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Experiment and Simulation of the Eddy Current NDT on an Aluminium Plate Using a Uniform Field Probe

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Abstract- In this paper we describe the work that has been developed in our laboratory using uniform field probes to detect cracks inside non-ferromagnetic metallic media, using the eddy current method. The experiments were carried out, and were accompanied by useful simulation work using conformal mapping. The experimental results agree with the simulations encouraging more complex work related to the characterization of defects by this experimental process.

I. Introduction

Different methods of non-destructive testing are currently used in industry. These methods rely on several physical phenomena. If the materials to be tested are non-ferromagnetic metals some common methods may be mentioned. Thus, methods based on ultrasound propagation [1], on electromagnetic induction [2] and on liquid penetrants [3] are usually employed. When a time-varying magnetic field is applied to a conductor an electromotive force is induced and eddy currents appear inside it. The nature of these currents depends on the electromagnetic properties of the material, such as the conductivity, and on the object geometry. Thus, the eddy current method may be applied to search for material inhomogeneities, flaws, cracks, or any other kind of material defects that causes perturbations of the eddy currents [4].

To apply this method, there must be a probe which applies a primary excitation field and reads the secondary field produced by the eddy currents. This probe is driven either manually by an operator or automatically by a mechanical positioning system. To extract useful information from the reading signals an acquisition system is mandatory and interpretation algorithms must be implemented in some kind of software application.

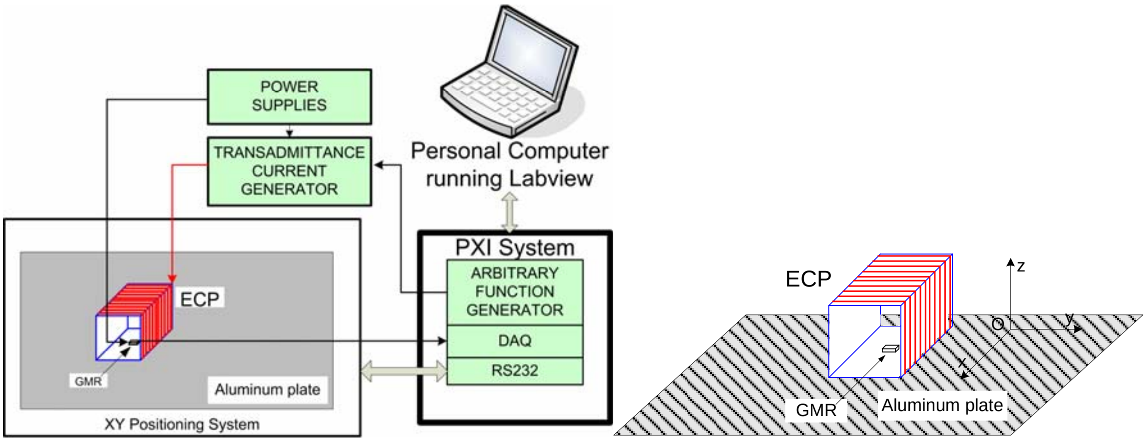
In the case of manual inspection, the achievement of reliable results is a tedious process and depends on the training capability of the human operator. Thus, the development of automated processes of data analysis is of great importance.

II. Description of the Experimental System

The experimental setup in use in our laboratory is represented in Fig.1 [4]. It includes a positioning system with a motion controller which drives an eddy current probe (ECP) over the surface of an aluminium plate where linear cracks were artificially machined. The complete system runs under the control of a LabView program via a modular NI-PXI system, which includes a data acquisition module to acquire the output signals from the ECP, an arbitrary function generator module and a serial RS232 interface to command the motion controller. The ECP excitation current is provided by a transadmittance generator, driven by the NI-PXI arbitrary function generator.

A. The Eddy Current Probe

The eddy current probe is composed of a rectangular cross-section coil and a giant magnetoresistor (GMR) sensor on the bottom plane, as depicted in Fig.1(a). This coil shape was chosen to obtain a spatially uniform magnetic field on a limited area of the surface of the aluminium plate that is being scanned. The giant magnetoresistor sensor, provided by Non Volatile Electronics, is composed of four giant magnetoresistors mounted in a bridge configuration and measures the magnetic field component parallel to the plate and perpendicular to the excitation coil axis. This giant magnetoresistor sensor must be polarised by a constant magnetic field in order to work in a linear region of its characteristic. This is achieved using a small permanent magnet attached to the probe. The GMR sensor presents a sensitivity of 3.7 mV/Oe for each volt applied by the bridge power supply. The ECP was excited with a sinusoidal current of I_{ex} =200 mA at the frequency f =1 kHz. Figure 1(b) depicts the ECP. The coil square cross section presents a lower surface in the close proximity of the plate. The wires of this bottom surface carry a current which is directed along the y-direction. The primary magnetic field under this surface is directed along the x-direction. The GMR sensitive axis is directed along Oy and, in theory, the magnetic field along Oy is of zero amplitude, on the condition that the plate is homogeneous. If the plate presents defects, a component Hy of the magnetic field will be detected.



