A TMR based triaxial ECT probe

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Abstract – **The paper proposes the improvement of an eddy current probe for non-destructive testing applied to the defect investigation on conductive materials. The goal is to increase the defects detection sensitivity regardless of the mutual orientation between the defect and the sensing axis of the probe while the test is performed. In particular, the paper describes the realization of a suitable triaxial magnetic field detection system based on three single axis TMR (Tunnel Magnetoresistance Effect) sensors assembled on an eddy current probe. A probe performance evaluation was carried out on two aluminium plates with surface and subsurface cracks of 8 mm considering different mutual orientations between the cracks and the probe direction.**

I. INTRODUCTION

With the advent of Industry 4.0, the predictive maintenance and the in-line production control of components and materials have become a crucial element of the industrial sector [1]-[2]. In this context, non-destructive investigation techniques (NDT), even more than in the past, are becoming increasingly important for correctly drive production and maintenance activities [3]-[4]. These techniques must guarantee high levels of reliability, with the aiming to reduce the costs and the inspection times. The requirement for reliability often involves the need to detect smaller and deeper defects by scanning large areas of the tested samples.

This aspect is crucial for the industrial sectors such as aerospace, public transport, automotive, and so on, where the defects onset, even very small ones, can compromise the structures integrity and, consequently, the citizens safety.

Within the numerous non-destructive investigation methods, when the inspection concerns electrically conductive materials, the techniques based on the induced currents (Eddy Current Testing - ECT) are deeply used thanks to their reliability and usefulness.

The ECT operating principle is based on the excitation of Eddy Current (EC) in the conductive material under test by an external alternating magnetic field generated by a suitable excitation coil. A reaction magnetic field is produced by EC and perturbed by the presence of any defect in the material. The analysis of the modified reaction magnetic field allows the defect detection and evaluation.

In the realization of an ECT probe, one of the typical solutions adopted for the analysis of the reaction magnetic field variation is made through a suitable magnetic sensor.

In this context, a modern challenge in the field of ECT is linked to the probe design to be able to improve the detection capability of buried and small defects [5]-[7].

In fact, although technologically advanced, the techniques and tools currently in use for ECT are characterized by the following limitations:
(i) the poor penetration of the EC in the material (skin effect), which involve in difficulties to identify buried defects also due to the problems related to lift-off [8];
(ii) the sensitivity loss in defect detection due to the mutual orientations between the defect and the sensing axis of the probe during the scan of the material under test [9]-[11];

Starting from the ECT probe developed in [12]-[13], this paper proposes an improvement of the reaction magnetic field detection by designing a suitable triaxial system based on three single axis TMR (Tunnel Magneto Resistance effect) sensors.

In the following, a description and a performance evaluation of the developed ECT probe with both the single magnetic field sensor, and the triaxial magnetic field sensor system is presented.

Finally, a preliminary experimental probe characterization confirms the goodness of the proposal.

II. SINGLE SENSING AXIS PROBE

First of all, starting from the solution proposed by the authors in [12]-[13], an ECT probe based on the same excitation coil system and substituting the sensing element with a single axis TMR sensor is made.

The excitation system has a double winding structure, made on an appropriate plastic support with dimensions shown in Fig. 1 (a). As better shown in Fig. 1 (b), the two legs of the winding structure have a D-shape. On each D-leg, a coil of 150 copper wire windings with a section of 0.5 mm^2 has been created; then, the two coils have been electrically connected in series.

