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SPEED-UP NDT BASED ON GMR ARRAY UNIFORM EDDY CURRENT PROBE

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Abstract: The usage of eddy current probes including single magnetic field sensor represents a common solution for defect detection in conductive specimens but it is a time consuming procedure when large surface specimens are tested. In order to speed-up the nondestructive testing procedure, eddy current probes including a single excitation coil and an array of detection coils represent one of the solutions to reduce the NDT times but mainly detects the surface defects. Deep defects require different sensing elements such as GMRs. In this work an optimized uniform eddy current probe architecture including two planar excitation coils, a rectangular magnetic field biasing coil and a GMR magnetometer sensor array is presented. An ac current is applied to the planar spiral rectangular coil of the probe, while a set of GMR magnetometer sensors detects the induced magnetic field in the specimens under test. The rectangular coil provides the dc uniform magnetic field assuring appropriate biasing of the GMR magnetometers of the probe, setting-up the functioning point on the linear region and at the same branch of GMR static characteristics. The differences of the images obtained on the same specimen surface for each GMR are reduced if all sensors are biased on the same working point. Elements of automated measurement system for NDT, including a validation procedure based on a 2D template matching algorithm and the corresponding experimental results are included in the paper.

Keywords: non-destructive testing, uniform eddy current probe, giant magneto-resistance sensors array, sensor biasing, 2D template matching

1. INTRODUCTION

Non-destructive testing of nonmagnetic metallic materials such as aluminum is a growing area that requires novel sensing solutions that assure defect detection deeply in conductive materials but also at reduced times required by the NDT procedures. Thus, traditional inductive sensors [1,2] of the eddy current probe (ECP) characterized by fully coil based architecture are replaced by new probes including single or multiple solid state magneto-resistive sensors such as "giant" magnetoresistances to detect the magnetic field associated with the eddy currents induced in conductive specimens through the usage of rectangular coils or even planar PCB coils [3,4].

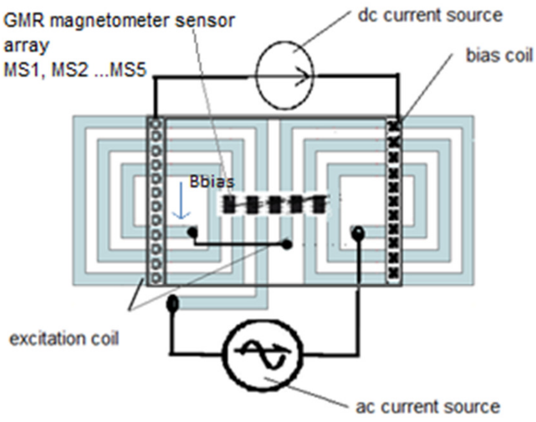
Nowadays the giant magneto-resistors as magnetometer sensors are generally used assuring higher sensitivity than the probes that are using detection coils but also permits the usage of broadband excitation frequency that assures the detection of deeply induced defects in conductive plates. During the last years several implementations of GMR based eddy current probes were designed and implemented by the authors [5,6] and part of the developed probes were characterized by uniform excitation field and single GMR magnetometer sensor [7,8].

Taking into account the necessity to increase the accuracy and reliability of the probe, reducing the dispersion effect of the GMR magnetometer characteristics but also to speed-up the NDT procedure a uniform eddy current probe including a GMR magnetometer sensor array represents a solution. Several results were reported by authors [9] and additional improvements were done regarding the uniform eddy current probe architecture. It is the case of the new uniform eddy current probe of rectangular coil that provides the appropriate dc magnetic biasing for individual magnetometers. This coil can be also used to perform on-line characterization of the GMR magnetometer sensor array as part of the magnetic biasing optimization procedure, but also as part of the fault detection and diagnosis procedure when anomalous functioning of individual sensing element is detected.

