

# Characterization of Defects in Aluminum Plates Using GMR Probes and Neural Network Signal Processing

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**Abstract** – Conductive specimens such as aluminum plates are tested in order to extract information about possible cracks, flaws and other mechanical damages. Nowadays, eddy current testing (ECT) despite its major benefits (e.g. low cost, high checking speed, robustness and high sensitivity to large classes of defects) implies the utilization of fully coil based architecture probes or hybrid coil-magneto-resistive probes. This work presents an eddy-current testing system based on a giant magneto-resistive sensing device. The application detects and estimates the size of cracks in an aluminum plate specimen. A neural network processing architecture is used to find out the correspondence between the cracks and the signal characteristics measured on the eddy current probe. The crack detection and the estimation of its size using different eddy-current frequencies are described in the paper.

## I. Introduction

Eddy current inspection is fast and effective in detecting and sizing most of the cracks and flaws that occur in conductive materials [1]. The eddy current measurement implies the utilization of different kinds of probes [2,3].

Recent developments in magneto-resistive sensor technologies lead to new kinds of solutions able to a more accurate estimation of the crack's depth and length in the conductive parts of different systems (e.g. airplanes). Two kinds of magnetoresistances, (anisotropic (AMR) [1,2] and giant magneto-resistive (GMR) [3]), are nowadays used for the detection of surface buried cracks and corrosion. Some of the advantages of magneto-resistive probes, when compared to conventional inductive types, are its higher sensitivity to low magnetic fields over a broader range of frequencies (e.g. 10 Hz to 1 MHz) and the ability of direct measurement of magnetic fields when compared to the measurement of electromotive forces proportional to the time variation of the field that characterize induction probes.

Measurements of amplitude and phase of the output signals are used to extract information about the dimensions of flaws such as length and depth. The measured values depend on several parameters such as the electrical conductivity of materials, magnetic permeability, frequency of the excitation, current intensity, distance between probe and specimen (lift-off effect), discontinuities in material types or non-homogeneities [4]. All this causes difficulties in the inverse problem associated with this type of non-destructive tests. Good solutions of the NDT eddy current inverse problem are based on neural networks (NN). The different types of NN architectures such as Multilayer-Perceptron, Radial-Basis function are mentioned on the literature [5,6].

The present work presents a practical approach concerning the GMR magnetometer characteristics and the eddy current sensing system implementation. The measured signals such as amplitude and frequency, were used as inputs of a neural network processing block that includes a classifier and an estimator of the crack's length and depth.

## II. System Description

In order to obtain the information about the aluminum plate under test through the GMR based eddy current sensing probe an eddy current automated measurement system was designed and implemented. The data acquired from the GMR magnetometer channel is processed in order to extract different characteristics of the sensing probe with the aim of classifying and estimating machined cracks and holes of several plate specimens.

## A. Eddy Current Automatic Measurement System

The main part of the eddy current automatic measurement system (Fig. 1) for aluminum plate testing is the GMR magnetometer eddy current sensing probe (ECP). The probe includes an excitation coil that is excited by an accurate ac-current provided by a Fluke 5700A calibrator remotely controlled by a PXI-GPIB controller. Different geometries for the excitation coil were considered and tested. Thus some characteristics (length and internal diameter) of the used coils are,  $L_1=12$  mm,  $D_1=32$  mm for the first coil and  $L_2=46.5$  mm,  $D_2=12$  mm for a second one. The used GMR sensors (NVE AA002 and AA006) contain four thin-film resistors in a Wheatstone bridge configuration being two of them magnetically shielded and acting as dummy resistors. The magnetometer delivers an ac-voltage according to the detected magnetic field originated by the eddy currents in the aluminum plate under test. The voltage is processed by a signal conditioning circuit, which includes an active high-pass filter ( $f_c=10$  Hz) based on a LM324 integrated circuit and an instrumentation amplifier INA118. The voltage obtained on the signal conditioning output is acquired using a NI PXI-6251 multifunction board (16 bits, 1.2 MS/s) and stored for off-line processing. Using a xy-positioning system that works under a motion control device provided with a GPIB interface, different (x,y) positions on the aluminum plate are reached. The PXI system works under a laptop PC control with a PC-MCIA CardBUS-8310 interface, and includes a PXI controller.