Thanks to this geometry, the magnetic excitation field is perpendicular to the surface of the specimen and it possible to allocate the magnetic sensor between the two coils, with
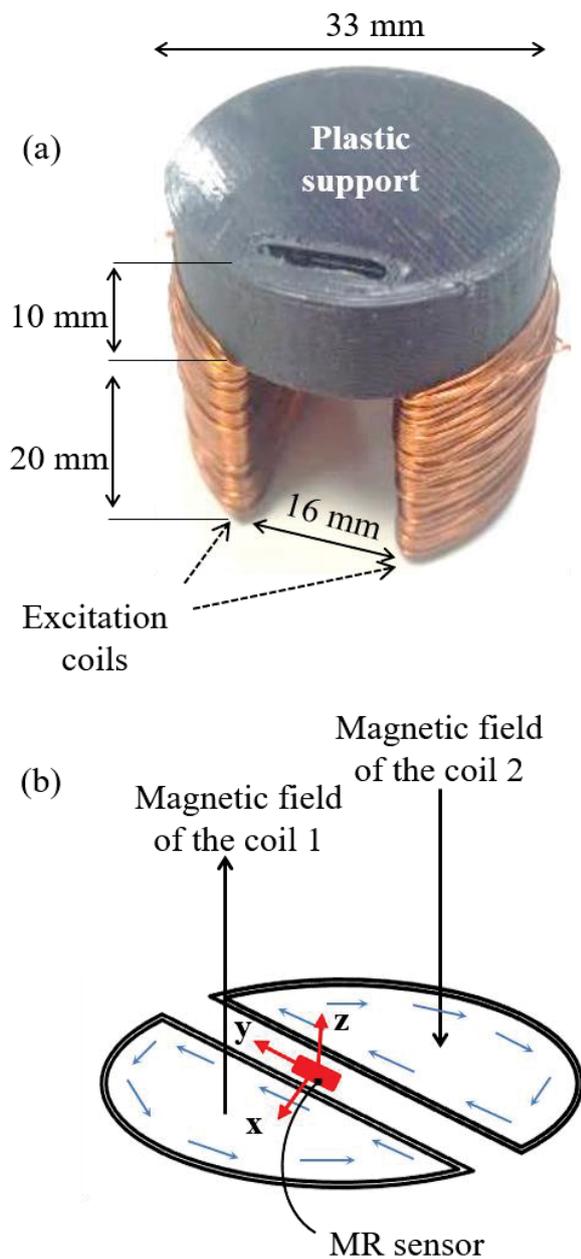
Fig. 1. (a) The Double-D excitation coil realized and (b) the MR sensor position with its sensitivity axis orientation.

its sensitivity axis orthogonal to the excitation magnetic field.

The sensor for detecting the reaction magnetic field is a TMR2905 by MDT (Multi Dimension Technology) [14].

The TMR sensors are manufactured with a high sensitivity material, making them useful for any low magnetic field application. In addition, this sensor has a bipolar input-
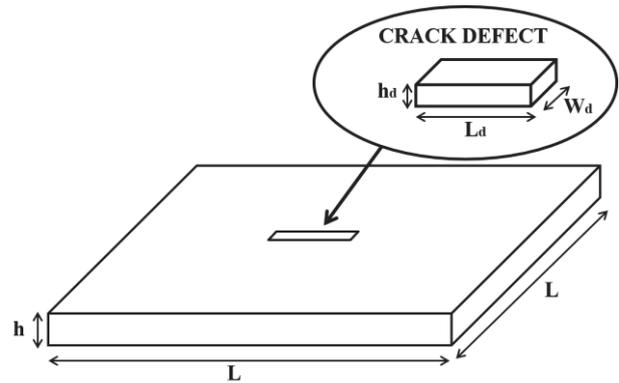

Fig. 2. Specimen under test.

output characteristic [15] solving the problems of other high sensitivity magnetic sensors like GMR (Giant Magneto Resistance [16].

In particular, the TMR2905 is a monoaxial sensor with ± 30G working range and 50 mV/G sensitivity for each volt of power supply. It features a Wheatstone bridge internal structure, consisting of four magnetoresistances whose value changes with the sensed magnetic field. In the realized ECT probe, the TMR sensor is positioned between the two D-shape excitation coils aligned with their end and with the sensitivity axis orthogonal to the excitation magnetic field, oriented along the y direction as shown in Fig.1 (b).

Furthermore, inside the probe there is also a conditioning circuit, realized by means of an AD620 amplifier, in a differential configuration [17]. The AD620 is a high accuracy instrumentation amplifier that requires only one external resistor to set gains. The AD620 features 8-lead SOIC and DIP packaging and requires a low power supply (only 1.3 mA max supply current). From the measurement performances point of view, the AD620 shows a 40-ppm maximum nonlinearity, a low offset voltage of 50 μV max, and an offset drift of 0.6 μV/°C max.

