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Present and Future Impact of Magnetic Sensors in NDE

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Abstract

Non Destructive Evaluation (NDE) techniques are widely used in several industries in order to control product quality or to ensure the integrity of a part. A wide variety of methods exist. They involve the application of a suitable form of energy to the specimen under test. One of these forms of energy can be electromagnetic and the most used imply the measurement of a magnetic field.

This presentation starts with a survey of today's magnetic field sensing elements. Then, it overlooks the electromagnetic methods used for inspecting materials involving magnetic field measurements. Among these methods are magnetic flux leakage (MFL) and eddy current testing (ECT). Some considerations on different excitation forms like sinusoidal, multi-harmonic, pulsed or transient or even velocity induced are untaken.

The presentation concludes with an analysis of the advantages and drawbacks of each class of magnetic sensing technology when applied to an electromagnetic method involving magnetic field measurement. The approach of this presentation follows some of the recent developments in the magnetic sensors technology and studies the present and future impact of the improvements in the nondestructive evaluation methods.

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Keywords: non destructive evaluation (NDE), non destructive testing (NDT), eddy current testing (ECT), magnetic flux leakage (MFL), magnetic sensor.

1. Introduction

Non Destructive Evaluation (NDE) methods have a wide field of application in manufacturing, power, construction and maintenance industries. These methods are used during product development, during manufacturing and to inspect the final product. Additionally they also permit products to be inspected throughout their lifetime in order to determine when to repair or replace a particular part. Thus, in a developed society faced

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with aging infrastructures, aging airline fleet, aging petrochemical or nuclear power plants and where a throng of other industries try to use their equipment beyond its designed lifetime NDE offers a margin of safety [1].

The increasingly importance of nondestructive evaluation endorses basic and advanced research development and drives technological progress. In the last two decades, some significant progress has been achieved not only in the technological development of sensors and on the design of probes but also on the testing of new types of excitation modes.

The objective of this paper is to present a comprehensive assessment of the capabilities and developments brought by some recent magnetic sensors or new probe designs and to discuss the development of new NDE techniques with enhanced capabilities, lower cost and ease of use.

Although there are several nondestructive techniques, this paper deals specifically with electrical and magnetic methods of testing materials. These methods include eddy current testing (ECT) [2, 3] methods, where induced eddy currents are produced in the specimen under test and the resulting magnetic field is measured and magnetic flux leakage (MFL) [3] methods, where a magnetic field is applied to the specimen under test and any resulting change of the magnetic flux is observed. Both techniques require sensors either active or passive to detect or measure a magnetic field. The magnetic particle inspection (MI) method will not be considered within this survey as magnetic particles are the only sensors that don't require electronic signal processing. As used at present, within this method magnetic particles just line up in the directions of the magnetic flux indicating flux diversions occurring at a discontinuity of magnetic permeability caused by surface or near surface flaws and a properly quantified mean of assessing flux leakage is not provided [3].

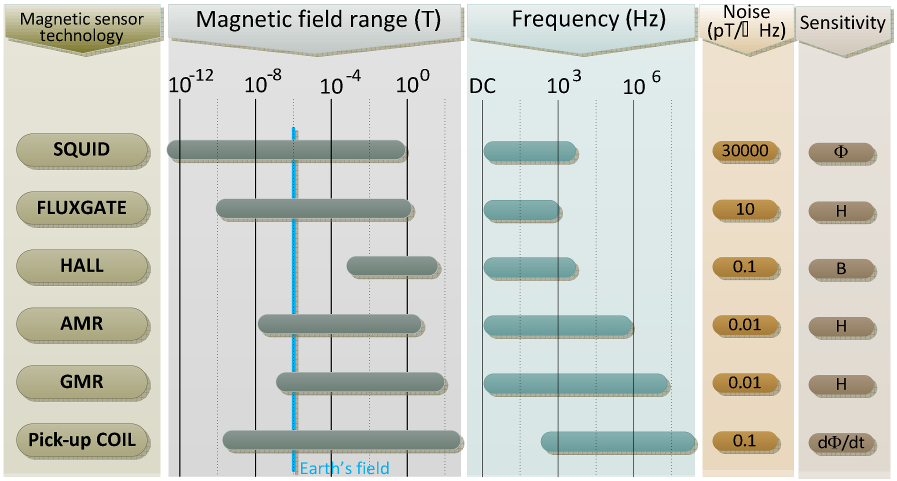
The paper begins with a survey of the magnetic sensors currently used the area of non-destructive evaluation [4, 5]. There are many types of magnetic sensors based on different technologies. Traditional inductive eddy current probes based on excitation/detection coils as well as magnetic field transducers are analyzed. Different eddy current inductive probe configuration and design are described. For instance, probes with the same coil or coils to generate eddy currents and to determine the resulting magnetic field (reflection probe) or probes with separate function coils with detection coils that can be absolute or differential are presented. In the magnetic detection elements, superconducting quantum interference devices (SQUID), fluxgates, Hall sensors, anisotropic or giant magnetoresistors (AMR and GMR) shall be reported. A comparison of the performances of different sensors is carried out. Some are very sensitive, able to measure magnetic fields or magnetic field gradients in the region of interest, some are tiny allowing a good spatial resolution, some present a large bandwidth from DC to the MHz zone.