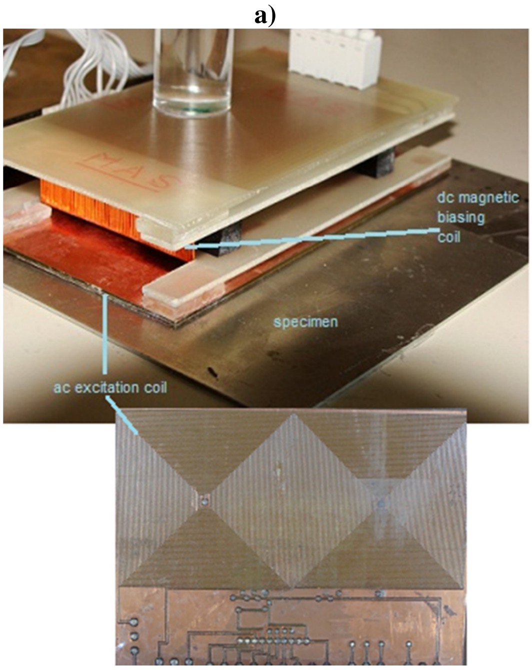
The novel eddy current capabilities were tested using an automatic measurement and control system (AMCS) based on data acquisition board, ac current calibrator, dc current power supply controlled by computer that also performs XY scanner control using RS232 interface. LabVIEW software was developed for AMCS that assures the instrument control processing and data representation of the NDT data but also includes a validation procedure based on a 2D template matching algorithm implemented in a Matlab script of the AMCS LabVIEW software. Experimental results regarding the GMR magnetometer sensor characterization, flaw detection using the novel eddy current probe as so as several validation results are presented.

2. GMR ARRAY UNIFORM EDDY CURRENT PROBE

The uniform eddy current probe (U-ECP) is mainly composed by two planar spiral rectangular excitation coils manufactured using the two side PCB technology and a GMR magnetometer sensor array. The design of the probe was done taking into account the GMR magnetometer sensors characteristics referring the magnetic field detection (magnetic field sensitive axis) and magnetic field distribution associated with the excitation coil position. The uniform eddy current probe based on GMR sensor array is presented in Fig.1



a)



b)

Fig. 1 Uniform eddy current probe based on GMR magnetometer sensor array, planar spiral rectangular excitation coils and rectangular magnetic biasing coil a) design b) implementation.

Fig. 1 represents the uniform eddy current probe that includes a GMR magnetometer sensor array with five magnetometers (MS1…MS5), an ac current source connected to the planar rectangular excitation coil pair and a dc current source connected to the rectangular biasing coil.

2.1. Excitation and biasing coils

The excitation magnetic field is produced by two planar spiral rectangular excitation coils with appropriate connection in order to assure an additive uniform magnetic field on the specimen level (e.g. aluminum plate). The characteristics of the planar spiral rectangular 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.

An ac-current source from a Fluke 5700 was used to inject values of currents between 50mA and 150mA with frequencies less than 10 kHz. The magnetic field associated with eddy currents (H_{ec}) that appear in the aluminum plate specimen under tests is characterized by values that highlight the existence or non-existence of anomalies (e.g. flaws, corrosion) on the specimen. The distribution of H_{ec} on the specimen plan is measured using a GMR magnetometer array with five magnetometers AA002 from NVE. Considering the slightly differences between the static characteristics of individual GMRs, but also differences between the positions of the functioning point from one sensor to another, a rectangular biasing coil mounted on the top of the GMR array was included as part of eddy current probe. Injecting the appropriate dc current into the coil, a uniform magnetic field is generated, polarizing each individual magnetometer. This means that the entire sensor array is subject to the same value of the applied dc magnetic field B_{bias}. The value of the applied dc current, I_{bias} is adjusted in order to obtain similar response for all of the sensor array elements when and ac excitation current is applied to the planar coil and a defect free specimen is used. The characteristics of the biasing coil are: length: 50mm, width: 82mm, 0.5mm turn width and number of turns N=92.

