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New architectures of uniform eddy current probes for NDT using GMR

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Abstract- Non Destructive Testing (NDT) techniques are more and more exploited in order to quickly and cheaply detect flaws into the inspected materials such as aluminium plates. Important solutions in this field are based on eddy current detection, different eddy current probes being mentioned in the literature. Uniform eddy current probes (uniform-ECP) represent a particular category characterized by less sensitivity to the lift-off effects and has been originally used to inspect weld zones. This paper presents novel architectures based on uniform-ECP that combine the tangential excitation coil having a parallelepiped shape with highly sensitive giant magnetoresistances (GMR). Two different architectures regarding the GMR sensor location within the excitation coil are considered. An automatic testing system to characterize the sensor and to perform tests on an aluminum plate specimen with different defects is also presented.

Keywords: Non Destructive Testing; Eddy Current Testing; Giant Magnetoresistance.

I. Introduction

Non Destructive Testing (NDT) of electrically conductive plates offers an exciting and interesting challenge to both researchers and applied technologists. For the materials under test, the major problem of interest is the detection, location and sizing of single flaws. The eddy current non-destructive testing method is based on eddy currents induced in the conducting sample under test using a time-varying magnetic field created by the time-varying current that flows in an excitation coil located above the sample surface. These currents generate a secondary magnetic field that can be measured either using detection coils or magnetic field sensors. Because the eddy current flow pattern depends on the electromagnetic properties of the material, one can evaluate the material characteristics and detect the presence of defects from the measured signals.

Advantages of eddy current testing (ECT) techniques include a rapid inspection speed and high sensitivity for surface flaws, whereas as drawbacks its applicability only to conductive material and distortion due to the lift-off effect can be pointed out [1]. The difficulty formerly pointed to ECT in locating subsurface defects due to the strong influence of the skin effect is nowadays surpassed or greatly minimised with the use of new magnetic sensors having a great sensibility even for low frequencies, which are replacing the detection coils in the ECP-probes. One can include in this class of modern sensors: the anisotropic magnetoresistance (AMR) [2], the “giant” magnetoresistance (GMR) [3], the tunneling magnetoresistance (TMR) [4], the Hall sensor or the SQUID. The sensitivity, the directional properties and the simplicity of the required conditioning circuit, make the GMR sensors the best solution for ECT application on flaws and flaw detection.

Different eddy current probe (ECP) architectures to detect flaws are reported in the literature. Ribeiro et al. report an ECP architecture, which includes a pancake excitation coil and a set of two coaxial detection coils, presenting good results in superficial flaws detection [5]. In other papers [6, 7], the detection coils inside the pancake excitation coil that constitute the eddy current probe were replaced to GMR magnetic sensors. These probes assure the detection of surface and subsurface defects due to its wide frequency operation range. Koyama et al. report better results with uniform eddy current probes that include tangential excitation and differential detection coils [8]. Our research group described in [9] the results obtained for the detection of cracks in weld zones of conductive plates using a rectangular excitation coil and GMR sensors.

In this paper, two novel ECP architectures that combine the performance of the tangential excitation coil and giant magnetoresistor sensors (GMRs) are presented. Both setups exhibit the required sensitivity requirements for the detection of subsurface flaws even when low frequency excitation fields are used. Using the novel eddy current probe architecture, the noise associated with the lift-off effects will be minimized assuring a more accurate flaw detection and a better estimation of flaw geometrical characteristics even for subsurface flaws. In order to perform the testing of the novel ECP an automatic NDT system was developed based on a PXI platform. This measurement system assures 2D motion of the eddy current probe over the conductive sample to be tested, provides the eddy current probe excitation current, the ECP output signal conditioning and acquisition, the primary processing of the acquired signal and the representation of data.

II. GMR-uniform eddy current probe architectures

The two GMR-uniform eddy current probe architectures considered in this paper are presented in Figure. 1. Both of them have a parallelepiped shape with a tangential excitation coil characterized by a rectangular section. The magnetic field caused by the flaws is measured by a high sensitive magnetometer sensor based on four GMRs. The location of the magnetic sensor in relation to the excitation coil originates two different architectures. In one case the magnetic sensor is located at the centre of the bottom plane of the rectangular excitation coil and outside of it (U-ECP-O), while in the second case the magnetic sensor is located inside the excitation coil at the centre of the bottom plane of the excitation coil (U-ECP-I).