The paper is divided into sections. Besides this Introduction and a review of some magnetic sensors specifications at Section 2, Section 3 presents briefly the methods that require the use of magnetic sensors, namely eddy current testing and magnetic flux leakage. Section 4 analysis the performance and limitations of competing technologies based on the work that is being developed by the authors and Section 5 relates the relevance of each type of sensor with a method and outlines some conclusions.

2. Magnetic Sensors

There are several magnetic sensors capable of determining values of magnetic flux density. Some of the most mentioned in the literature of non-destructive testing are SQUIDS, fluxgates, Hall probes, magnetoresistive sensors and sensing coils [4, 5]. Sensing coils are used to access the electromotive force (e.m.f.) due to time varying magnetic fields and the other magnetic field sensors measure the magnetic flux density directly. Table 1 summarizes the specifications of the magnetic sensors that the text that follows surveys.

Table1. Magnetic sensor technology



2.1 SQUID

The most sensitive low field sensor is the superconductivity quantum interference device (SQUID). Developed about 1962, its operation is based on two effects: the Josephson junction and the flux quantization. SQUIDs give a measure of the magnetic flux across the pick-up coil section or can have a more complex configuration with two pick-up coils wound in opposite direction, functioning as a magnetic gradiometer [6]. Advantages of SQUID systems for NDE include high sensitivity (≈10-100 fT $Hz^{-1/2}$), wide bandwidth (from DC to 10 kHz) and broad dynamic range (>80 dB). Although the extensive research done in the past two decades in the context of NDE in areas like flaw characterization, analysis of the magnetic properties of materials and corrosion, cooling is still a barrier to the acceptance of the method. The development of high temperature superconductivity (HTS) materials in SQUIDs will certainly increase the number of applications but due to their unavoidable higher cost and handling convenience, SQUIDs will always be used only when other NDE sensors fail to ensure the required performance [6,7].

2.2 Fluxgate

Another magnetic sensor that can provide field sensitivities in the range of a few tens of nano Tesla is fluxgate [8]. Fluxgate sensors measure the absolute strength of a surrounding magnetic field. In the most common type, the measuring principle is based on the "second harmonic principle". The sensor incorporates two coils, a primary and a secondary, wrapped around a common high-permeability ferromagnetic core. A current in the primary coil produces a field which periodically saturates (in both directions) the probe coil. If an external magnetic field is applied to the sensor, the symmetry of the cycling saturation is disturbed and a second harmonic amplitude of the reference signal corresponding to the external field strength appears. Fluxgate sensors have a field sensitivity up to 10 pT/√Hz in the range [10^{-10}; 10^{-3}] T, a frequency bandwidth from DC to 1 kHz and a dynamic range of more than 140 dB. As depicted in Table 1 fluxgate sensors present some advantages for nondestructive testing when compared with other magnetic sensors, however these devices tend to be bulky and not so rugged as smaller more integrated sensor technologies [8-10].

2.3 Hall Sensor

Hall sensor is a slab of a semiconductor material and its operation is based on Hall effect. When a current is applied from one end of the slab material to the other charge carriers begin to flow. If at the same time an external magnetic field, B, is applied to the slab, the current carriers are deflected by Lorentz force and give rise to an output voltage proportional to B. The effect occurs either with direct or alternating fields and the voltage across the two parallel faces varies at the same frequency as B, provided the current is DC [11, 12]. Flux density can be measure from 100 nT with a resolution better that 1 nT. The active areas are as small as $(0.1\times0.025).10^{-3}$ m. The sensitive layer of the device lays parallel to the surface of the testing sample and measures the magnetic field in a direction perpendicular to the surface.

2.4 Anisotropic Magnetoresistance

The dependence of the change of electrical resistance of a material on the angle between the direction of electric current and direction of magnetization, known as anisotropic magnetoresistance (AMR), was first observed by William Thomson (Lord Kelvin) in 1851. It was only 100 years later that thin films technology made possible the manufacture of practical sensors exhibiting a sufficiently large magnetoresistive effect to be used in measurements [13-17]. AMR have a sensitivity 1 mG to 6 G, a frequency bandwidth from DC to 5 MHz and a dynamic range of 120 dB. They have a limited magnetic field range meaning that their saturation field is quite low. These solid state magnetic sensors can be one, two and three-axis.

2.5 Giant Magnetoresistance

Giant magnetoresistors (GMR) are devices based on the giant magnetoresistivity phenomenon reported for the first time in 1988. The best use of GMR for magnetic field sensors is with a Wheatstone bridge configuration as depicted in Fig. 1(a) [14, 18-19]. Four giant magneto-resistors are connected in a bridge configuration, with two of them magnetically shielded.

(a) (b)

Fig. 1 (a) GMR bridge sensor AA002-02; (b) Output characteristic for a supply voltage of 5 V.

