



UNIFORM EDDY CURRENT PROBE IMPLEMENTATION USING PLANAR EXCITATION COIL AND GMR SENSOR ARRAY

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Abstract: Defect detection in conductive plates represents an important issue. This work presents designed and implemented uniform eddy current probe architecture (UECP) that includes a planar excitation coil and a GMR magnetometer sensor array as part of a non-destructive testing (NDT) system developed using a virtual instrument system technology. The usage of GMR sensors provides frequency independent sensitivity to the UECP, assuring speed, depth, and higher resolution in eddy-current testing, while the usage of a set of GMR sensors allows rapid scanning of an area for defects in a single pass.

A practical approach concerning the UECP design, implementation and experimental results obtained on cracks detection machined in aluminum plates for a single or multiple GMR sensor usage as main parts of UECP are presented. Experimental results regarding the usage of the novel eddy current probe to detect induced flaws in aluminum plates are included in the paper.

Keywords: non-destructive testing, uniform eddy current probe, giant magnetoresistance sensors array.

1. INTRODUCTION

Defect detection in electrically conductive plates offers an exciting and interesting challenge to both researchers and applied technologists. For non magnetic metallic materials such as aluminum, the major problem of interest is the detection, location and geometric characterization of the non-uniformities caused by different elements such the existence of flaws [1] or the bad quality of processed weld lines [2]. An important solution in this field is obtained by using induced eddy currents [3] that create a secondary magnetic field which can be measured with coils or magnetometers.

Eddy current testing has the important advantage of non-contact and fast testing of conductive plates. Thus, different eddy current probe (ECP) architectures to detect flaws are reported in the literature [3][4][5]. An excitation coil and detection coils usually form the eddy current probe. This architecture is still considered a standard one and corresponds to the commercial systems for NDT. Olympus company can be mentioned as NDT systems and eddy current probes [6] manufacturer. At the same time, mainly in the research field, the usage of giant magnetoresistors to replace components of classical ECP became a reality. Using giant magnetoresistors as magnetometers for field detection, makes this probe more sensitive for a broadband excitation frequency [7][8]. This ECP architecture that combines a

pancake excitation coil with a GMR for field detection, still presents large noise and distortion due to the lift-off effect and to the electromagnetic material characteristics. Several implementations of this kind of probe were developed by the authors and different kinds of defects were detected and later analyzed to extract information related with flaw localization or flaw geometrical characteristics estimation [9][10][11].

A significant improvement of the ECP capabilities including the diminishing of the noise associated to the lift-off effect is related to the usage of uniform eddy current generation. Thus, uniform eddy current probes were developed by Koyama [12] and Smith [13]. These eddy current probes have a rectangular excitation coil and several coil detectors disposed inside the excitation coil. These ECP architectures are still characterized by a limited sensitivity and cannot be used to detect deep flaws in conductive materials due to the high frequency operational range.

Combining the advantages of uniform magnetic field generation with the high sensitivity of the GMR magnetometer sensors, new architectures of uniform eddy current probes (UECP) were reported by the authors [2][14].

Good results were obtained on flaws detection using these new architectures. However, the size of the excitation coil was one of the main drawbacks, and the scanning time when a big region of a plate might be scanned was too high. The main reason for the high scanning times was the measurement type, which was done point by point using a single GMR magnetometer.

The above mentioned drawback relating the size of the rectangular coil used to generate the uniform magnetic field was eliminated using a new uniform eddy current probe (UECP) that includes two planar spiral rectangular excitation coils. The detection part is expressed by high sensitivity magnetometers with a set of GMR sensors that are used to detect the magnetic field component tangential to the sample and perpendicular to the primary excitation field.

A signal conditioning circuit including an analog multiplexer and multichannel programmable gain amplifier connected to the GMR sensor outputs deliver the voltage signals that depend on the magnetic field under measurement. A modular PXI system provides the excitation signal, the control of the conditioning circuits and the acquisition of the signals provided by the magnetometer channel.