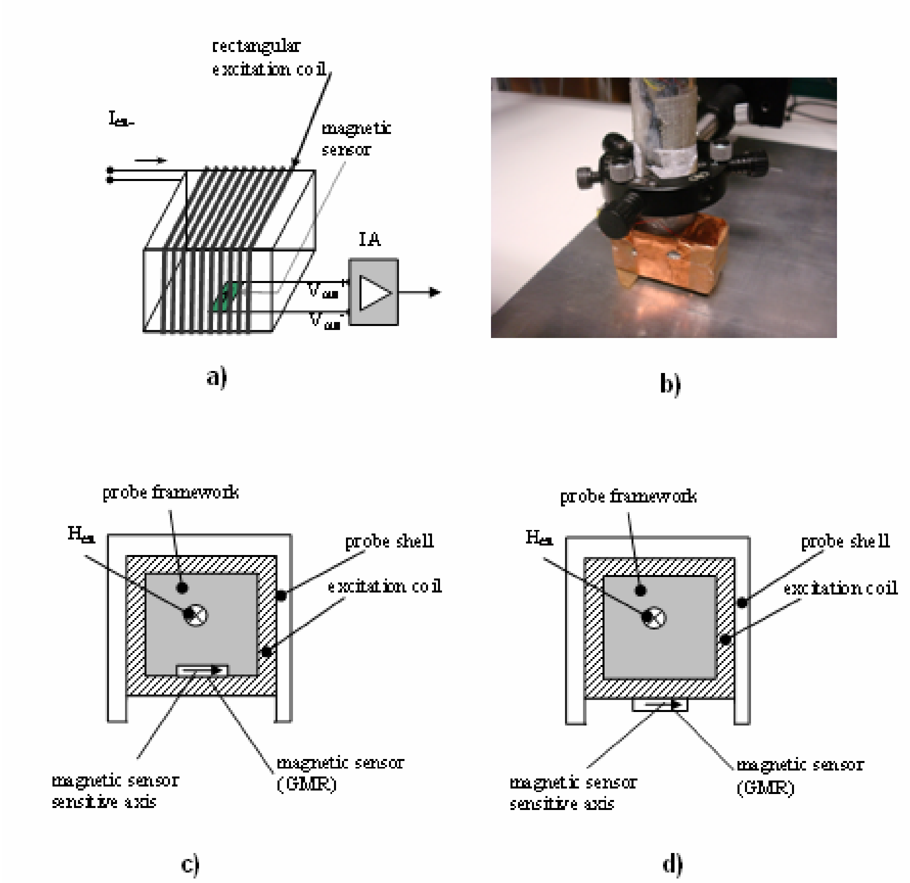


Figure 1. Probe architectures: a) schematic diagram; b) sensor photo; c) cross-section of U-ECP-I; d) cross-section of U-ECP-O

A. Parallelepiped shape excitation coil

In order to detect cracks and other non-uniformities in the aluminium plate, eddy currents must be created in the region under test. These eddy currents are due to the EMF induced by the ac current that flows in the excitation coil. It is the perturbation on the eddy current lines caused by the flaws that generate the magnetic field measured by the GMR sensor. The geometrical characteristics of the parallelepiped shape excitation coil are: 20 mm width, 20 mm height, 40 mm length, with 80 turns and uses a 0.5 mm diameter copper wire.

This large wide tangential excitation coil presents a reduced lift-off effect and it originates a uniform time-varying magnetic field in a large area of the sample under test. A copper probe shell is used to improve the SNR shielding external electromagnetic fields.

The rectangular coil was electrically characterized using an RLC-meter and the impedance modulus and phase characteristics are presented in Figure 2.

The amplitude of the excitation current values applied to the excitation coil varies in the interval [100, 300] mA depending on the input frequency. During the uniform eddy current probe testing, currents were provided by a

Fluke5700 calibrator that is part of the automatic measuring system working under GPIB control. However a low cost AC current driver including a signal generator based on Xicor 2206CP followed by a voltage-to-current converter was also designed and implemented in order to provide a more portable system.