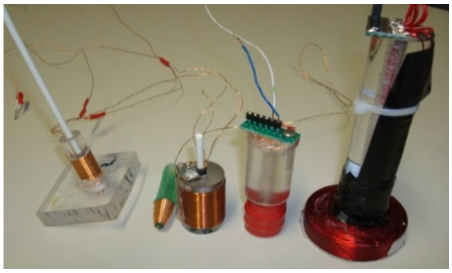
Fig. 1(b) represents the sensor output voltage as a function of the magnetic flux density. The typical V-shaped characteristic determines the necessity of a DC bias that can be obtained with a magnet or with a DC current [19-21]. In the linear regions the AA002-02 sensor presents a sensitivity around 4 mV/V-Oe. This sensitivity corresponds in S.I. units to the characteristic in Fig. 1(b) for a DC supply voltage of 5 V.

GMRs have a limited field resolution as depicted in Table 1. Nevertheless, they present advantages that make them robust probes in industrial noisy environments. For instance, they are insensitive to magnetic fields perpendicular to their direction of sensitivity and their sensor characteristic will not be disturbed if they are subject to strong magnetic fields.

2.6 Pick-up Coil

Coils can be used as detectors by measuring the values of the magnetic flux density across the coil section. Faraday induction law states that the voltage induced in a coil is proportional to the changing magnetic field across it. Their sensitivity depends on the number of turns, section diameter and permeability of the core. Advantages of pick-up coils are their robustness (provided they are properly encapsulated), ease of manufacture, shape and size to suit the inspection task. When compared with semiconductor magnetic sensors they are larger and thus particularly suitable for scanning surface areas. Because search coils work only with a varying magnetic fields pick-up coils show decreasing sensitivity at lower frequencies, nevertheless one gets comparable performance under same working conditions [15, 16]

(a)



(b)

Fig. 2 (a) Commercial ECT probes; (b) Inductive probes projected and built at our laboratory.

3. Methods

Magnetic sensors can be used in two methods to determine the magnetic flux density that informs about the cracks and other defects of the inspected materials. These magnetic methods are Eddy Current Testing (ECT) and Magnetic Flux Leakage (MFL). In both of them a magnetic field is applied to the object under test and any resulting changes in the magnetic flux density in the region of interest are observed.

3.1 Eddy Current Testing

Eddy current testing (ECT) are currently applied in nondestructive evaluation of metallic materials [1-3, 22-24]. They are widely used to detect, localize and characterize flaws and other defects in those materials. They are especially useful when the objects under test are only accessed from one external surface. Advantages of eddy current testing (ECT) techniques include rapid inspection speed and high sensitivity for surface flaws, whereas as drawbacks one may refer their applicability only to conductive material and a distortion due to the lift-off effect can be pointed out [25]. Besides, no contact with the object under test is required and surface preparation is usually unnecessary

ECT includes several techniques based on eddy current theory. In all of them the eddy currents are induced in the specimen under test by a magnetic field produced by an excitation coil carrying a time-varying current. These loop currents are proportional to the conductivity distribution. Cracks or flaws within the material distort the flow of these eddy currents and create a secondary magnetic field that contains the information about the defects in the specimen. The total magnetic field can be measured either using detection coils or magnetic field sensors.

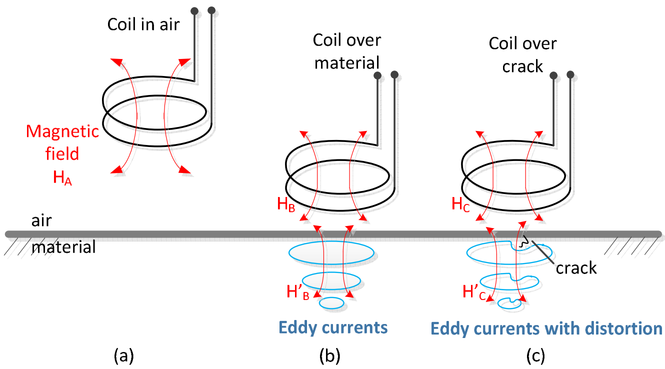
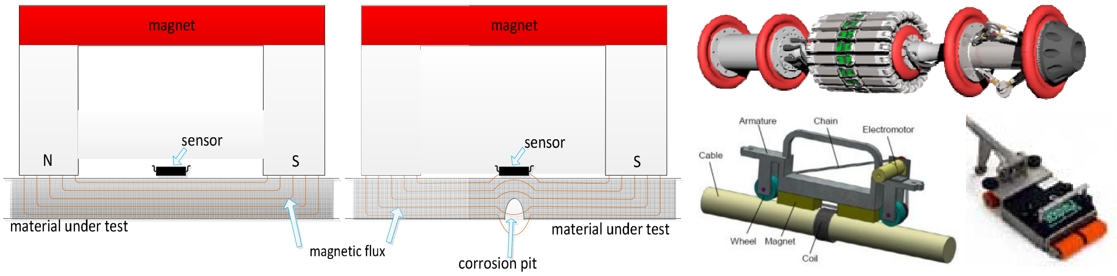


Fig 3 ECT: (a) the alternating current flowing through the coil generates a magnetic field around the coil; (b) when the coil is near a conductive material, EC is induced in the material; (c) a flaw in the material disturbs the EC circulation, the magnetic coupling with the probe changes and a defect signal can be measured.

3.2 Magnetic Flux Leakage

Magnetic Flux Leakage (MFL) non destructive testing consists of magnetizing a test part and scanning its surface with a magnetic sensor. Applications are confined to ferromagnetic materials and include flaw detection, measuring dimensional changes and observing variations in the magnetic permeability.



