small surface breaking cracks detection of different size. All arrays are sensitive to the normal component of magnetic field. Sensitivity of GMR elements is 20V/T. Receivers based on TMR sensors consist of arrays of MgO-based magnetic tunnel junctions with sensitivity of 150V/T measured with 2V bias.

IMAGIC consortium also has developed ASICs in order to process the signals coming from a high number of MR-elements [10]. The ASIC comprises of amplifying and multiplexing among other functions. Additional electronics has been placed onto PCB of the prototypes to adjust sensor signals and amplification gain.



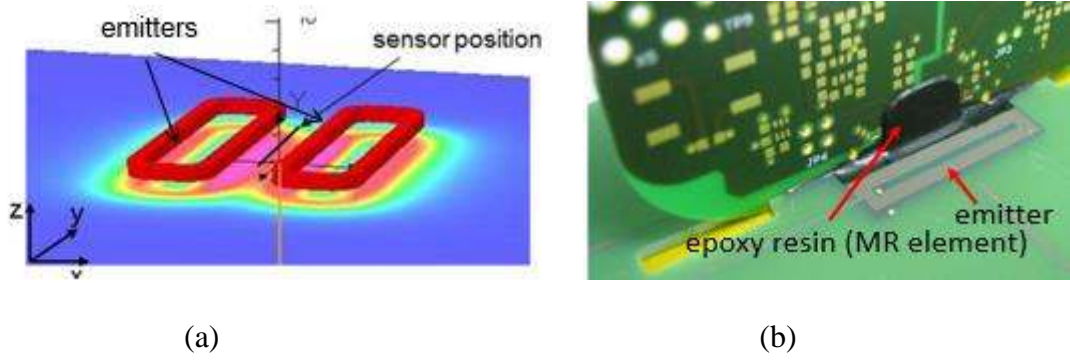
**Fig.1.** Emitter configuration: (a) single wire coil in planar alignment; (b) double coil in planar alignment; (c) single wire coil in perpendicular alignment. From top to bottom: FEM model; cross section through x-z plane illustrating current density; current density along the vertical black line for different frequencies.

## 2.1 Probes for buried flaws detection

The emitter coil is realized by printed circuit technology. Double coil emitter has been chosen following the simulation results. PCB with MR sensor array and electronics is fixed perpendicular to the PCB with emitter coils (Fig.2). The MR sensing elements are placed exactly in the center between two coils otherwise the emitter field is detected by the sensor immediately. MR elements are sensitive to the normal component of magnetic field. To avoid the interference between emitter field and sensor, a compensation circuit is integrated on the emitter coil to balance or unbalance the current between the two coils.

Arrays of size of 1mm for each element have been fabricated for this application. Sensors are connected with bonding wires and protected with epoxy resin.

Performances of the developed probes for detection of buried flaws have been evaluated.



**Fig.2.** Probe for buried flaws detection (a) scheme emitter and receiver position (b) Photo of the IMAGIC MR probe for buried flaws detection

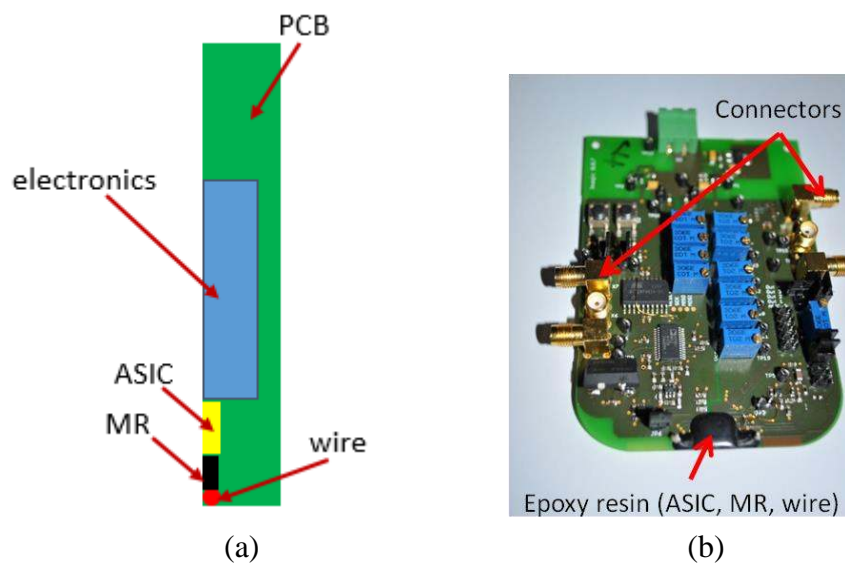
## 2.2 Probes for surface cracks detection

For surface cracks' detection GMR/TMR sensor arrays of small size in the order of  $60\ \mu\text{m}$  for each element have been developed as receivers. Arrays with 32 and more elements have been fabricated.