A signal processing component implemented on a PC that controls the PXI modular system performs the

amplitude and phase calculation of the acquired signals and the graphical representation of the scanned region. In order to diminish the scanning time to detect a defect in the conductive plate under test different scanning procedures that use single or multiple GMR sensors are considered.

This paper is organized as follows: section 2 presents the uniform eddy current architecture including the sensor and the conditioning circuits. In section 3 the modular PXI system and XY scanning system used on the NDT tasks together the UECP are presented. Section 4 presents the several results obtained for the new probe. Finally, section 5 states our conclusions.

2. UNIFORM PROBE ARCHITECTURE

In order to reduce the dimension of eddy current probe, through the diminishing of the excitation coil size and assuring at the same time better performances, the present prototype uses planar spiral rectangular excitation coils manufactured using the two side PCB technology. (Fig. 1).

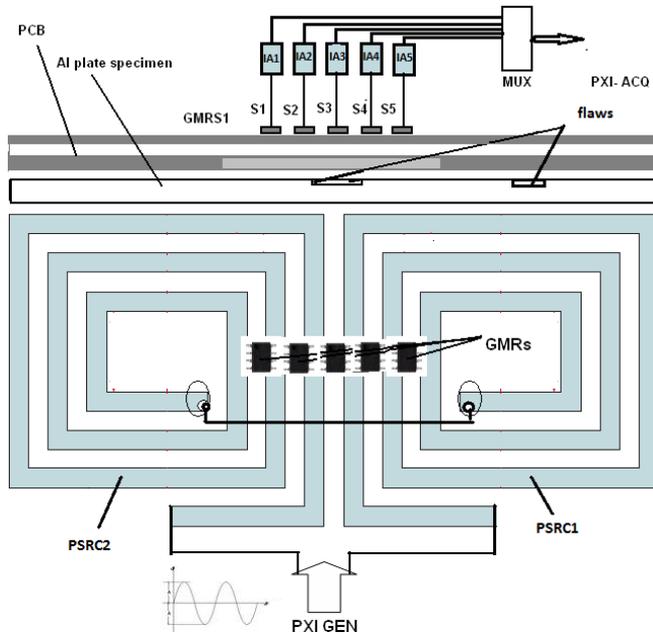


Fig. 1. Uniform eddy current probe (UECP) architecture based on a GMR sensor array and a planar spiral rectangular coil (S1..S5 – GMR sensors, PRC1.PRC2- planar spiral rectangular coils, MUX- multiplexer, IA-instrumentation amplifier, PXI-GEN – sinusoidal generator PXI-5401)

The UECP is implemented on a double side PCB. Thus, on one side two planar spiral rectangular coils (PSRC1, PSRC2) are implemented while on the other side an array of GMR AA-002 NVE sensors were inserted. Appropriate conditioning circuits including the magnetometer signal amplification and multiplexing are disposed on the GMR magnetometer side.

The practical implementation of the described eddy current prototype mounted on the XY scanner system is presented in Fig. 2.

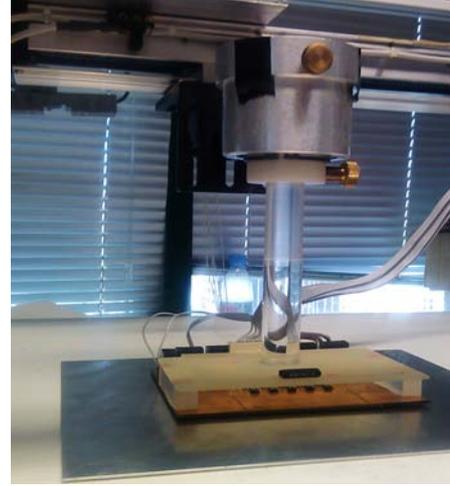


Fig. 2. The prototype of uniform eddy current probe (UECP) architecture based on a GMR sensor array

2.1. Uniform Eddy Current Generator

In order to detect cracks and other non-uniformities in the aluminum plate, the uniform field excitation coils was connected to an ac current source. The defect detection is related to the existence of a perturbation on the eddy current lines that generate the secondary magnetic field to be measured by the magnetometer GMR sensor. The characteristics of the planar spiral coil are:

- 4 mm inner diameter,
- 30 mm outer diameter,
- number of turns 55 for one planar spiral coil,
- 0.2 mm turn width,
- 0.6 mm distance between two successive turns.