(a) (b)

Fig. 4. (a) principle of MFL for detecting wall loss; (b) commercial equipment

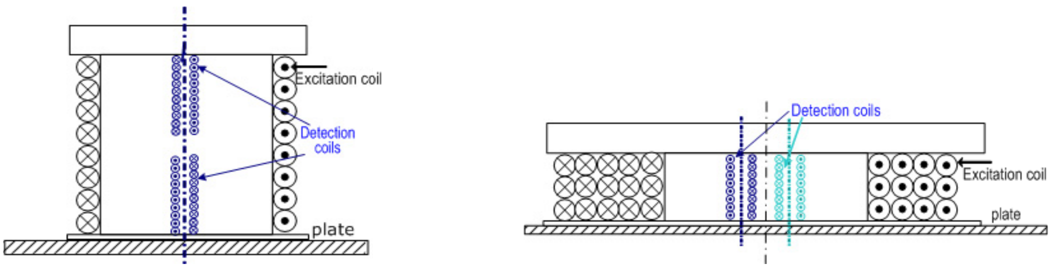
Within this technique the magnetic field can be created either by a permanent magnet or by electrical means either AC or DC and the flux leakage can be detected with sensing coils or magnetic sensors. Some commercial equipment is depicted in Fig. 4 (b). With MFL methods a magnetic field is induced inside the part under test and the distribution of the resulting lines of magnetic flux is determined by the magnetic permeability changes in the region under interest. Fig. 4 (a) shows how a defect disturbs the flux lines distribution not only at the surface where the defect exists but also over a wider region. To obtain the maximum sensitivity of detection the component of the applied magnetic field must cut the defect at right angles [26-28].

4. Performance and Limitations of Competing Technologies

4.1 Eddy Current Testing

In the early days of ECT a coil was simultaneously used to create and sense the eddy currents produced in the electrically conductive object being tested. Its impedance changes due to the modifications that occur in the total magnetic field when the presence of a defect disturbs the eddy current distribution [24]. Over the years several improvements to the probe design have been proposed. The first to be considered was the use of two separate coils, one to induce eddy currents and another to sense the magnetic field. With this geometry the heating caused by the current that runs in the excitation coil modifies less measurement conditions [2, 22-23].

Based on the operation modes the coils can be classified as absolute or differential. In the absolute eddy current probes (ECP), the probe's impedance or the induced voltage in the coil is measured directly. In the differential-type the signal containing the information about the defects in the plate is detected by two separate coils with opposite winding directions connected in series. The output voltages from these two coils can be subtracted meaning that they are cancelled out when both coils experience identical conditions. Fig. 5 presents two differential probes built at our laboratory and Fig. 6 depicts results measured when the probe in Fig.5(b) scans a linear crack in a metallic plate[25, 29-30].



(a) (b)

Fig. 5 Differential coils that have been projected and built at our laboratory.

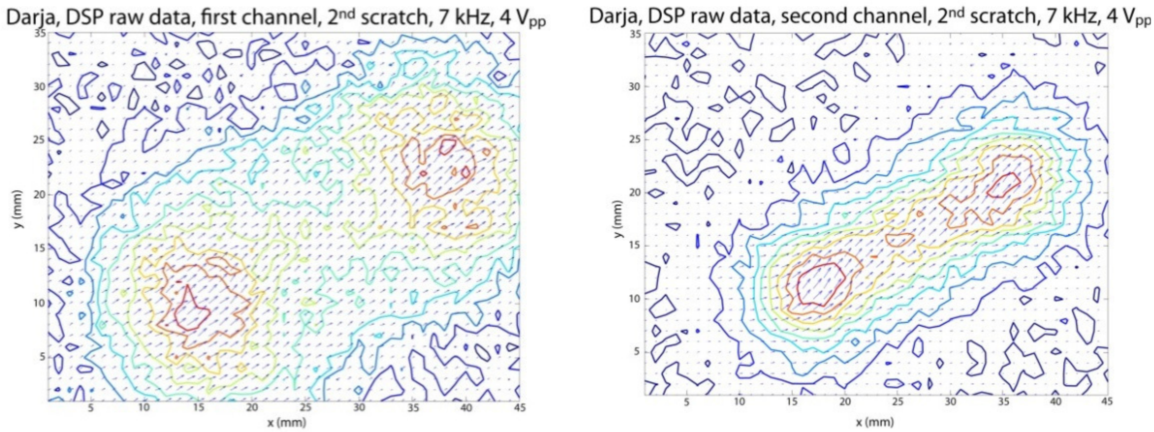


Fig. 6. Contour plots of the normalized voltage amplitudes and an arrow representation of the normalized amplitudes and phases of the output voltages sensing coils.

Different coil probe structures are available in eddy current inspection. Encircling or bobbin probes are used for cylindrical geometries like tubes or pipes externally or internally [31].