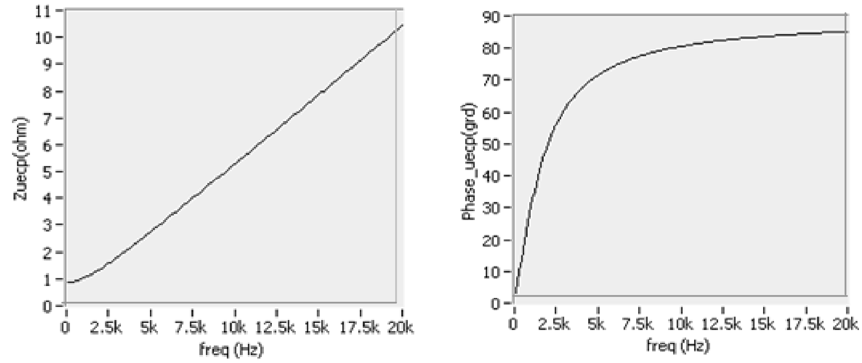


Figure 2. Characteristics of the excitation coil: a) impedance modulus vs. frequency; b) phase vs. frequency

Special attention was given to the excitation signal frequency taking into account the dependence between the frequency, f, and the skin depth, δ:

$$\delta = \sqrt{\frac{2}{\omega\ \sigma\ \mu}} \tag{1}$$

where μ is the magnetic permeability and σ the electric conductivity of the medium. For the particular case of the aluminum plate to be tested, Al-2024-T4, $\mu = \mu_0$ and $\sigma = 1.75\times10^7$ S/m, the electromagnetic field penetration inside the aluminum, δ, versus frequency is presented in Figure 3.

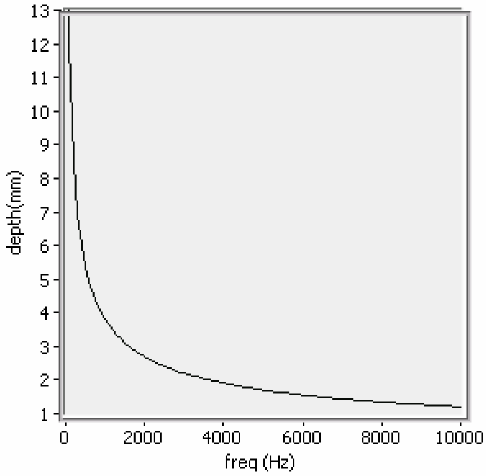


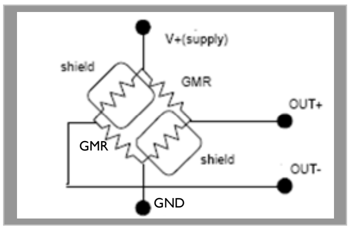
Figure 3. Skin depth vs. excitation signal frequency

It is clear that a low frequency excitation (e.g. f =500Hz) can be used to inspect cracks that penetrate deep into the plate (about 5.4 mm), while for detecting superficial flaws high frequency values (e.g., for f =10 kHz the penetration depth is1.2 mm) are recommended.

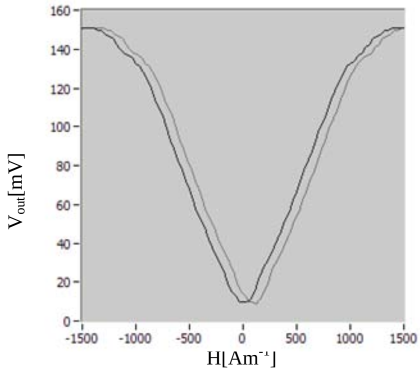
B. GMR sensor

The magnetic sensor is an important part of the proposed U-ECP-I and U-ECP-O probes. It is used an AA002, from NVE, that includes four 5 kΩ GMR configured in a Wheatstone bridge as presented in Figure 4-a). Two GMRs are shielded by two large plate structures that act also as flux concentrators. The other two GMRs decrease in resistance when a magnetic field is applied and it is this imbalance that leads to the bridge output. This configuration, better than the usage of a standalone GMR, provides higher precision and accuracy to the sensor.