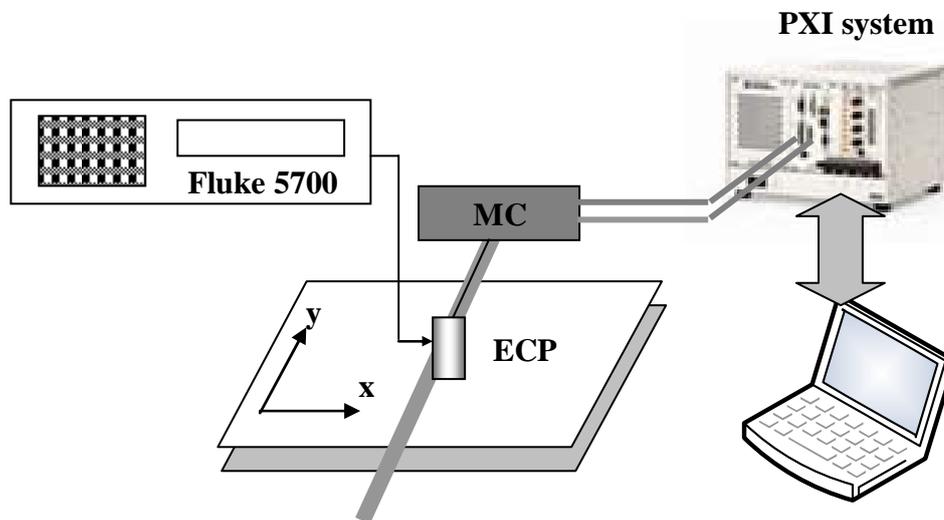


Figure 1. Eddy current automatic measurement system (ECP-eddy current probe, MC-motion control, Fluke5700 universal calibrator).

## B. System control and processing software

The system software includes different components: One eddy current automated measurement control module, one GMR probe characterization module, and one signal processing unit including digital filtering and signal feature extraction. The obtained information is applied to the network classifier that performs the aluminum plate defects classification according to their geometrical characteristics which are estimated in this last module.

The software modules for the measurement control system and for the probe characterization were developed in LabVIEW using *GPIB read* and *GPIB write* functions together with the remote control commands. These programs control the Fluke 5700 calibrator and the xy-positioning system included in the system. Additional DAQmx functions were used to acquire the signal from the eddy current GMR probe (ECP), during the probe characterization and the aluminum plate testing phases. A software block was designed and implemented in order to obtain the direct characteristics  $V_{out} = V_{out}(I_{ex})$  of the GMR magnetometer and the lift-off effects on the eddy current GMR probe response related to the aluminum plates characterization.

The output voltages delivered by the ECP during the aluminum plate tests were applied to the ACH0 analog input of the PXI-6251. Considering that the tests were performed for dynamic excitation current

values,  $I_{ex}$ , characterized by amplitudes included in the 10 to 200 mA range and for frequencies between 500 Hz and 7 kHz. The gain and the acquisition rate of the board were adjusted in order to provide accurate representation of the response signals. Thus, values from 10 kS/s to 70 kS/s for the acquisition rate and acquisition time intervals from 1 ms to 20 ms were used to obtain the information associated to the ECP output signal.

Taking into account the low level of the ECP output and the reduced noise immunity of the implemented aluminum plate testing system prototype, a digital filtering software block including high pass ( $f_c=100$  Hz) or/and band pass filters ( $f_1=100$  Hz,  $f_2=7000$  Hz) were used. Different kinds of filters such as Butterworth, Bessel and Chebyshev, of 3<sup>rd</sup> to 10<sup>th</sup> order were tested.

After digital filtering a set of periods of the ECP acquired signal,  $V_{ECP}(n)$  were used to calculate the amplitude, the phase and the frequency using the LabVIEW Express Function *ToneMeasurements*. The evolution of the amplitude and phase of  $V_{ECP}(n)$  were used to characterize the aluminum plate under test concerning the existing flaws: cracks, holes, or other defects induced deliberately.

Being the penetration depth  $\delta$  of the eddy currents a function of the excitation signal angular frequency  $\omega$  and of the magnetic permeability  $\mu$  and electric conductivity  $\sigma$ ,

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (1)$$

the utilization of different frequencies assures an accurate detection of defects, considering the used plate thicknesses between 1 and 2 mm, with flaws at different depths. The ECP amplitude responses for a given excitation current frequency are used as inputs for neural network defect classifier and defect characteristics extraction based on a neural network algorithm implemented in Matlab. The block diagram of the neural network processing for defect detection is represented in Fig. 2.