Both planar spiral coils are connected in order to originate a uniform time-varying magnetic field in an area of the sample under test.

Taking into account the crack depth, special attention was given to the excitation signal frequency taking into account the dependence between the frequency f and the aluminum plate standard penetration depth, δ :

$$\delta = \sqrt{\frac{1}{\pi \cdot f \cdot \sigma \cdot \mu}} \quad (1)$$

where μ is the magnetic permeability and σ is the electric conductivity of the plate. For the particular case of the aluminum plate to be tested, Al-2024-T3, $\mu = \mu_0$ and $\sigma = 18.7 \text{ MS/m}$.

2.2 GMR sensor array

The GMR sensor array includes a set of five individual magnetometers AA002 from NVE and materializes the detection part of the uniform eddy current probe. Each AA002 includes four 5 k Ω GMRs configured in a

Wheatstone bridge, this configuration providing higher precision and accuracy to the sensor (Fig. 3).

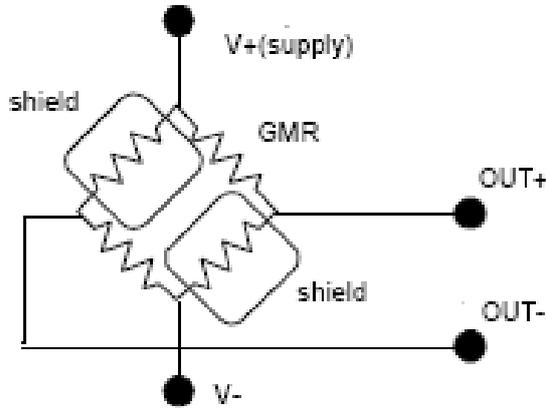


Fig. 3. AA002 magnetometer internal scheme (GMR- giant magnetoresistor)

The evolution of the GMR Wheatstone bridge voltage output versus applied DC magnetic excitation field is presented in Fig. 4.

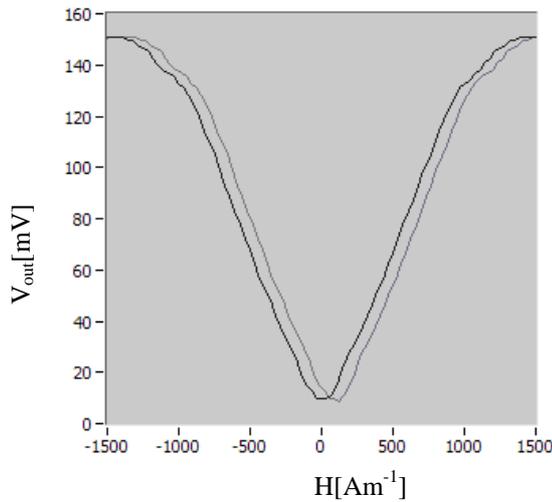


Fig. 4. V-shaped GMR sensor characteristic

In Fig. 4 a double trace due to the hysteresis effect can be observed. This effect is related to the diminishing of reproducibility and flaw location accuracy.