III. PERFORMANCE EVALUATION OF THE SINGLE SENSING AXIS ECT PROBE

The performances of the realized ECT probe were evaluated in terms of the defect detection capability, with reference to two experimental cases related to superficial and buried defects.

Several tests have been carried out on two aluminium specimens (square plates) with known defect (Fig. 2), moving the probe along the specimen in correspondence of the defect. In detail, each of the two specimen has a thickness (h) of 2 mm, a length (L) of 200 mm, the crack defect is located at the centre of plate, and has a thickness (Wd) of 0.1 mm, a length (Ld) of 8 mm, a height (hd) of 1 mm.

For the specimen 1 the defect is located on the surface (depth of 0 mm under the specimen surface), while for the
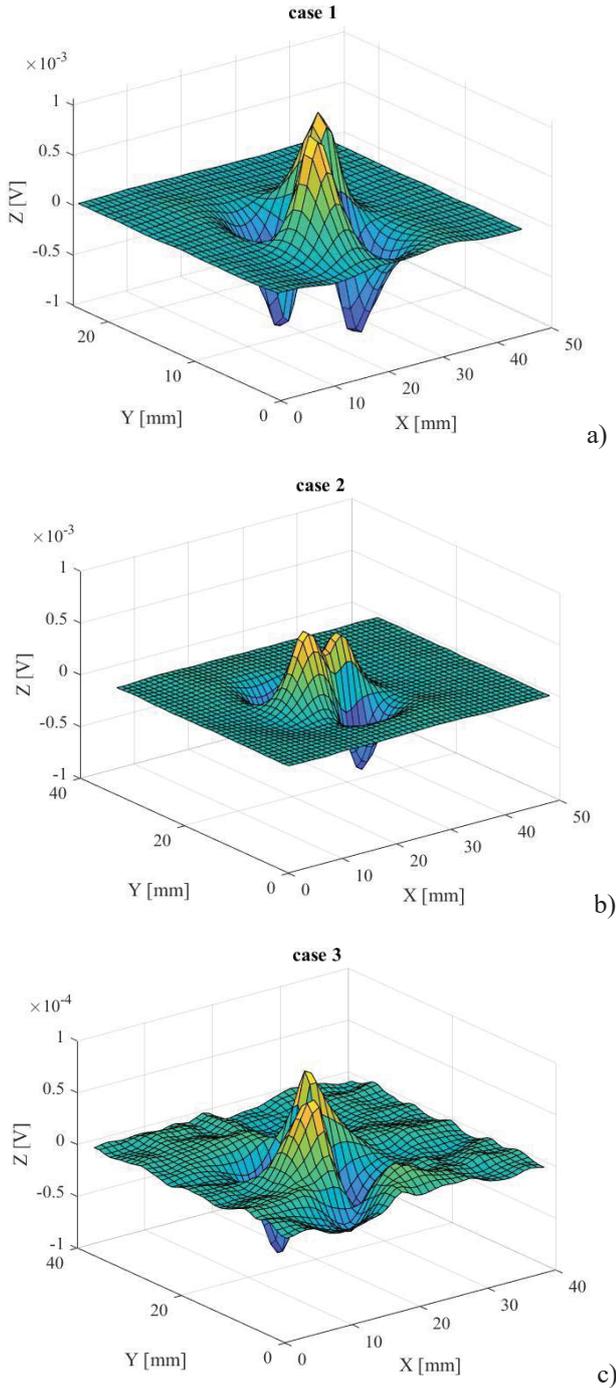
case 1

a)

case 2

b)

case 3

c)

Fig. 3. Magnetic field maps of specimen 1, a) for the case 1, b) for the case 2 and c) for the case 3.

specimen 2 the defect is located at a depth of 1 mm under the specimen surface.

The specimens are scanned moving the ECT probe following three different paths:

case 1 - the defect orientation is orthogonal respect to the sensing axis of the TMR sensor;

case 2 - the defect orientation is oblique (specifically 45

degrees) respect to the sensing axis of the TMR sensor;

case 3 - the defect orientation is parallel respect to the sensing axis of the TMR sensor.