2.2. Magnetometer sensor array

In order to diminish the testing (scanning) times of the aluminum plates specimens through the measurement of induced magnetic distribution a set of GMR magnetometer sensor NVE AA002 are used. Considering the geometry of the used magnetometers expressed by the usage of SOIC8, but also the limitations associated with PCB manufacturing the distance between the GMR magnetometer sensor axis of the designed eddy current probe is about 13mm. Referring to the internal electrical architecture of AA002 it includes four 5 kΩ GMRs configured in a bridge differential form, thus assuring high sensitivity but also reduced temperature influence. Referring the AA002, the hysteresis existence is mentioned in the characteristics data sheet and the necessity to apply an appropriate biasing magnetic field in order to avoid the distortion of the detected ac magnetic field for the wrong positioning of magnetometer sensor functioning point. The NVE solution usually includes the usage of permanent magnets that assure the right positioning of the magnetometer sensor functioning point and good results are also reported by authors regarding this method [10]. However, when different magnetometer sensors are considered the usage of a small dimension permanent magnet is not the proper solution considering the spatial distribution of the sensors, which will be affected by the dc magnetic field in different manner. The non-uniform distribution of the magnetic field conducts to distorted inductive images obtained from different individual GMR magnetometer sensors, when the same flaw induced in a conductive plate is scanned. Using the novel architecture, the dc magnetic biasing problem is over passed through the usage of the rectangular coil that is able to generate a controlled uniform dc magnetic field on the sensors according to the previous obtained sensor static characteristics. The rectangular biasing coil is also used as part of a fault detection procedure implemented on the system software. Individual sensors are characterized on-line, imposing different magnetic fields using a programmed current source attached to the system.

3. NDT AUTOMATED MEASUREMENT SYSTEM

An automated measurement system was designed and implemented to perform the nondestructive tests using the proposed eddy current probe. It includes a Fluke 5700 calibrator working as an ac-current source, an Agilent E3631 working as a dc-current source, a USB DAQ for signal acquisition, and a ROTRA XY positioning system. The instruments are remote controlled using an application developed in LabVIEW and installed in a desktop PC that communicates with the instruments through RS232 (XY scanner), GPIB (Fluke 5700 and Agilent E3631A) and USB (NI USB DAQ 6251).

The application performs the XY eddy current probe motion control, the ac and dc excitation current control, the GMR magnetometer sensor array element selection, the signal acquisition and the signal processing of the acquired voltages. To extract the amplitude and phase information a three parameters sine fitting algorithm [11] was applied and a 2D graphical representation of the amplitude and phase variation for the scanned region of the specimen was carried out. In order to highlight the capability of the system to diminish the scanning time preserving the main elements of 2D amplitude variation profiles that are obtained through the usage of individual MSi (i=1..5) of the GMR magnetometer array an image template matching algorithm software component was added as a Matlab script on the NDT LabVIEW application. This template matching algorithm considers a square window image (W–having the same number of pixels in the X and Y directions) as a reference. This reference image (Rim) is obtained from the values measured with only one of the elements of the GMR sensors array of the uniform eddy current probe (e.g. MS3 the center sensor of the MSi array). It includes the area with the maximum amplitude therefore corresponding to the area having a crack machined on the aluminum plate surface. This image is compared with the target images (TIim) which are obtained with the other elements of the GMR sensors array embedded in the probe. The aim is to correlate pixels in the two images.

Finding the correlated pixels in the target images obtained for the same specimen using different elements (MSi) of the GMR sensor array allows the validation of the simultaneously use of multiple MSi diminishing the scanning time of the area.

The template matching algorithm is based on the calculation of the sum squared difference (SSD) and of the normalized cross correlation (NCC) for the I1 and I2 target template images.

$$SSD(i,j) = \sum_{(nx,ny)\in W} \left(I_1(i,j) - I_2(i+nx, j+ny)\right)^2 \qquad (1)$$

$$NCC(i,j) = \frac{\sum_{(nx,ny)\in W} \left(I_1(i,j)\cdot I_2(i+nx,j+ny)\right)}{\sqrt{\left(\sum_{(nx,ny)\in W} I_1^2(i,j)\cdot \sum_{(nx,ny)\in W} I_2^2(i+nx,j+ny)\right)}} \qquad (2)$$

The possibility to find a correlated region on the target images is related to an appropriate biasing of the MSi sensors. The appropriate bias corresponds to similar MSi functioning points on the linear region of the characteristics.