ECP can be classified according to the type of detection element. If the detection is performed with sensing coils they are named inductive. If they use magnetic sensors one may call them hybrid probes considering that the excitation is still achieved with a current that runs in a coil [32-37]. The inductive type probes must be used with excitation frequencies high enough to produce measurable voltages as sensing coils sensitivity depend on frequency. On the contrary, reliable detection of subsurface flaws can be increased using magnetic sensors. In fact, as illustrated in Fig.7, the electromagnetic field penetration inside a conductor is limited by its frequency that restricts the depth at which flaws may be perceived [34]. Thus, as solid state sensors present high sensitivities at low excitation frequencies lowering test frequency, deep buried flaws can be detected.

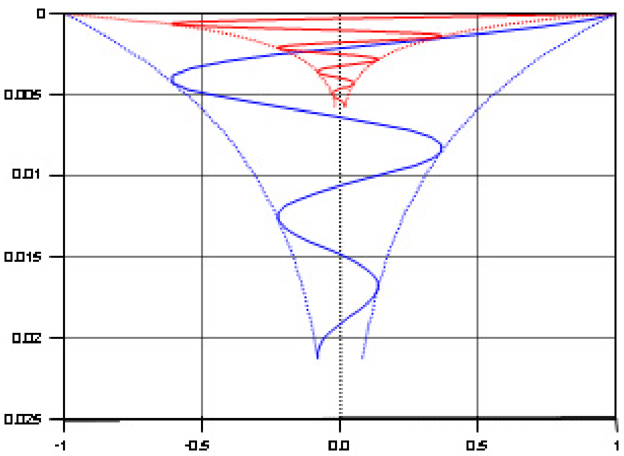


Fig.7. Electromagnetic field penetration inside aluminum for two frequencies: 200 Hz and 10 kHz.

Figs. 8-10 show some probes designed and implemented at our laboratory with an excitation coil and a giant magnetoresistor (GMR) centrally located.

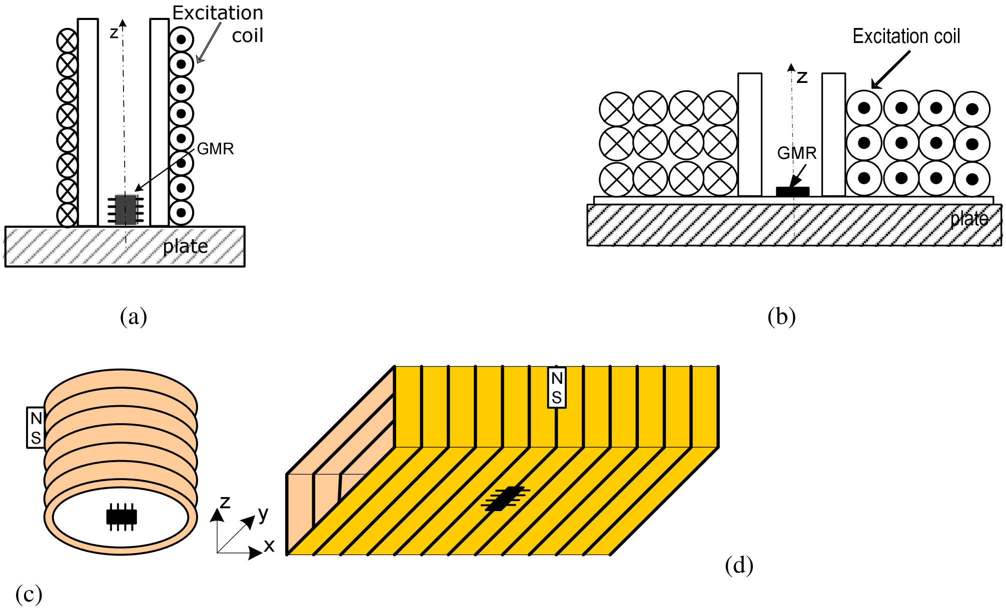
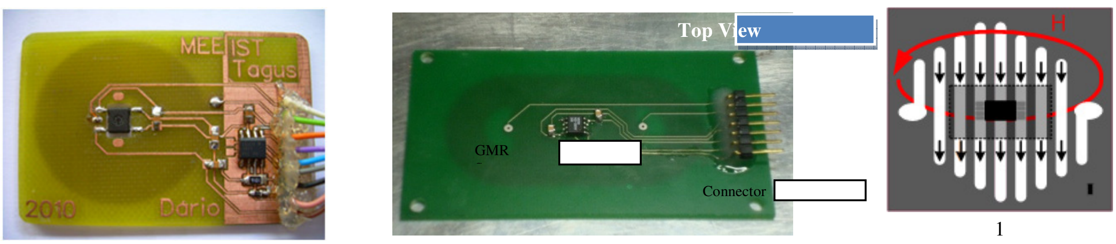
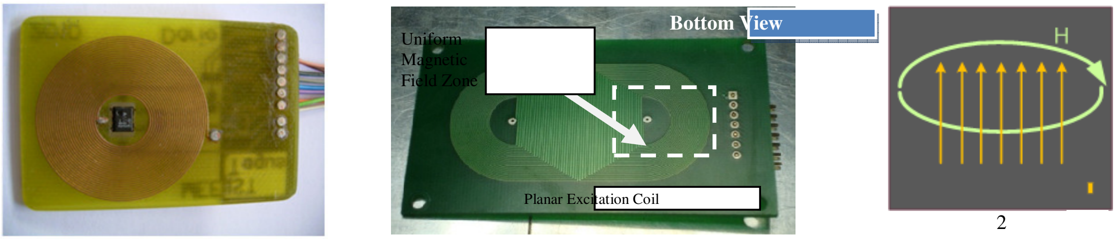


Fig. 8. ECP: (a) solenoid; (b) (c) pancake; (d) parallelepiped. Polarizing magnets are positioned on the sides.