(a) (b)

Figure 1. (a) System block diagram. (b) Probe with the GMR sensor.

B. The Experimental Method

The method was experimentally tested by scanning a 2 mm thick aluminium plate with , where a crack with 1 cm of length was machined. The area scanned by the probe was such that the eddy currents being perturbed by the presence of the crack were inside the constant excitation field at all times. This condition imposes that the probe dimensions must be scaled to the length of the crack to be detected, and is a necessary condition to match the experimental to the simulation results.

Due to the high sensitivity of the GMR sensor, the magnetic field component to be measured must be orthogonal to the direction of the excitation field to avoid sensor saturation since the primary field is several orders of magniture greater then the secondary field. In our probe the field component under measurement is parallel to the aluminium plate. Under these conditions, and for an ideal geometry, the GMR sensor only detects the perturbations of the eddy current magnetic field in one direction.

III. Conformal Mapping and Modelling Results

In this section we use a conformal mapping to preview how the current lines deviate from a crack, and the Biot-Savart law is used to preview the resulting magnetic field components.

A. Conformal Mapping

To determine the geometric configuration of the current lines in the presence of a linear crack we may use a conformal transformation [5]. Considering the $\bar{Z}$ complex plane, with $\bar{Z} = x + jy$, and the complex potential $\bar{P}$, with $\bar{P} = u + jv$, the following transformation allows us to determine both the scalar potential $u = u(x, y)$ and the flux function $v = v(x, y)$ as functions of position:

$$\bar{P} = u + jv = K\left[\bar{Z}\cos\alpha - j\left(\bar{Z}^2 - 1\right)^{1/2}\sin\alpha\right] \qquad (1)$$

If the lines of current are perpendicular to the crack direction the angle α is $\alpha = \pi/2$. To obtain the lines of current we must take the $v = const.$ and invert (1) to determine the corresponding curve in the $\bar{Z}$ plane. To determine the equipotentials, the condition $u = const.$ must be taken.

To determine the corresponding flux density the derivative of $\bar{P}$ is calculated. In our case the flux density must be interpreted as a current density. Taking $\alpha = \pi / 2$:

$$\frac{d\bar{P}}{d\bar{Z}} = K\left[-j\frac{\bar{Z}}{(\bar{Z}^2 - 1)^{1/2}}\right] = J_x + j\,J_y \qquad (2)$$

The graphical representation of this current density can be seen in Fig.2.

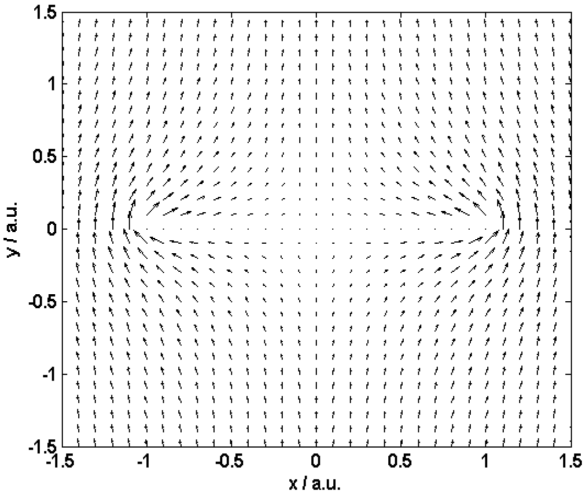


Figure 2. Current lines deviating from a linear crack.

We wish to determine the perturbation on the magnetic field originated by the corresponding perturbation on the currents. Thus, we must calculate the magnetic field from the difference between the currents represented in Fig.2 and the unperturbed currents without crack. This difference is represented in the following Fig.3.

