EDDY CURRENT PROBES BASED ON MAGNETIC SENSORS FOR COMPLEX NUCLEAR PARTS INSPECTION

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ABSTRACT

Eddy Current Technique (ECT) is a powerful mean of inspection to check the integrity of metal parts. In nuclear industry, ferritic steel as for instance 18MND5, are often used. Because of skin depth effect, the magnetic permeability of this material leads to a limited efficiency of EC into the parts. Low frequency is therefore required and the control becomes less effective when conventional technologies are used. Furthermore, remanent magnetic field may occur into the parts and then disturbs EC measurements. That is the reason why new methods and technologies have to be investigated to improve the inspection of such material and bring more efficient solutions.

Preliminary studies achieved in the framework of a joined R&D program between CEA LIST and IRSN, led to the development of a prototype probe, based on one Giant Magneto-Resistance Sensor (GMR). Such sensor has the asset to be effective at low frequency. First experimental results have demonstrated its efficiency in the detection of flaws into magnetic parts. Thanks to modelling tools included into CIVA software, a new 8-GMR probe has been designed and optimized. Magnetic sensors are arranged into a staggered rows matrix (2x4) so that the spatial resolution is enhanced. Sensors are wired on a flexible Kapton film set on a conformable mount. An electronic loop has been embedded into the probe, in order to monitor the polarization point of every GMR, and then balance offsets that may happen when remanent magnetic field occurs.

Design of the probe will be given in this article and experimental results of complex 18MND5 part inspection will be shown. They reveal how the flexible technology reduces the lift-off noise, optimizes the coupling between the sensors and the part and consequently enhances the detection of defects.

INTRODUCTION

A lot of critical components in a Pressurized Water Reactor are made of ferritic steel material as 16 or 18 MND5. For safety reasons, their integrity has to checked, in the production line as well as in service. Traditionally, Ultrasonic, X-Ray and Dye Penetrant methods are used. They have already proven to be efficient but have also revealed some limits, mainly in terms of accessibility and implementation difficulties. Eddy Current Technique has assets which makes it a promising alternative technique to control such parts. Nonetheless, the nature of the material itself leads to difficulties. Because it is a ferromagnetic material, it has a rather high magnetic permeability ($\mu_r$) which prevents the induced current from penetrating deeply into the part. The relationship between penetration depth, magnetic permeability and frequency shows that the higher the permeability, the lower the frequency. When conventional EC probes based on classical winding coils are used, the size of the sensor can become pretty large to match the low frequency. In consequences, probes become rather bulky and flexibility is hardly achievable, which makes the inspection of complex parts non effective and accessibility to some areas impossible. On the contrary, the use of magnetic chip as sensors appears to be a promising solution. Such sensors are very small (one hundred of micrometers) and have a large bandwidth. Therefore, they offer the possibility of developing arrays working at low frequency embedded into a flexible mount.

In the framework of a joined R&D program between CEA LIST and IRSN, magnetic sensors and their performances for NDT application on magnetic parts has been investigated. Preliminary studies have led to the development of a first prototype probe, based on one Giant Magneto-Resistance Sensor (GMR) [1]. The first part of this paper details the probe, the way it works and the reason why embedded electronic is required. Experimental results are given and demonstrate its efficiency in the detection of flaws into magnetic parts.
Thanks to modelling tools included into CIVA software [2], an array composed of 8 GMR sensors has been designed and optimized. A new prototype probe has then been developed. The second part of the paper describes this probe and experimental results on magnetic mocks-up are provided and discussed.

DEVELOPMENT OF AN EC PROBE BASED ON A GMR SENSOR

Context
Magnetic sensors have the assets to be very small, large bandwidth and low cost, that makes them attractive to be used as receivers into EC probes. Making an array of Eddy Current sensors on a conformable substrate is feasible and developments at CEA LIST have already proven their efficiency. For these reasons, this technology appears to be promising for the inspection of components made out of magnetic material as 16 or 18 MND5. Nonetheless, one inconvenient of GMR is their need to be correctly polarized. Indeed, the external magnetic field has to be such that the response of the GMR is linear. So, the use of a polarization coil, close to the sensor, is required. As GMR are sensitive to continuous magnetic field, like the Earth’s magnetic field or like remanent magnetic field that may occur into magnetic materials, this polarization is required to make the GMR works in normal condition [3, 4].