Improvements have been carried out to tailor the probe geometrical configuration for the specific object to be tested. Fig. 8(a) shows a solenoid with a GMR positioned to allow plate thickness determination [35-36]. Pancake probes (Fig. 8(b)) are more efficient to inspect metallic plates [37]. To characterize geometrically defects from the measurements taken (inverse problem solution) special shape probes have been developed. For instance, by measuring with the ECP depicted in Fig. 8(b) two arbitrary orthogonal components of the magnetic field, it is possible to determine the field along any other direction parallel to the plate. The result is valid under the condition that the excitation coil applies a magnetic field which is invariant under a probe rotation [38-39]. The probes depicted in Figs. 8(d) and 9(b) produce eddy currents in the plate which in the case of flawless material, have an uniform density and point along a pre-defined direction inside a given area on the plate surface. The applied magnetic field is spatially constant inside that area and invariant under a probe translation [39-40].

The use of planar probes as presented in Fig. 9 has been proposed by several authors [28, 41-42]. The manufacture using printed circuit board techniques is easy and inexpensive. It makes possible to minimize probes and enhance spatial resolution. It can be produced on a flexible printed circuit board allowing the inspection of non-flat surfaces.

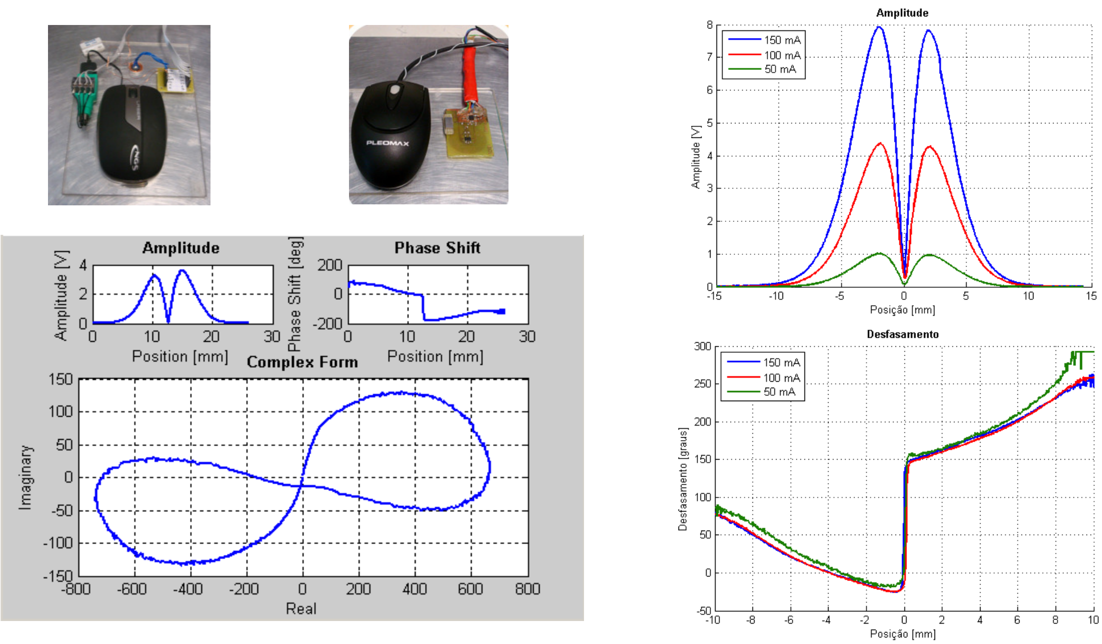




(a) (b) (c)

Fig 9. (a) (b) photos of the ECT probes; (c) 1-Uniform current lines; 2-Uniform EC lines on a homogenous plate

Fig. 10 shows some handheld probes that use a PC mouse as positioning system [42].



(a) (b)

Fig. 10. Results over a 0.5 mm width crack, 20 mm length and 2 mm depth

Most traditional EC testing uses AC magnetic fields but nowadays research is focus in other excitations. To optimize the evaluation of a specific characteristic of a defect techniques with different excitations have also been tested with success. One of them is the multi-frequency use [34, 43]. By measuring the response at different frequencies, each frequency response accentuates one parameter and others are minimized. Fig. 11 shows the magnetic field component orthogonal to the crack length measured when the aluminum plate is scanned over the linear crack at two different excitation frequencies (200 Hz and 10 kHz).

Recently, transient eddy currents (pulsed eddy currents) produced by a square wave received interest in applications such as the detection of defects, the characterization of sub-surface cracks, and the measurement of a specimen thickness or its electrical conductivity. Due to the rich frequency content of the signal used deeper penetration of the electromagnetic field on the sample is achieved and simultaneous evaluation of the material at different depths can be carried out [36, 44-45]. Fig. 12(b) presents the results obtained experimentally with a pancake coil with a GMR with a sensitive axis perpendicular to the plate whose thickness id to be measured.