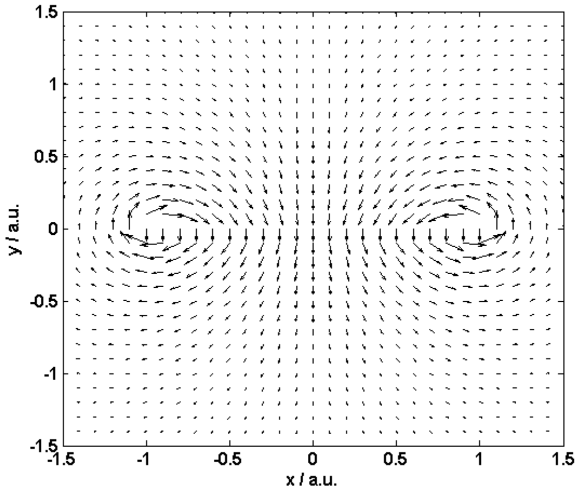


Figure 3. Perturbation of the current lines due to the crack.

B. Components of the Magnetic Field

The determination of the magnetic field originated by the current distribution represented in Fig.3 is performed using the Biot-Savart law [6], which for continuous media takes the form:

$$\mathbf{H}(\mathbf{r}) = \frac{1}{4\pi}\iiint_V \frac{\mathbf{J}(\mathbf{r}')\times\mathbf{R}}{R^2}\,dv \qquad (3)$$

In (3), $\mathbf{r}$ represents the point where the field is calculated, and $\mathbf{r}'$ the point where the element of current $\mathbf{J}(\mathbf{r}')$ is located inside *dv*. The vector $\mathbf{R} = \mathbf{r} - \mathbf{r}'$ connects the middle-point of *dv* to the point where the field is calculated. In our calculation the current is supposed to lie in a plane at the plate mid-thickness, and the points where the field is calculated are supposed to lie in a plane above and parallel to the plate, where the GMR sensor is supposed to travel.

We used an iterative approach in our calculations. Thus, the pair (m,n) references the position of each current element in the plate and the pair (k,l) references the position of each point where the field is evaluated. The discrete version of equation (3) takes the form:

$$\mathbf{H}(\mathrm{k,l}) = \frac{1}{4\pi}\sum_{\mathrm{m,n}} \frac{\mathbf{J}(\mathrm{m,n})\times \mathbf{R}_{\mathrm{m,n}}^{\mathrm{k,l}}}{R^2}\Delta v \tag{4}$$

The field map was determined and the results are depicted in Fig.4.

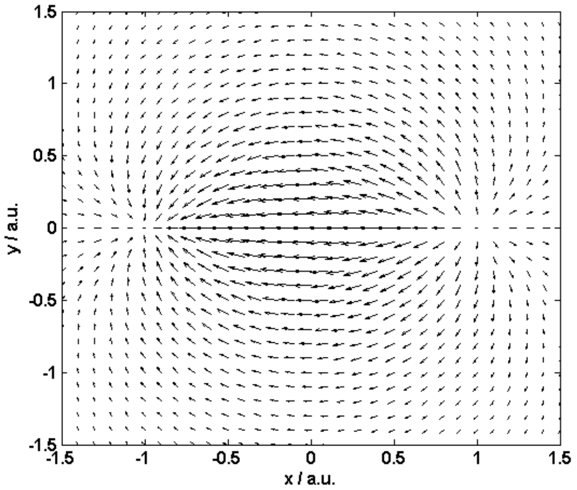
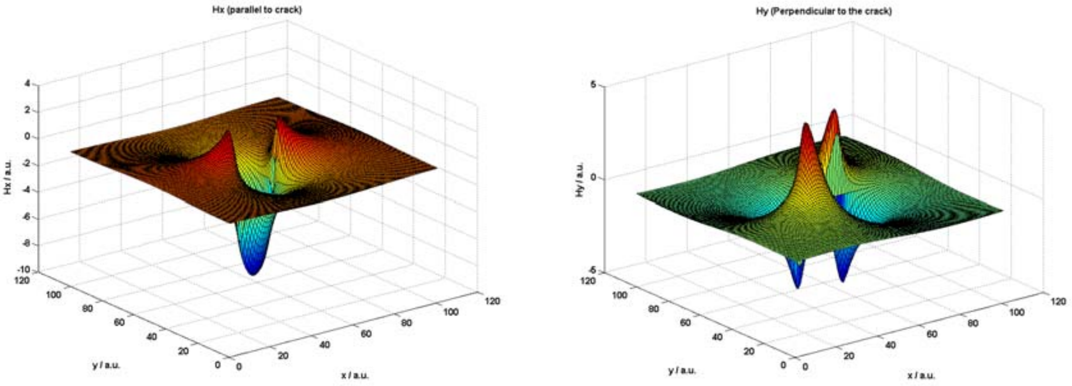


Figure 4. Components of the magnetic field in the (x,y) plane.