The tests have been carried out feeding the excitation coil with a sinusoidal current with an amplitude of 50 mA RMS. The adopted excitation frequencies were 5 kHz for the specimen 1 and 2 kHz for the specimen 2. Finally, the TMR's voltage supply was fixed to 6V and the AD620's gain is fixed to 9.82.

In order to evaluate the performance of the defect detection, the following figure of merit SNR [dB] has been defined and estimated during the tests:

$$SNR = 20 \, log_{10} \, (V_s/V_n) \qquad (1)$$

where V_s is the RMS value of the voltage variation sensed by the TMR sensor when the probe in located in the defect zone and V_n is the RMS voltage of the noise floor (detected in correspondence of no-defect zones).

A typical graphical representation of the obtained results in terms of magnetic field maps have been reported in Fig.3 for the specimen 1.

Table 1. SNR values obtained analysing the two specimens for the three cases.

Case number	Specimen 1	Specimen 2
	SNR [dB]	SNR [dB]
1	25.7	22.3
2	20.2	15.5
3	20.9	15.2

Looking Fig. 3, it is possible to note as, for all the examined cases, the defect is detected by the presence of voltage peaks in correspondence of its position. In detail, for case 1, Fig. 3a, the map shows an excellent voltage variation in the defect area (about 2.1 mV peak to peak) compared to the non-defect area, where the noise is very low (about 0.012 mV of mean value).

In this situation the defect detection is very good. Also, for the case 2, Fig. 3b, the map shows a good defect detection capability, even if a variation of the voltage peaks slightly lower than in the case 1 can be observed (about 1.4 mV peak to peak,)

Finally, for case 3, Fig. 3 b), it is possible to highlight how the voltage peaks variation is much less significant than in the previous cases (0.17 mV peak to peak) while the noise in the non-defect area is slightly greater, making lower clear the defect detection.

The analysis performed by observing the magnetic field maps is also confirmed by the considered figure of merit (SNR) shown in Table 1 for the specimen 1 and 2 and considering the three considered cases.

The obtained results show how the probe sensitivity is deeply dependent on the defect orientation respect to the axis of the magnetic field sensor.

In particular, if the defect orientation is orthogonal to the sensor sensitivity axis, case 1, the performance is better than when considering different orientations, cases 2 and 3, where the performance decreases. This behaviour has been observed for both surface (specimen 1) and buried (specimen 2) defects even if it is more evident for the latter.

IV. IMPROVEMENT OF PROBE SENSITIVITY

In order to improve the performance of the adopted ECT probe also with reference to different orientation of the defects, a new solution for the magnetic field detection, based on a triaxial magnetic field sensor, has been introduced.

Given the absence of an adequate commercial solution of a triaxial magnetic field sensor, a suitable configuration has been developed and implemented to be placed within the ECT probe considered. Using the KiCad software, an appropriate PCB (printed circuit board) support has been realized. On this support, three monoaxial magnetic field sensors, TMR2905, have been positioned. In detail, with reference to Fig. 4, the three sensors are positioned so that their sensitivity points were aligned on the same axis, Fig. 4b, with a known distance (3 mm) from each other, Fig. 4a. The final dimensions of the prototype are 10.8 x 6.6 x 4.5 mm.
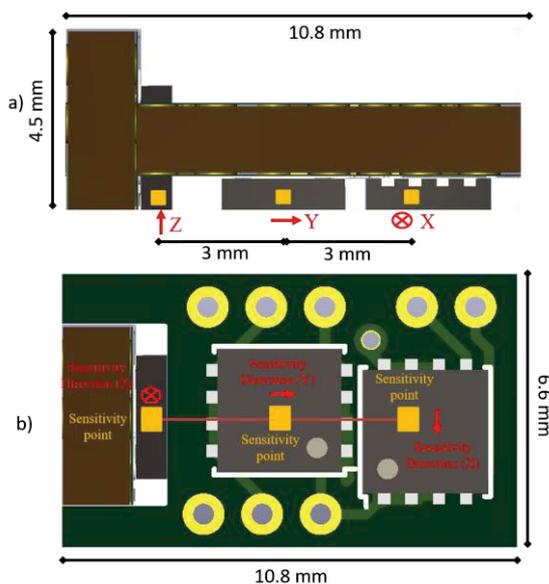

Fig. 4. Layout of the triaxial magnetic field sensor, a) side view and b) bottom view.

