MR sensors arrays for Eddy Current testing

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Abstract

Eddy Current (EC) technique is a powerful method for detection of surface notches or buried flaws during inspection of metallic parts in particular for aerospace components. Classical winding coils are the most commonly used EC sensors. Nevertheless, when the size of flaws decreases or when the defect is buried deep inside the material, traditional winding coil probes turn out to reach their limits. For this reason, other technologies are investigated to improve this technique. Spin electronics MagnetoResistive (MR) sensors present the advantages of flat frequency response and dimensions down to the micron size. These sensors are hence very attractive for the detection of buried defects that requires low frequencies because of skin depth effect. Also, MR sensors are suitable for very small surface defects due to their high spatial resolution without losing their field sensitivity. In addition, several magnetic field components can be simultaneously detected for a better analysis of defects. We will present recent advances of MR based probes containing arrays of Giant Magneto Resistance (GMR) or Tunnel Magneto Resistance (TMR) elements for EC testing. The experimental data will be compared with simulations on Aluminium and Titanium mock-ups.

1. Introduction

Eddy Current (EC) technique is widespread, ensuring buried or surface-breaking flaws detection in conductive materials. Probes with magnetoresistive sensors as receivers are investigated as a solution for detecting small surface defects and rather deep flaws [1-4]. Magnetoresistive sensors are attractive for EC testing because of their flat frequency response for a large frequency range and high sensitivity. At low frequencies they are more sensitive than conventional winding coils for the same size. Thus, GMR (Giant Magneto Resistance) and TMR (Tunnel Magneto Resistance) sensors are promising for low frequencies applications, i.e. sub-surface flaws detection, because of the skin depth effect [4-6]. In order to increase the spatial resolution of detection, GMR and TMR sensors could be used [7]. These sensors show good field sensitivity and spatial resolution due to the possibility of their miniaturization during fabrication. Moreover large arrays of elements can be realized in order to decrease the inspection time.

In this paper, experimental measurements from GMR/TMR based probes for buried flaws and surface cracks are presented [6, 8, 9, 11, 12]. In some of the developed probes,ASICs (application-specific integrated circuit) for interfacing up to 32 MR-elements sensor signals have been used. [11]. Aluminum and Titanium mock-up have been investigated.

2. EC probes

Two kinds of applications have been considered: low frequencies applications and high frequencies applications. The emitter part of the probes has been optimized using semi-analytical methods of CIVA software [8,12]. For low frequencies applications, i.e. for detection of flaws at several millimeters of depth, arrays of 32 MR sensors of 1mm length have been chosen. For high frequencies applications, arrays of sensors of 30µm length with a pitch of 100µm have been used in order to obtain high spatial resolution for small cracks detection. In parallel, we have also developed probes able to measure the three components of the magnetic field to evaluate the impact on the defect reconstruction[13].

2.1. MR receivers

GMR sensors are metallic spin valve stacks deposited on silicon substrates (SiO₂-500m/Si) by sputtering, and microfabricated by standard UV lithography technique in yoke shapes [14]. Details of the GMR stacks are given in that reference. Typical response of the GMR sensor is shown in Fig.1. The sensitivity of this receiver is 20 V/V/T.

![Figure 1: Voltage output variation as a function of in plane field of a single GMR sensor (field applied along the sensitive axis of the sensor).](http://www.ndt.net/?id=25038)

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been used [9]. They do not bring an advantage at low frequencies due to their high 1/f noise but they are better for high frequencies applications.

2.2. MR array probe for low frequencies applications

The emitter coil is realized by printed circuit technology. Double coil emitter has been chosen following the simulation results [12]. PCB with MR sensor array and electronics is fixed perpendicular to the PCB with emitter coils (Fig. 2). The MR sensing elements are placed exactly in the center between two coils to avoid direct coupling. With that configuration, MR elements are sensitive to the normal component of the magnetic field. To further reduce the coupling between the emitted field and the sensors, a compensation circuit has been integrated on the PCB to balance or unbalance the current between the two coils. Arrays of 16 elements with 1mm pitch have been fabricated for this application. Sensors are connected with bonding wires to the ASIC which incorporates low noise preamplifiers, multiplexers and current sources [10]. Additional electronics has been placed onto PCB of the prototypes for the power supplies and the interfaces of the ASIC.