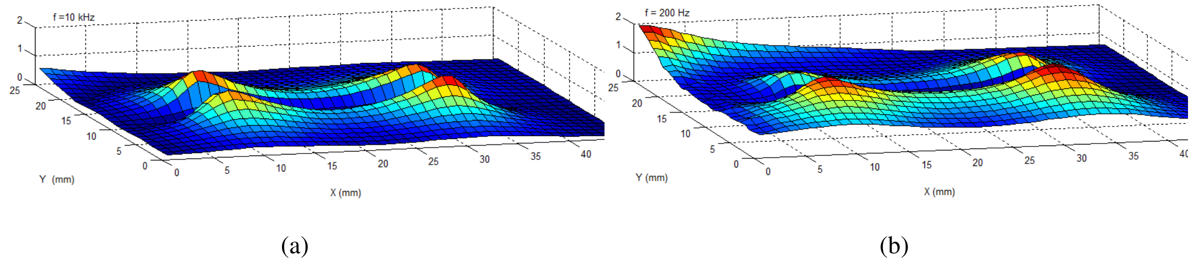


Fig 11. Magnetic field component measured for a crack scanned with testing frequency: (a) 200 Hz; (b) 10 kHz.

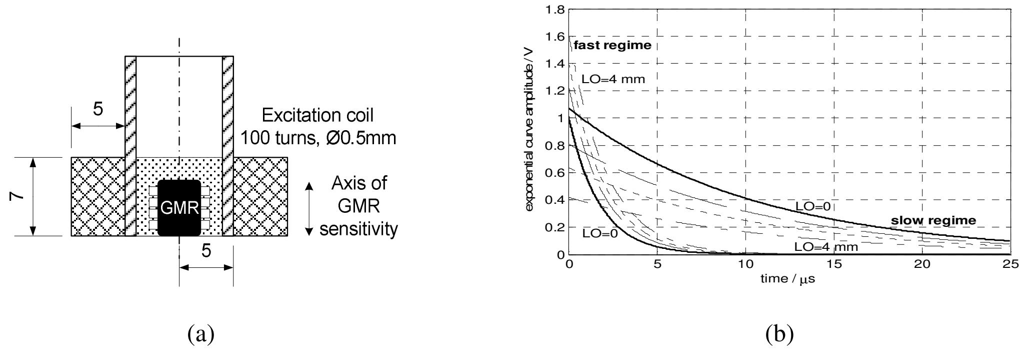


Fig. 12. (a) ECT probe; (b) exponencial components of pulsed GMR responses for different lift-offs

The induction of the eddy currents in the material under test can be performed with a DC magnetic field moving in the vicinity of the sample under test (Faraday effect) and the use of very sensitive GMRs to infer the presence of cracks by measuring the magnetic field resulting from the currents flow pattern [46-47]. The method presents undoubted advantages when the material to be tested is in motion relative to the test sensor because the sensitivity of the method increases with speed. Fig. 13 (a) shows the experimental setup and (b) the results obtained for four similar cracks having 100 mm long, 0.5 mm wide and depths 0.5 mm, 1 mm, 1.5 mm and 2 mm respectively.

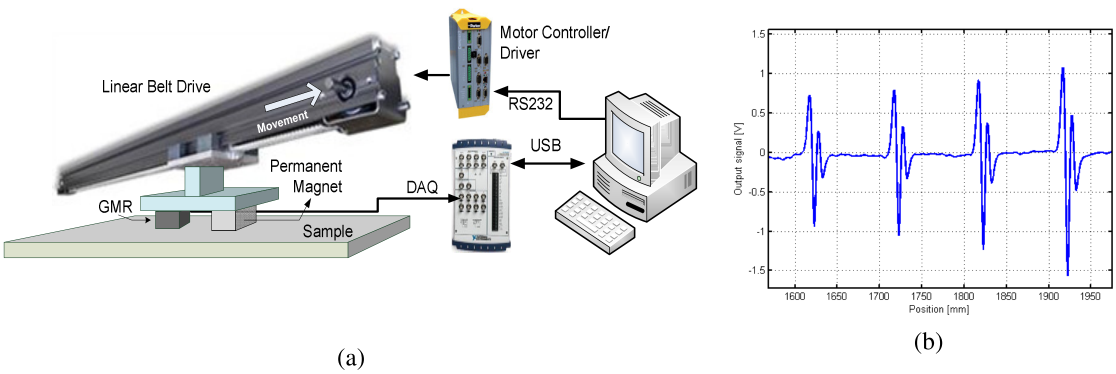
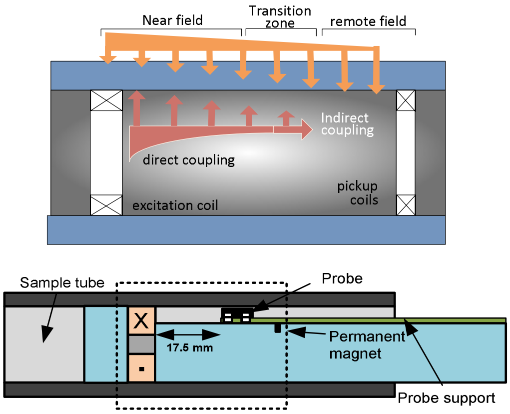
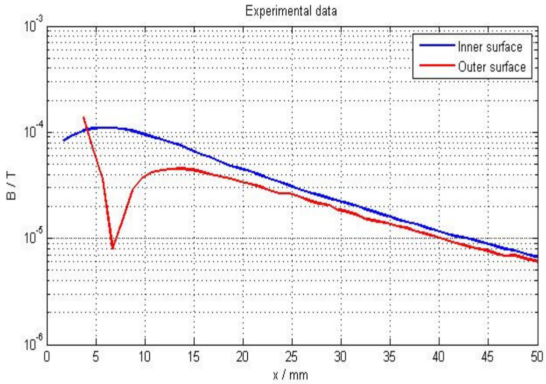