To explain the principle of magnetic material inspection with a magnetic sensor, three cases can be considered. For the three following cases, \( V_{GMR} \), \( V \), \( H \), \( H_{POL} \), \( H_{CF} \), \( S \) and \( S' \) stand for:
- \( V_{GMR} (H) \): characteristic of the magnetic sensor (GMR)
- \( V_{GMR} (t) \): voltage given by the GMR sensor [V]
- \( V (t) \): voltage corresponding to the amplitude of the signal \( V_{GMR}(t) \), After demodulation, [V]
- \( H_{POL} \): magnetic field required to polarize the GMR [A/m]
- \( H_{CF} (t) \): variation of the magnetic field at the Eddy Current frequency (due to the emitter) [A/m]
- \( S \): polarization point without remanent magnetic field
- \( S' \): polarization point with remanent magnetic field

When there is no defect and no remanent magnetic field into the inspected material the response of the correctly polarized GMR sensor is a sinusoidal curve which frequency is the same as the Eddy Currents one (Figure 1). After demodulation, the signal will be the continuous voltage corresponding to the amplitude of the signal \( V_{GMR}(t) \).

![Figure 1: Inspection of a part without defect, without remanent magnetic field, with a GMR.](image)

When there is a defect but no remanent magnetic field into the inspected material, the response of the correctly polarized GMR sensor is a sinusoidal curve which frequency is the same as the Eddy Currents one. The defect produces an amplitude modulation of the response of the sensor (Figure 2). After demodulation, a variation of the voltage out from the sensor appears: the defect can be detected.
Finally, when there are both a defect and a remanent magnetic field into the inspected material (Figure 3) the defect produces an amplitude modulation of the response of the sensor. But, the remanent magnetic area adds a continuous magnetic field which is measured by the sensor. In consequences, the polarization point of the GMR is modified and moves from state S to state S’. In this state, the sensitivity of the GMR and then, the amplitude of $V_{GMR}(t)$, have decreased, as shown on Figure 3.

After demodulation, two variations of the output voltage are detected: one comes from the defect while the other one is due to the remanent magnetic field. This signal may be interpreted as a defect one and leads to a false alarm. Or else, this signal may be superimposed to the one of the defect and conceals it.

Development of the probe and its embedded electronic

One objective of the embedded electronic is to avoid a change of the polarization in case of remanent field happens when magnetic material is inspected [5]. The principle is to balance the effect of the continuous magnetic field by setting the suitable current into the polarization coil. The block diagram of the electronic loop is given on Figure 4. The polarization voltage is compared to the output voltage of the GMR. The difference between these two voltages is injected to the corrector. The corrected voltage is then injected to the polarization circuit, and the GMR has a new output voltage. This feedback loop is run until the difference between the two voltages is equal to zero. Thus, when remanent field occurs, the polarization voltage will be automatically corrected.
A drawing and photos of the prototype Eddy Current probe are given on Figure 5. The emitter is a classical winding coil, without ferrite. The receiver is a GMR sensor which measures the vertical component of the magnetic field. The distance between the emitter and the receiver can be set from 10mm to 25mm and therefore optimized with regards to the frequency of the Eddy Current. Emitter and receiver are as close as possible to the inspected surface. Housing allows a mounting on a mechanical bench. A LED signal shows if the GMR is well polarized. It is possible to activate or not the feedback loop thanks to a switch.

![Top view of the EC probe](image1)

![Bottom view of the EC probe](image2)

**Figure 5 : Photos and drawing of the new EC probe based on GMR sensor**

**First evaluation**

The new Eddy Current probe has been evaluated using a 16MND5 mock-up. It contains two surface holes which characteristics are given in Tab 1. A little circular magnet has been horizontally put on the surface of the part and then removed.

<table>
<thead>
<tr>
<th>Hole #1</th>
<th>Diameter (mm)</th>
<th>Depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole #1</td>
<td>5</td>
<td>2.5</td>
</tr>
<tr>
<td>Hole #2</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

**Table 1 : Characteristics of the defects into the 16MND5 plate**

The experimental CSCANs obtained at 70 kHz are given on Figure 6. As expected, when the feedback loop is not used, both holes but also the remanent fields are detected (Figure 6b). For an unknown part, such signature could be interpreted as a third defect or could hide the response of an adjacent defect. On the contrary, when the feedback loop is activated, the signature of the remanent field has almost disappeared (Figure 6c). Besides, both holes are better detected and SNRs have increased. The electronic circuit has proven its efficiency and the inspection of magnetic parts using magnetic sensor EC probe is now possible.
Hole #1:
Diameter: 5mm
Depth: 2.5mm

Mock-up plate:
16MND5
σ = 2.08 MS/μm
µ = 50

Hole #2:
Diameter: 4mm
Depth: 2mm

Horizontal magnet

Configuration of the experience: two holes in a 16MND5 plate + a horizontal magnet

Experimental CSCAN at 70kHz: magnetic sensor without control loop

Experimental CSCAN at 70kHz: magnetic sensor with control loop

The signature of the residual magnetic field has disappeared

Better detection of hole #1
Better detection of hole #2

A second testing has been performed using an 18MND5 cylinder in which artificial notches have been realized in the inner wall. A photo of the mock-up and characteristics of the notches are given on Figure 7.