Finally, the triaxial magnetic field sensor created was inserted inside the double winding probe, with sensitivity axes orientation as shown in Fig.1 (b).

To obtain a comparison between the two types of magnetic field detection systems, the same Double-D excitation coil was used, using the same conditioning circuit for each sensor described in section II.

Furthermore, the tests were performed with reference to the same operating conditions and to the same specimens under test.

For the sake of brevity, in Fig.5 only the graphical representations related to the tests carried out on the specimen 1 are shown.

Looking Fig.5, it is possible to highlight as the defect detection capability is granted, for all axes, thanks to the good voltage peaks variation in the defect area compared to the non-defect area.

Furthermore, it is possible to observe as, depending on the considered case, there are axis that show a greater voltage peaks variation in the defect area respect to the other axes which however can show a more contained noise in the defect-free area.

Analysing the SNR's trend for the specimen 1 and for the specimen 2, reported in Fig.6 a) and Fig.6 b) respectively, it is possible to observe that:

- when the defect is superficial, specimen 1, all axes detect the defect, whatever its orientation, with a good value of SNR;
- when the defect is buried, specimen 2, the performance of all axes decreases slightly.

Finally, comparing these results with those related to the single magnetic field sensor, it is possible to point out that, the obtained SNR's values by triaxial magnetic field sensor show as for each defect orientation, there is always at least one sensitivity axis which has a better detection capability. This aspect is very important, as it allows to obtain a greater sensitivity in the defect detection which is independent of the scanning direction of the probe.

V. CONCLUSION

The paper proposes the improvement of an eddy current testing probe through the realization of a triaxial magnetic field detection system.

The developed probe was experimentally tested, and its performance have been also compared with a single axis magnetic sensor probe considering the same excitation. The experimental campaign was made on two known defects for different angles between the defect orientation and the probe direction. The obtained results show that the use of the triaxial magnetic field detection system increases the defect detection capability, making possible the detection regardless of the defect orientation respect to the scanning direction of the probe.