The magnetic field sensor output characteristics were obtained experimentally using a Fluke5700 calibrator, GPIB controlled by NI-PXI-GPIB that injects current in a solenoid. The sensor to be tested was introduced inside the solenoid with its sensitive axis coincident to the solenoid axis. The typical omnipolar characteristic obtained is presented in Figure 4-b).



a)



b)

Figure 4. Magnetic sensor internal architecture and magnetic field sensor output characteristics

C. Uniform eddy current probe calibration

A suitably precise method to accurately adjust the uniform eddy current probe/specimen gap is required for calibration. In the present case the z axis adjustment was done using a long-travel high-resolution micrometer attached to the probe support. Using this manual positioning system for the z-axis the calibration is performed. Thus the U-ECP is moved to increase the distance between the GMR plane and the aluminum plate under test till minimum amplitude, A_{min}^{cal} of the detected signal is registered. This value corresponds to probe in the open air scenario and is measured using the acquired samples of the signals delivered by the GMR for a frequency range 0.1<f<10 kHz of the sinusoidal current injected in the excitation coil. The A_{min}^{cal} calculation is done using a sine fitting algorithm, as part of the "Crack Software" of the NDT testing system described in [11], and used to make the offset correction of the measured amplitudes associated with aluminum plate non destructive testing. The offset value is generally related to the misalignment of the GMR sensor which makes the sensor sensitive to the sinusoidal magnetic field generated by the excitation coil.
During the calibration procedure the magnetic field biasing is also checked. Thus, with the probe closed to the aluminum plate specimen, the position of the permanent magnet is adjusted to maximize the voltage value delivered by the GMR and to minimize the THD(%) values for a given excitation current. More elements are included by authors in [12].

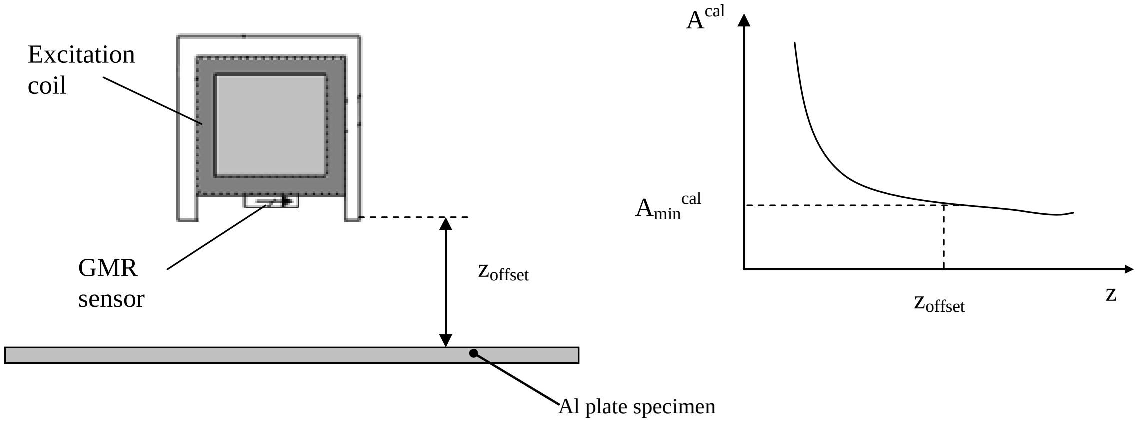


Figure 5. Graphical representation of the calibration procedure of U-ECP-I "in open air".

III. Results and discussion

The two probes, U-ECP-I with the magnetic sensor located inside the excitation coil and U-ECP-O with the magnetic sensor located at the external bottom plane of the parallelepiped excitation coil, were tested to detect

defects in a duraluminium plate using an automatic measurement system already described in [9], that includes a XY motion system, a PXI system with a NI PXI-6251 multifunction acquisition board. Different defects such as flaws and holes were machined on the plates and scanned with the probes.
For a machined straight crack with 15 mm length, 1 mm width and 2 mm depth, the image obtained from the values measured when the U-ECP-O scans the plate is presented in Figure 5. The excitation current is 200 mA with 5 kHz.