4. RESULTS AND DISCUSSION

The novel architecture of the eddy current probe includes dc excitation current that accomplishes magnetic biasing of the magnetometer sensors. It allows an on-line characterization of each GMR sensor before the specimen scanning process associated with the non-destructive testing procedure. Considering the magnetic field intensity associated with magnetometer sensor saturation the dc current supply is controlled to cover an extended dc magnetic field applied to the magnetometer sensor under test. The imposed dc currents were considered in the -1200mA to 1200mA interval and the test can be done simultaneously for all the GMR sensors included in the magnetometer sensor array in order to highlight the difference between the static characteristics of the MSi. The results obtained for the MS1 and MS2 static characteristics including the hysteresis behaviour of the sensors are presented in Fig. 2.

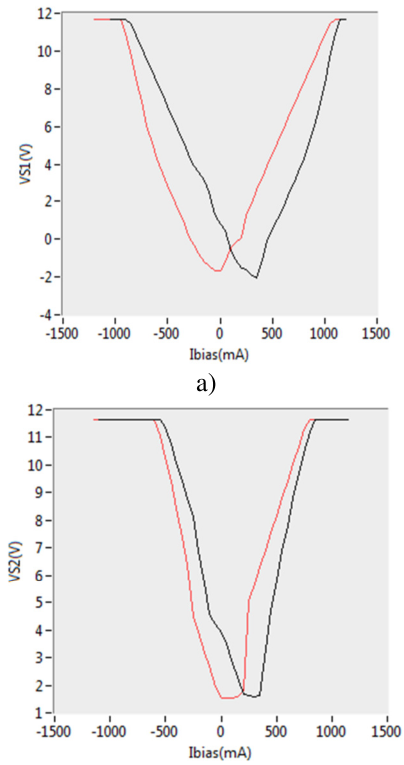


Fig. 2 The MSi static characteristic: a) MS1 case b) MS2 case.

As shown in Fig 2 there is a great dispersion in the characteristics of the sensors. However it depicts also linear regions where the position of the functioning point can be chosen for each sensor in order to reach similar amplitude variation on the sensor output voltage.

Using the middle sensor of the GMR magnetometer sensor array the reference inductive image for a 300mA dc current injected on the magnetic biasing coil while the excitation ac current injected in the excitation coil is characterized by 100mA, with frequency equal to 1000Hz. The image obtained from this middle sensor is depicted in Fig. 3.

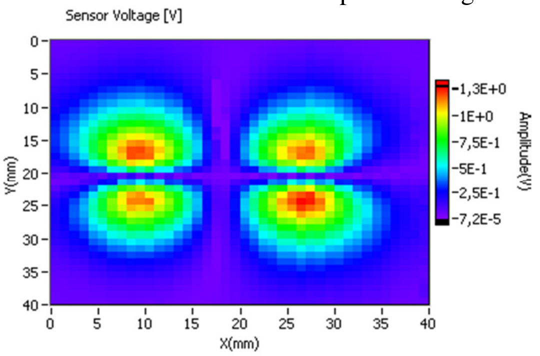
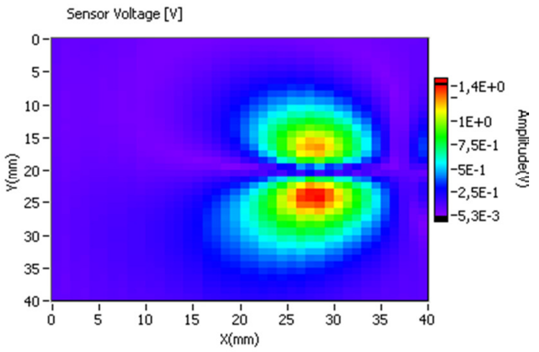
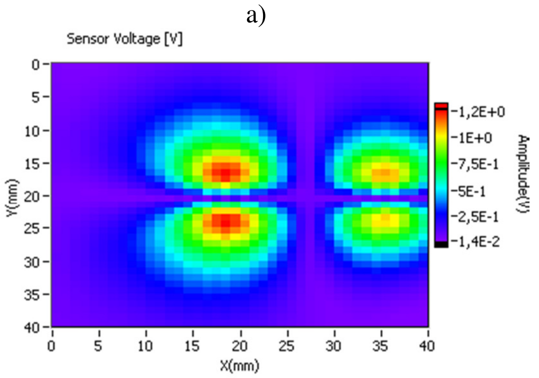


Fig. 3 MS3 amplitude image for (10x1x3)mm crack in an aluminium plate.