Figure 6: a) Configuration: two holes and a horizontal magnet into a 16MND5 plate - b) Scan without using the feedback loop – c) Scan with the feedback loop

Figure 7: Photo of the 18MND5 cylinder and characteristics of the notches

The notch #01 has been inspected from the outer wall of the cylinder. Experimental CSCANs given on Figure 8 show that without electronic, the notch is hardly detected. Noise coming from the material itself is too important. However, when electronic is switch on, this noise has been greatly reduced and the signature of the notch appears clearly. Comparison of both lines of the CSCAN leads to the same conclusion.

Figure 8: CSCANS of notch #01 at 1 kHz, with and without feedback loop
DEVELOPMENT OF AN EC FLEXIBLE PROBE BASED ON A GMR SENSORS ARRAY

Design
Design and simulation of the performances of the probe has been performed using CIVA software. A lot of different geometries have been studied, and parameters have been optimized taking into account feasibility and limits of technology. The scheme of the final design is presented on Figure 9. The probe is composed with rectangular coils as emitters and a matrix of eight GMR, ordered in a matrix 4x2, as sensors. GMR are oriented along the [0x] axis so that they measure the tangential X component of the magnetic field. Thus, the expected response of one notch will be a mono-polar signal, which eases its detection and analysis. The pitch between sensors gives the spatial resolution of the probe. It has been defined from the required specifications in terms of size of defect to be detected while regarding the space requirement of each chip. Thanks to a staggered row arrangement, the pitch has been reduced to 1.25mm.

![Figure 9: Final scheme of the 8-GMR probe](image)

When designing a multi-element probe, disparity between signals given by every sensor has to be estimated. Simulations have been done and CSCAN obtained from two separated chip are presented on Figure 10. It turns out that in the worst case (the most separated sensor) the difference between both amplitudes is less than 6% which confirms the homogeneity of the matrix.

![Figure 10: Evaluation of the disparity between elements of the array](image)

The probe has then been developed and a photo of it is given on Figure 11. Emitters and polarization coils are etched on a Kapton film when GMRs are connected thanks to “Flip-Chip” technique on this very film. This film has a flexible mount which makes the inspection of complex geometry parts achievable. Besides, the flexibility ensures a good and constant contact of the probe with the inspected surface that reduces lift-off noise and then enhances the SNR. Embedded electronic amplifies both emitted and received signals and monitors the polarization of each sensor. An embedded multiplexer 8→1 is required to drive each GMR. The probe can be manually or mechanically used.
First evaluation

The experimental CSCAN of a 5mm surface notch located into a stainless steel plate is presented on Figure 12. This CSCAN corresponds to a one line inspection: the 8 GMR are activated thanks to the multiplexer and each line of the CSCAN corresponds to the response of one sensor when excited at 500kHz. The notch is detected by three GMR with a good SNR.

A second experimental CSCAN of a 10 mm sub-surface notch, located in a stainless steel cylinder with a 2 mm ligament is presented on Figure 13. The inspection is performed from the outer wall. Only one GMR is activated.

The defect is detected with a good SNR of 20dB. This first result is promising and shows that it is possible to detect a sub-surface crack into a complex part thanks to the multi-element flexible EC probe.
CONCLUSION

Eddy Current Technique is an efficient method for the inspection of metal parts. Nonetheless, specific constraints occur when the material is ferromagnetic. Because of skin depth effect, low frequency is required which implies the use of sensors sensitive at such frequencies. Because of their large bandwidth, GMR sensors seem to be well adapted for such applications, but they are sensitive to the remanent magnetic field that may occur into the part.

To bring a solution to this issue, a new Eddy Current Probe based on a GMR sensor has been developed, with optimized electronic embedded. It consists in a control loop which monitors the polarization of the GMR so that it remains in its linear range. Experimental testing performed on magnetic materials has demonstrated the efficiency of the electronic and the ability of the EC probe to detect defects even when remanent field happens.

To go further in this study, more experimentation considering defects with different sizes and depths should be done.

REFERENCES