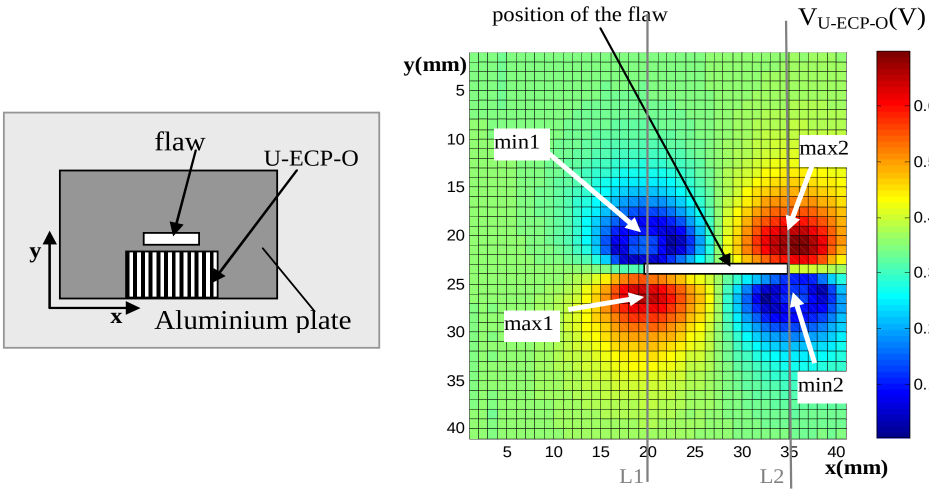


Figure 5. Image when V $_{U-ECP-O}$ scans the sample and the magnetic field lines are parallel to the crack axis

At each position of the scanning, data is acquired during some periods of the excitation current at 400kS/s. The data acquired from the sensor are adjusted using a four-parameter sine fitting algorithm. This method uses data from two inputs, excitation current from the coil and output voltage from the GMR sensor, to estimate the signal amplitude. To suppress (or minimize) the noise which is superimposed to the informative part of the signal, several processing techniques have been developed to improve the available measurement data. After applying the processing algorithm described in [10] the image presented in Figure 5 is obtained. The picture depicts a crack with 15 mm length and 1 mm width, which corresponds to the dimensions of the crack machined in the plate. The crack length can be estimated as the distance between the L1 and L2 lines defined by the position of min1-max1 and min2-max2.
Other tests were carried out for defects machined in welding zones using U-ECP-I and U-ECP-O. Figure 6 presents the raw data obtained for the amplitude and phase of the U-ECP-O output voltage for a 51x11 mm scanned area using a 1 mm scanning step. The phase graph is more informative about the defect localization in the weld zone being the amplitude graph strongly affected by the lift-off effect.

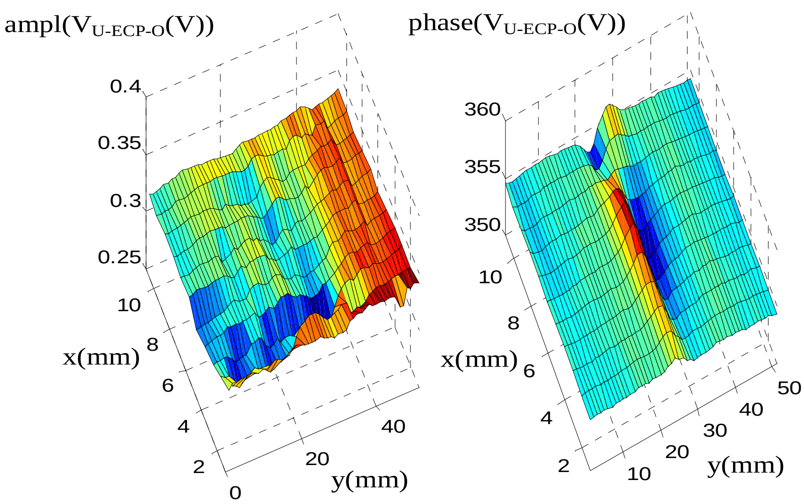


Figure 6. V $_{U-ECP-O}$ signal amplitude and phase vs. x-y position where the excitation uniform magnetic field lines are parallel to weld line

IV. Conclusions

The experimental results have shown that the proposed architectures for uniform eddy current probes are highly sensitive, especially when the magnetic sensor is located outside the parallelepiped shape excitation coil. Flaws parallel and perpendicular to the line of the uniform magnetic field induced in the conductive material under test can be detected. In this work a characterization of the parallelepiped shape excitation coils and of the GMR magnetic sensors was done. Tests to detect different kinds of defects including cracks in a weld zone were carried out with very positive results for duraluminum specimens that were especially used taking into account the involvement of the team in NDT on aircraft aluminum plates.

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