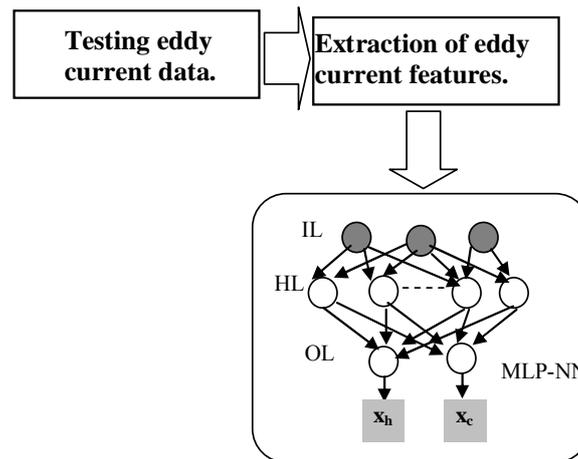


Figure 2. Eddy current advanced processing block diagram (MLP-NN –multilayer perceptron neural network, IL-input layer, HL-hidden layer, OL-output layer).

In Fig. 2 the MLP-NN represents a Multilayer Neural Network architecture designed to perform the classification of the defects as cracks or as holes that were deliberately machined in the aluminum plates. An additional neural network was designed to extract the defect geometrical characteristics such as defect depth.

The neural network includes an input layer (IL) with  $n_{input}=2-3$  neurons that correspond to the number of the considered features. Thus  $n_{input}=2$  when the chosen features are the maximum amplitude of the acquired signal associated with the scanned defect (e.g. crack) and the corresponding signal frequency. Additional information can be taken, considering the detected maximum phase difference between the excitation current and the detected voltage, as a third feature for a  $n_{input}=3$  neural network architecture.

The number of neurons in the hidden layer,  $n_{hidden}$ , characterized by a tansigmoid transfer function was established in order to obtain a good performance on the defect classification and/or defect estimation for a reduced number of neurons. The values of  $n_{hidden}=3-12$  were considered in this application. The output layer corresponds to the defect type or defect size.

In the designed neural network classifier the output layer includes a number of neurons equal to the number of possible defects. In the present work the kinds of defects considered were cracks and holes.

This imposes  $n_{\text{output}}=2$  in the output layer. For the geometrical characteristics considered in the prototype algorithms only the crack depth was classified. The related data were taken from the unidirectional scanning ( $x-x'$ ) performed during the tests, and considering the extension set of data necessary for training the neural network architecture. This neural network is composed by a single linear neuron that classifies the cracks according to their depth. The Levenberg-Marquardt training algorithm [7,8] was used to calculate the weights and the biases ( $W_i, B_i$ ) for both neural network architectures.

### III. Results and discussions

Using the designed eddy current automated measurement system different kinds of GMR magnetometers were characterized statically. Different values of dc-current were used to produce the DC magnetic field in the coils. For the practical case of the GMR-AA006 the  $V_{\text{out}} = V_{\text{out}}(I_{\text{ex}})$  characteristic obtained for a solenoid with dimensions  $L=46.5$  mm,  $D=12$  mm and  $N=425$  turns is presented in Fig. 3 where  $V_{\text{out}}$  corresponds to a gain  $G=250$  imposed on the INA118 instrumentation amplifier stage.

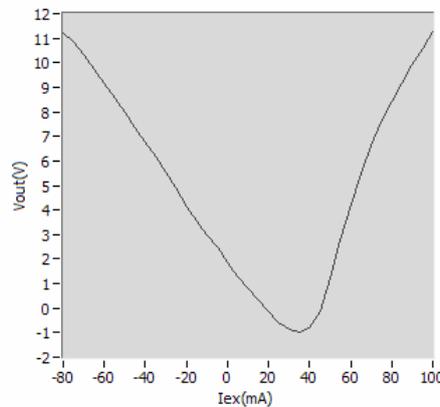


Figure 3. GMR magnetometer static characteristic.

The obtained static characteristic presents high nonlinearity for positive values of applied magnetic field and presents an asymmetry in the region of the null magnetic field. Considering the particular setting of the GMR sensor on the ECP in order to detect the eddy currents induced in the plate defect regions, the injected currents were in the range of the 100 mA to 500 mA, for the second considered ECP. For the first ECP the injected current amplitudes were less than 100 mA, and a permanent magnet was used to provide the GMR biasing. A study concerning the GMR characteristics, including the total harmonic distortion (THD) of the detected signal for different biasing was carried out and the results are presented in Fig. 4.