One wire has been chosen as emitter for these probes. The advantages of such emitter geometry are following: it could be placed at the same PCB as receiver arrays and ASIC (Fig.3), and it could be very close to the surface of testing material that will reduce the excitation loss. MR sensor array is placed just behind the wire in order to be placed also very close to the surface of material under test. Emitter consists of a bonding ribbon and is electrically connected to PCB.

Sensors and ASIC are connected with wire bonding and ASIC is connected with PCB also due to wire bonding. Emitter, sensor array, and ASIC are protected by an epoxy resin.

Performances of EC probes based on TMR arrays with a high number of small MR elements have been studied. Spatial resolution and the possibility of detection of  $\mu\text{m}$ -sized surface cracks have been evaluated.



**Fig.3.** Probe for surface cracks detection (a) scheme emitter, receiver and electronics position (b) Photo of the IMAGIC MR probe for surface cracks detection



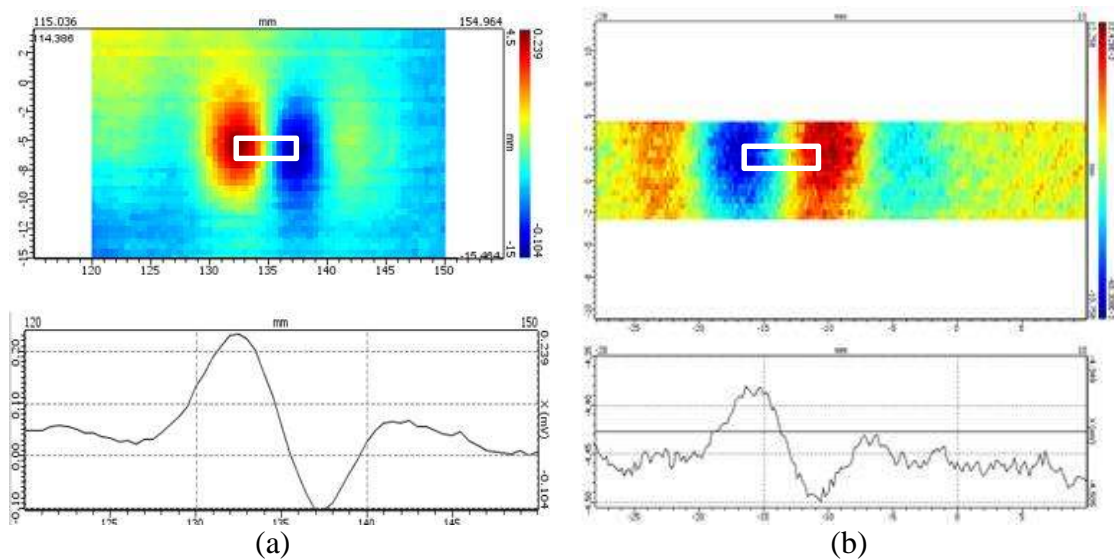
### 3. Results

#### 3.1 Buried flaws detection

Experimental testing in Aluminum mock-ups has been performed for evaluation of MR probes developed for buried flaws detection. GMR based probe has been used for testing.

The flaws with following dimensions: length  $\times$  width  $\times$  depth = 5 mm  $\times$  0.2 mm  $\times$  2 mm and 5 mm  $\times$  0.2 mm  $\times$  0.5 mm, have been made in the external side of the mock-up with ligament of 0.5 mm and 2 mm. Measurements have been realized from internal part of the mock-up. All defects are well detected. Then aluminum plate with thickness of 2 mm has been added and same defects have been studied. The excitation frequency of 1 kHz has been chosen. Experimental CSCAN and imaginary part of defect with ligament of 2.5mm (l  $\times$  w  $\times$  d = 5 mm  $\times$  0.2 mm  $\times$  2 mm) are shown in Fig.4. The extremities of defect are well seen as the normal component of the field is detected. The flaw is well detected with SNR = 11 dB and amplitude 0.2 mV

An Al-plate with thickness of 4 mm has been added on the top of the mock-up, same defects have been studied. An excitation frequency of 500 Hz has been chosen. The flaw 5 mm long (l  $\times$  w  $\times$  d = 5 mm  $\times$  0.2 mm  $\times$  2 mm) with ligament of 4.5 mm with air between the plates is well detectable with SNR = 6.7 dB (Fig.3 (b)).