Fig. 13. Experimental setup depicting a PC, the brushless motor controller and driver, the linear belt drive and the probe, which includes a permanent magnet and a GMR sensor.

Another modified ECT technique that is worth mentioning to inspect tubes is the Remote Field Eddy Current (RFEC). The basic setup and the measuring principle are depicted in Fig. 14(a) with both excitation and sensing coil inserted in a tube [48]. The eddy currents induced in the tube wall, produce a magnetic field that opposes the primary field, thereby reducing the direct magnetic field affecting the inside tube wall. A magnetic field also appears on the exterior of the tube that is guided along the tube. As this field propagates, it re-diffuses back in the interior wall of the tube. In other words, there are two magnetic fields inside the tube: the direct fields and the indirect that has twice penetrated the thickness of the tube. A detector (that can be a pickup coil or a solid state magnetic sensor) placed two or three tube diameters from the excitation coil is able to detect the response from the indirect field. Fig. 14(b) shows the measured data in the inner and outer surface obtained with an GMR.



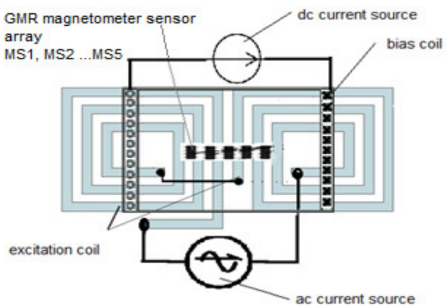
(a)



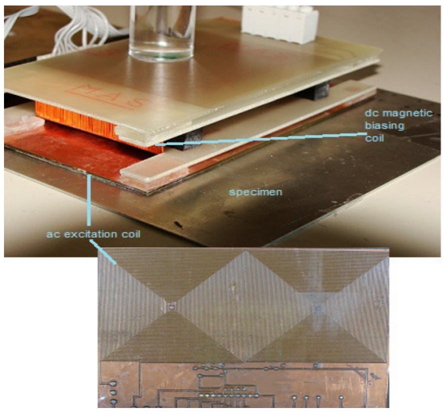
(b)

Fig. 14. (a) RFT probe structure; (b) experimental magnetic field obtained with the setup

In order to increase scanning speed research has been carried out to automate the measurement and to resort the use of sensor arrays [20]. Some manufacturers already propose solutions with sensor arrays. It is appropriate to note that the sensors included in the ECT arrays do not work like in other inspection techniques as ultrasounds by complementing the information collected by each. The use of arrays of sensors in ECT as presented in Fig 15, simply allows the detection of anomalies in a time less than that which is necessary in the traditional method with one sensor.



(a)



(b)

Fig. 15.Uniform eddy current probe based on GMR magnetometer sensor array, planar spiral rectangular excitation coils and rectangular magnetic biasing coil a) design b) implementation

4.2 Magnetic Flux Leakage

Concerning the magnetic flux leakage method most development has been carried out in the detection field based mainly in the technology development of magnetic sensors and not in the field generation.

5. Discussion

For successful defect detection, properties such as high linearity, large dynamic range, and good spatial resolution are required.

Very good results are achieved using the most sensitive magnetic sensors that work at low frequencies (SQUIDs and fluxgates), nevertheless they can hardly be used in real industrial applications due to the complexity and costs of such systems and their insufficient robustness.

When comparing solid-state magnetic sensors with sensing coils two protruding features have to be assessed. One is related with the robustness and high flexibility in configuration that is greater in encapsulated coils than in solid-state sensors and the other is the very small active area of the latter so that they approximate to magnetic field point sensors. Concerning the measuring quantities, sensing coils present an output voltage proportional to the magnetic field time derivative while in magnetoresistors it is proportional of the magnetic field.

An issue to be considered especially when considering magnetic sensors with a limited dynamic range (AMR, GMR) is their insensitivity to the excitation field.

6. Conclusions

It is clear that there is not a general purpose method for inspecting materials as well as there is not a magnetic sensor able to respond to all requirements for non destructive evaluation. It is our opinion that although AMR and GMR magnetic sensors still require some more improvements they already present improvements in EC probes performance and in the future solid state magnetic sensors will replace traditional inductive sensors in most of the situations. The prospects for arrays of identical magnetoresistive sensors for rapid scanning of large areas are also promising.

Acknowledgements

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