In Fig.5 we plot the surfaces $H_x(x,y)$ and $H_y(x,y)$, representing the two components of the in-plane magnetic field. Unfortunately the H_x component is not measurable experimentally, because it superimposed to the excitation field.



(a) (b)

Figure 5. Surface plots of the components of the magnetic field in the (x,y) plane. (a) Hx , (b) Hy.

IV. Experimental Results

Figure 6 represents the voltage measured with the ECP. The excitation frequency was set to $f_{ex} = 1\,\mathrm{kHz}$. The sampling frequency was $f_S = 400$ kHz and the number of samples was set to N=10^5, which corresponds to a total of 250 periods of the excitation for each point under measurement. A total of 50×50 points separated by 1 mm of distance were measured over an aluminium plate with 2 mm of thickness where a crack with 1 cm of length and 0.5 mm wide had been cut. The gap between the probe and the plate was set to 1 mm.

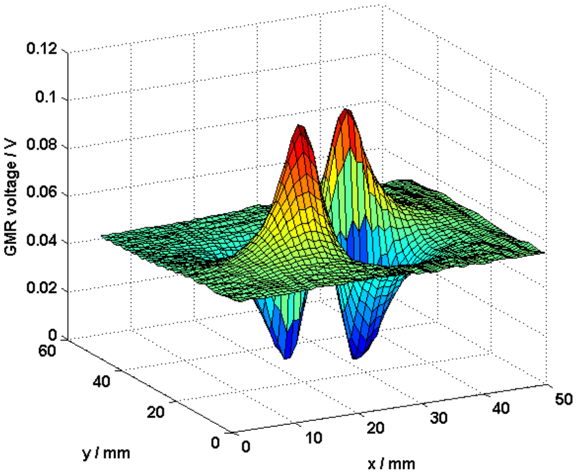


Figure 6. Surface plot of the measurement of the Hy component using the ECP probe.

The resemblance between the pictures obtained by simulation and experimentally is remarkable, and shows how useful the simulation work can be to preview the experimental results. The offset of 40 mV, visible on Fig.6, is produced by a very small amount of the excitation field that is detected by the GMR sensor.

V. Conclusions

In this paper we reported the results obtained using a conformal transformation to preview the spatial variation of the voltage detected by an eddy current probe when an aluminium plate was scanned.

The simulation work was followed by a real experiment. In this plate a crack with 1 cm of length and 0.5 mm wide had been machined. The probe under use generates a uniform excitation field parallel to the surface of the metallic plate under test. The sensor element in the probe is composed by four magnetoresistors assembled in a bridge configuration. The sensor measures one component of the magnetic field produced by the eddy currents and parallel to the plate surface.

The surface plots of the results obtained by simulation and experimentally are in a good agreement. Thus, it is reasonable to conclude that the simulation process constitutes a very good tool to test the inversion algorithms that will be the subject of our future work.

References

[1] M. Kubinyi, A. Docekal, H. G. Ramos, A. L. Ribeiro, “Signal processing for non-contact NDE”, *Przeglad Elektrotechniczny (Electrical Review)*, R. 86 Nr 1/2010.

[2] A. Bernieri, L. Ferrigno, M. Laracca, M. Molinara, “Crack Shape Reconstruction in Eddy Current Testing Using Machine Learning Systems for Regression”, *IEEE Transactions on Instrumentation and Measurement*, vol.57, No.9, Sept. 2008.

[3] I. G. Palmer, “The use of acoustic-emission techniques and liquid penetrants to detect surface cracks”, *Non-Destructive Testing*, Vol.7, Issue 1, pp. 25-27, Feb. 1974.

[4] A. Lopes Ribeiro, Francisco Alegria, O. Postolache, H. Geirinhas Ramos, “Eddy Current Inspection of a Duralumin Plate”, *Proc. I2MTC-IEEE International Instrumentation and Measurement Technology Conference, Singapore*, pp.1367-1371, May, 2009.

[5] R. V. Churchill, J. W. Brown, Complex Variables and Applications- 5th edition, McGraw-Hill, 1990.

[6] Martin A. Plonus, *Applied Elecromagnetics*, McGraw-Hill, New York, 1978.