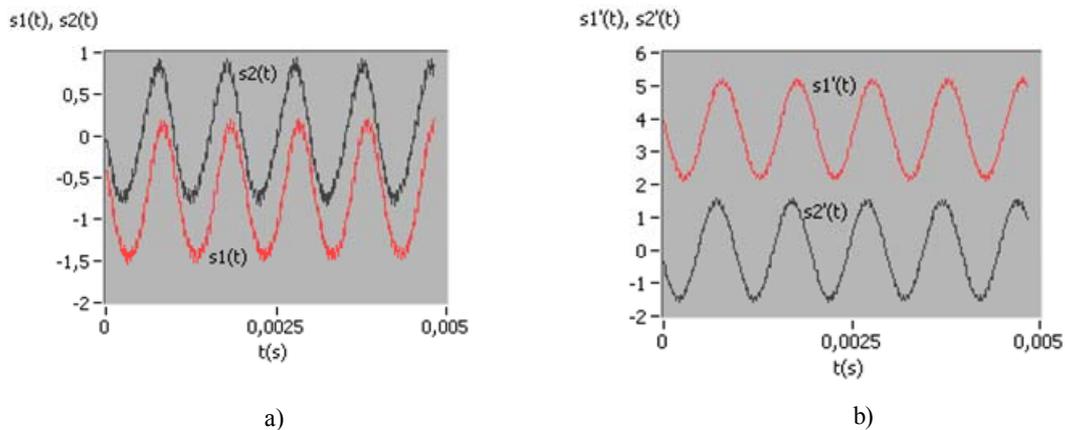


Figure 4. The ECP signal output for aluminum plate defect free, high pass filtered, without a) and with b) magnet biasing

Regarding the THD without biasing the values of THD are about 9.2% and after biasing the signal distortion falls to 0.6% in this case.

Additional measurements were performed in order to characterize the lift-off effect for the eddy current GMR sensing probe. Considering an aluminum plate specimen with different known defects (cracks and holes), a practical approach concerning the detection of defects and the estimation of their size was carried out for different values of the injected current in the excitation coil ( $I_{ex} = 50-500$  mA) and for different values of the signal frequency (500-7000 Hz), taking into consideration the penetration depth requirements. Some results obtained for crack and hole defects, are presented in Fig.5a and Fig. 5b.

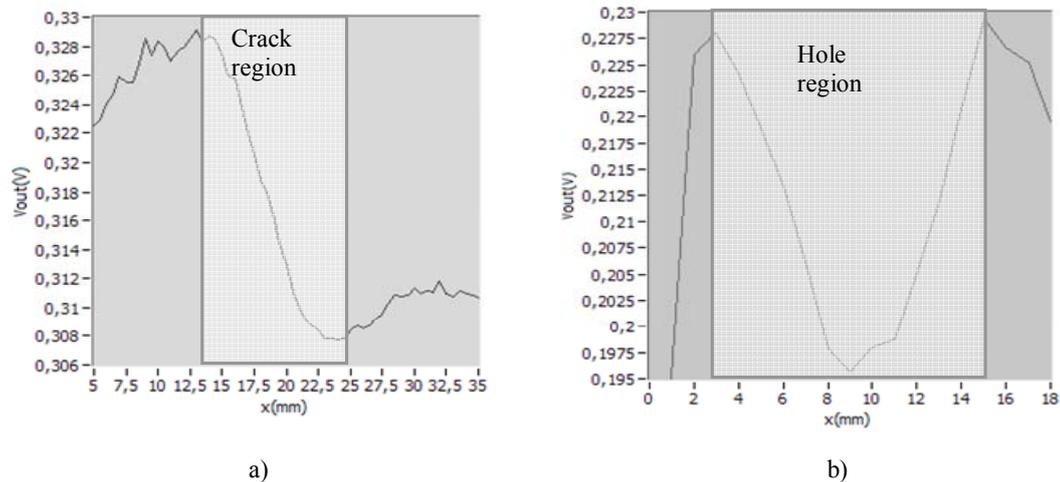


Figure 5 The evolution of the output voltage amplitude  $V_{out}$  of the ECP based on GMR probe for crack and hole plate scanning

In order to investigate the best feature that can be used for crack detection, a study concerning the THD during the one dimensional scanning test of the aluminum plate was carried out but it was difficult to extract useful information.

In what concerns the neural network, the classification performance was strongly dependent on the training set when the maximums of the measured signals associated to the cracks and to the holes were considered, as it is presented in Fig. 5. For reduced training sets (5 to 20 different cracks and holes), with depths between 0.5 and 2 mm and holes with diameters up to 5 mm, the crack-hole classification results based on the neural network algorithm included 80% of correct classifications while the depth estimation of the crack is characterized by errors of 10% to 20% in the estimated depth.

#### IV. Conclusions

This work presents elements related to the utilization of eddy current probes, based on giant magnetoresistance sensors. A neural network algorithm for fast classification of the aluminum plate defects such as cracks and holes is proposed.

The results presented include the study of the probes optimization and some preliminary results on defect classification using a limited number of features and a reduced number of defects to be classified.

Concerning our future work, we intend to optimize the neuronal network classifier to obtain better results on defect classification which implies an extended number of measurements including x-y scanning measurements of the plate defects.

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