Future work will involve in making a complete metrological characterization of the realized triaxial probe on smaller and deeper defects trying to demonstrate the usefulness of the proposal not only in the defect detection but also in the defect characterization phase.
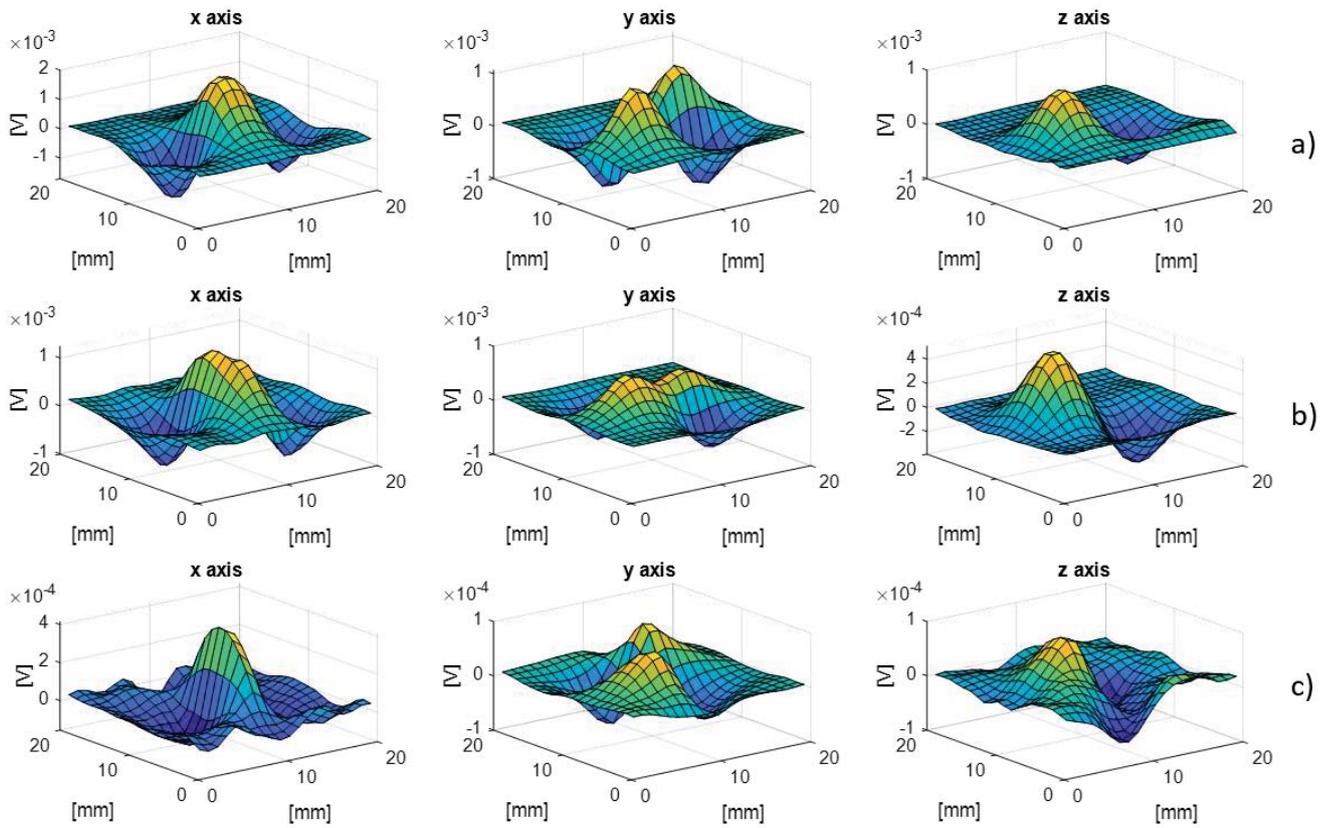
Fig. 5. Magnetic field maps obtained with the triaxial sensor for the specimen 1. a) case 1, b) case 2 and c) case 3.
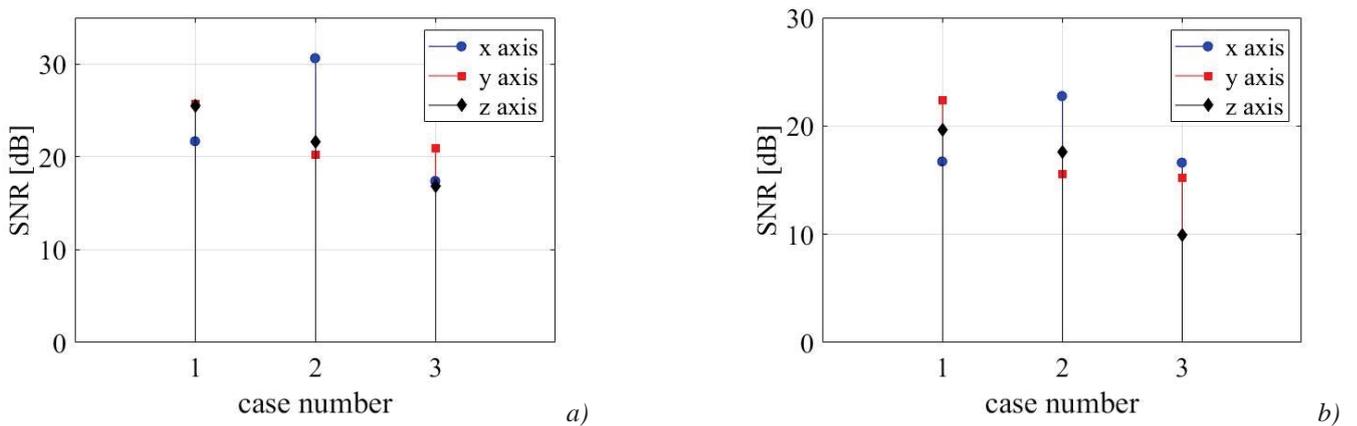

Fig.6. Comparison of calculated SNR values for x axis (blue circle), y axis (red square) and z axis (black diamond) sensors response, for the specimen 1 (a) and 2 (b), for the three considered cases.

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