![Figure 2: Picture of the MR array probe with the position of the sensor array and the double coil emitter on the PCB. The size of the array is 16 mm.](image)

2.3. 3D probe for high frequencies applications

The 3D probe is composed of a double coil emitter and GMR sensors as receivers. Four 30µm long GMR sensors are mounted on a pyramidal mechanical support, each of them being oriented at 45° with respect to the pyramid axis (Fig. 3). In this way, information of the three magnetic field components can be obtained. The GMR sensors are mounted in a Wheatstone bridge followed by a very low noise preamplifier before demodulation at the emitter frequency. Mechanical support with MR sensors is placed in the center of the coils.

The reconstruction of the three magnetic field components is carried out by multiplying the four sensor measurements with the experimental sensitivity matrix and inverting the derived system of equation:

\[ \mu_0 H = S e^{-1} V \]  \hspace{1cm} (1)

A detailed description of the reconstruction of field components and the according processing is given in [13].

![Figure 3: Schematic of the 3D probe based on a GMR array receiver and two current foils emitters. The size of the probe is 2x2cm.](image)

3. Discussion

3.1. Low frequencies applications

Experimental testing in Aluminum mock-ups has been performed for evaluation of MR probes developed for buried flaws detection. GMR array probe has been used for testing. Flaws with following dimensions: length × width × depth = 5 mm × 0.2 mm × 2 mm and 5 mm × 0.2 mm × 0.5 mm, have been made in the external side of the mock-up with ligaments of 0.5 mm and 2 mm. Measurements have been realized from internal part of the mock-up. All defects are well detected. Then aluminum plate with thickness of 2 mm has been added and same defects have been studied. The excitation frequency of 1 kHz has been chosen. Experimental CSCAN and imaginary part of defect with ligament of 2.5mm (l × w × d = 5 mm × 0.2 mm × 2 mm) are shown in Fig. 4. The extremities of defect are well seen as the normal component of the field is detected. The flaw is well detected with SNR = 11 dB and amplitude 0.2 mV.

An Al-plate with thickness of 4 mm has been added on the top of the mock-up, same defects have been studied. An excitation frequency of 500 Hz has been chosen. The flaw 5 mm long (l × w × d = 5 mm × 0.2 mm × 2 mm) with ligament of 4.5 mm with air between the plates is well detectable with SNR = 6.7 dB (Fig. 4 (b)).
3.2. High frequencies applications

Titanium samples have been investigated for surface cracks detection. This material is rather difficult due to its low conductivity ($\sigma = 0.6 \text{ MS/m}$) compared with other materials like Aluminum, thus EC signals are small. This makes the detection of small defects harder as EC signals are small. 3D probe has been used for testing. The crack with following dimension: length $\times$ width $\times$ depth = 0.6 mm $\times$ 0.05 mm $\times$ 0.03 mm have been made in the mock-up. Applied current for emitters is 50 mA. The excitation frequency of 1 MHz has been chosen. The applied voltage to the GMR sensors is 1 V. The distance between the 3D probe and the mock-up is fixed to 400 $\mu$m.

Figure 5 shows the reconstruction of two components of magnetic field ($H_x$ and $H_z$) from experimental results obtained with 3D EC probe. The $H_y$ component being very weak is not shown. Real part of the signal is studied. The defect is detected with a maximal amplitude of 1.5 $\mu$T and with SNR = 12.3 dB for $H_x$ component and with a maximal amplitude of 1.9 $\mu$T and SNR= 13 dB for $H_z$ component of magnetic field.

Figure 5: Horizontal cut of surface defect (0.6 mm $\times$ 0.05 mm $\times$ 0.03 mm ) in Titanium (a) $H_x$ component of magnetic field (b) $H_z$ component of magnetic field

4. Conclusions

For buried flaws applications, the developed probes have demonstrated their capability of detection. Defects at ligament of 4.5 mm in Aluminum mock-up are well detected.

For surface cracks detection application the obtained results are very promising in terms of detection and spatial resolution and size determination with the 3 components detection.

Using of MR array based probes is reducing the testing time allowing a greater area inspection at one time.

Optimization of electronics (ASIC and supporting components, sensing elements and emitter) in the case of buried flaws detection is a subject of future work for probes development.

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References