For the present prototype a distance of 10 mm was imposed between the sensitive axes of the magnetometers that permit to detect non-uniformities covering a relatively high region of the aluminum plate in only one scan. Due to the GMR magnetic field sensor output V-shaped characteristic, presented in Fig. 4, a dc magnetic field generated by a set of small permanent magnets (AlNiCo type with $H_c=51$ kA/m) was applied for biasing. Considering the high dispersion of the magnetometers and the permanent magnet characteristics, different responses of the AA002 individual sensors in the magnetometer array were observed. Combining an appropriate applied excitation

current to an appropriate geometrical position of the permanent magnet array the differences between the magnetometer sensor responses can be diminished. A calibration procedure can be included in order to find out the multiplication coefficients that can be used to perform the correction of magnetic sensors individual response.

2.3 Conditioning circuits

The UECP conditioning circuit was designed to assure the appropriate level of amplification but also to permit the connection of the sensor to the single analog input or multiple analog input acquisition system. Thus each UECP GMR magnetometer differential output (see Fig. 2) is connected to the In+ and In- inputs of the INA118 instrumentation amplifier (IAi).

The RSE (Out1...Out5) outputs of the instrumentation amplifiers (IAi) (see Fig. 1) are directly connected to the analog inputs of the PXI-6231 acquisition module when 5 analog inputs are available or are connected to the CD4051 multiplexer analog inputs, the output being connected to the AI0 analog input of the acquisition module. The channel selection is done in this case using one of the PXI-6231 digital output port.

3. MODULAR PXI AND XY SCANNING SYSTEM

In order to perform the NDT tests, the designed and implemented probe is mechanically fixed on the cursor of a XY scanning systems from Rotra with a resolution up to 100 μ m. The XY scanning control is performed using a RS232 communication port associated to a PXI modular system and a software component of the "Crack" software described in [15]. The "Crack" software was developed in LabVIEW and implemented on a PC that communicates with the PXI modular system using a PCI-PXI bridge. The main tasks performed by the "Crack" software are:

- Conditioning circuit control
- Acquisition control
- XY scanning system control
- Signal processing based on 3 parameters sine fitting algorithm for amplitude and phase calculation
- Inductive image representation (amplitude and phase representation) for a given scanned area
- Data storage

An additional software component was included on the "Crack" software to allow the control of the multiplexer of the eddy current probe and the distribution of the calculated amplitudes in individual images that correspond to each individual GMR.

4. RESULTS AND DISCUSSIONS

A set of aluminum plate specimens with induced cracks was used in the present work for testing the novel uniform eddy current probe with the GMR array. For the particular induced flaws the system including the eddy current probe was used according to the NDT implemented procedure:

a) performing a 40 mm x 10 mm scanning with acquisition and data processing of the data associated to the selected GMR sensors (e.g. S1 and S2). b) graphical representation of the magnetic field distribution corresponding to the selected GMR sensor from the GMR sensor array. For the particular case of 10 mm x 0.7 mm x 1 mm crack the graphical representation of the measured field distribution corresponding to S1 and S2 is presented in Fig. 4.

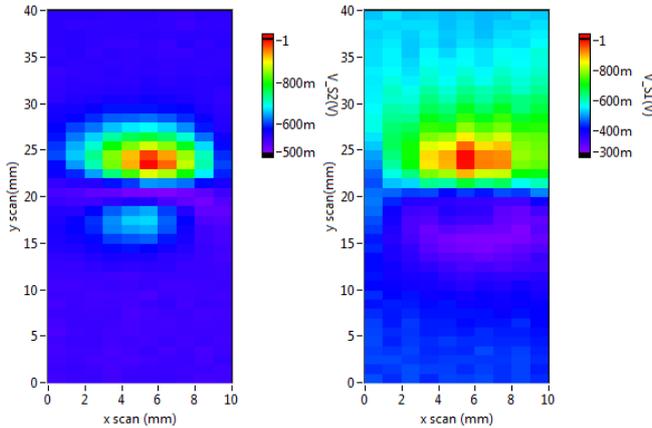


Fig. 4. Amplitude inductive images obtained using the GMR S1 and S2 sensors from the GMR array (V_S1, V_S2 – voltage amplitudes associated to the S1 and S2 measurement channels)

As it can be observed in Fig. 4 the sensitivities of the GMR sensors S1 and S2 are different, because the GMRs are working in different functioning points of their characteristic (see Fig.3). Additional work will be done to improve the capability of the proposed eddy current probe with appropriate polarization of the individual GMR sensors. However, merging the images of S1 and S2 the resulting image is quite similar to the image obtained using the S2 individual measurement channel (Fig. 5) for 40 mm x 20 mm scanning region.