**Fig.3.** CSCAN and horizontal cut of defect with ligament of 2.5mm CSCAN and horizontal cut of defect with ligament of 4.5mm

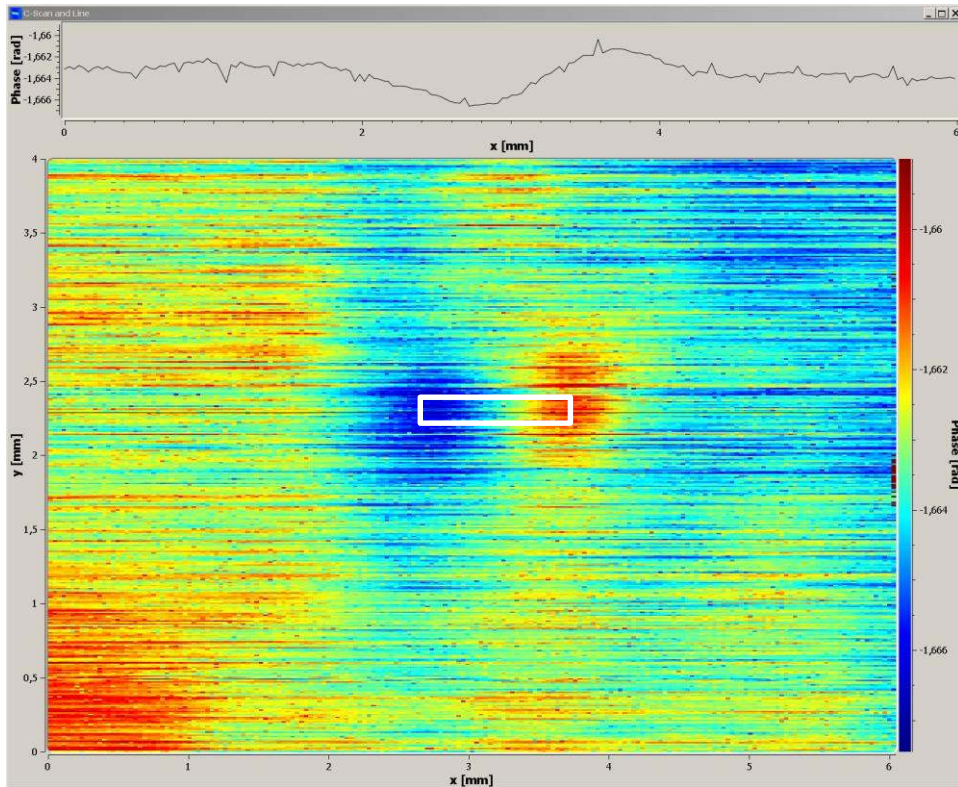
#### 3.2 Surface cracks detection

Titanium samples have been investigated for surface cracks detection. This material is rather difficult due to its low conductivity ( $\sigma = 0.6$  MS/m) compared with other materials like Aluminum, thus EC signals are small.

The excitation frequency  $f = 1.3$  MHz has been chosen for the inspection with TMR probe. The gain of 40 dB has been used for pre-amplification of signals. NI system has been used for recording data [11].

Measurements have been performed on Ti mock-up with the notch of following dimensions: length  $\times$  width  $\times$  depth = 1000  $\times$  30  $\times$  50  $\mu\text{m}^3$ .

The extremities of defect are seen as the normal component of the field is detected. This notch is well detected with SNR of 8 dB (Fig.4).



**Fig.4.** EC testing of Ti sample with artificial notch:  $1 \times w \times d = 1000 \times 30 \times 50 \mu\text{m}^3$

#### 4. Conclusions

During the IMAGIC-project EC-probes based on TMR and GMR probes with adapted ASIC have been developed. Performance of these probes have been evaluated in cases of buried flaws and surface cracks detection.

For buried flaws application, developed probes have demonstrated their capability of detection. Defects at ligament of 4.5 mm in Aluminum mock-up are well detected. However, more investigations concerning number of layers of emitter coils should be done in order to increase the performance of developed probes.

For surface cracks detection application the obtained results are very promising in terms of the possibility of detection and spatial resolution.

Using of MR – array based probes will reduce testing time with the possibility of greater area inspection at one time.

Optimization of electronics (ASIC and supporting components, sensing elements and emitter) in the case of buried flaws detection is a subject of future work of probes development.

#### Acknowledgement

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