For the same crack and for the same initial position the MS1 and MS2 amplitude inductive images were obtained when the scanning region was 40x40 mm^2, with 1 mm scanning steps (Fig. 4).



a)



b)

Fig. 4 MS1 (a) and MS2 (b) amplitude images for a (10x1x3) mm crack in an aluminium plate

The images represented in Fig. 4 are considered as target images, where the template image (MaxTemplate) corresponds to peak 1 of the reference image presented in Fig. 3. The results obtained after the application of template matching algorithm are presented in Fig. 5 and in Fig.6.

The values of mapped SSD and NCC obtained during the 2D template matching procedure are varying between 0 (black) and 1 (white), the maximum values corresponding to matching points. Additionally, tests were done considering as template image the bottom-left maximum of the reference image no failure being registered on maxima associated with target images obtained through the MS1 and MS2 scanning.

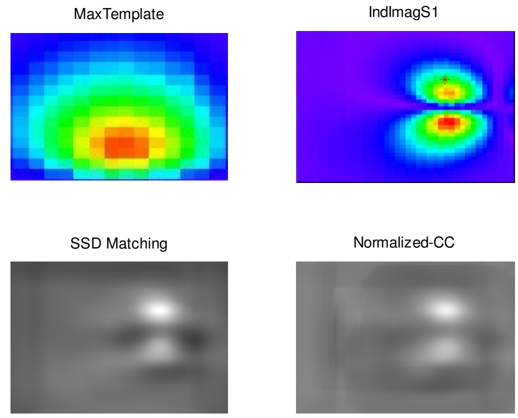


Fig. 5. The 2D template matching results obtained for MS1 amplitude inductive image (IndImagS1) as target image.

In Fig. 5 and Fig. 6 top-right the maximum recognition in the MS1 and MS2 inductive image is indicated using a "red star", based on the calculated values for SSD and NCC that are presented in Fig. 5 and Fig.6 (bottom-left) and (bottom-right).

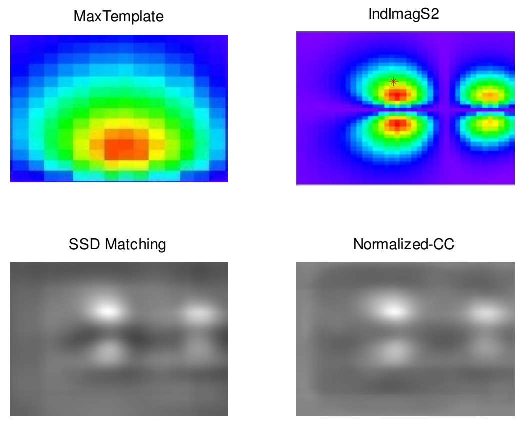


Fig. 6. The 2D template matching results obtained for MS2 amplitude inductive image (IndImagS2) as target image.

5. CONCLUSIONS AND FINAL WORK

A novel architecture of a uniform eddy current probe with on-line static characterization of embedded magnetometer sensors allowing the speed-up of the nondestructive testing procedure is presented in the paper. The novelty of the presented solution is the existence of magnetic biasing for the GMR sensors by the excitation current in the rectangular coil. The dc currents generate a uniform magnetic field in the magnetometer sensor array vicinity. Additionally the planar rectangular spiral coils provides an ac excitation on the specimen and the GMR magnetometer sensor array is used to detect the anomalies on the aluminum plate surface. The use of the array of sensors allows fault detection in a time less than that which is necessary in the traditional method using only one GMR sensor. The testing procedure involves the construction of picture images for the large area being tested at the expense of merging smaller individual amplitude inductive images obtained by individual sensors of the GMR magnetometer sensor array. The software developed for the measurement setup which includes a script for the validation procedure based on a 2D template matching algorithm, regarding the capability of the individual sensors to provide images highly correlated with reference image is also included in the paper.

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