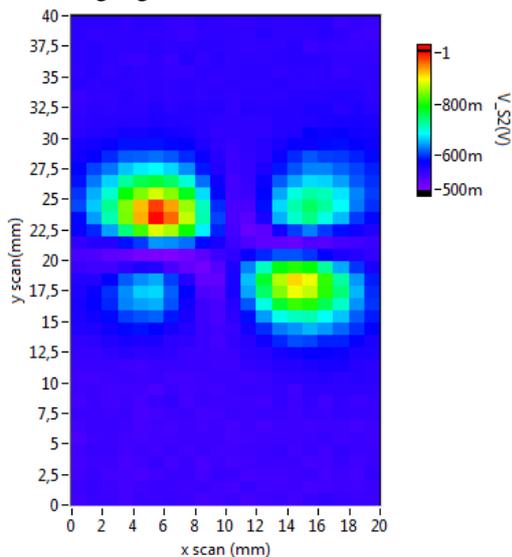


Fig. 5. Amplitude images obtained using S2 from the GMR array (V_S2 – voltage amplitude associated with S2) for 40 mm x 20 mm scanned area.

The magnetic field disturbance caused by the crack existence is also well sensed by the S3 sensor (Fig. 6).

However, the asymmetry of the 40 mm x 10 mm images did not permit to use this image for localization and geometrical feature extraction of the detected crack as can be done using the information from S2 and S1 images.

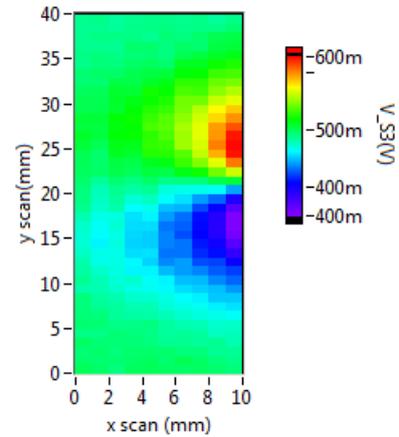


Fig. 6. Amplitude inductive images obtained using S3 from GMR array (V_S3– voltage amplitude associated with S2) for 40 mm x 10 mm scanned area.

Considering the usage of all five GMR sensors, the scanning time corresponding to the NDT procedure can be diminished up to 5 times. However, due to the dispersion of the GMR characteristics (different position of the operating points) the image matching of the five “puzzle” pieces, is far from optimal in the already performed tests. To solve this problem different solutions are considered such as the usage of additional transversal permanent magnet that is able to impose an appropriate functioning point for each of the GMR sensors. Even without a proper biasing of the individual elements of the GMR array the presented eddy current probe shows good characteristics and a fast detection procedure of flaw regions by merging few single scans.

If high quality image is required, the best positioned GMR array element can be chosen to extract the proper inductive image.

3. CONCLUSION

A uniform eddy current probe architecture, based on the usage of two planar spiral rectangular coils and a distributed magnetometer materialized by a set of GMR sensors was presented. Flaws parallel and perpendicular to the line of the uniform magnetic field induced in the conductive material under test can be faster detected. Better results are obtained in crack detection and accurate localization using more than one sensor. This procedure can be considered as part of the crack detection validation. The defect critical area can be faster identified for one or two single track of the GMR array.

The future work will consist on improving the characteristics of the developed uniform eddy current probe in order to assure an accurate inductive matching of the individual GMR scanning image when a GMR array is used. Special attention will be granted to the magnetometer biasing problem.

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