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A MEASUREMENT SYSTEM FOR INDUCTANCE TOMOGRAPHY ON CONDUCTIVE MATERIALS

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Abstract − The paper describes the realization of a measurement system for executing Eddy Current Non Destructive Testing (EC-NDT) to detect defects on conductive materials. The measurement method is based on the adoption of a useful parameter, *the mutual impedance matrix*, obtained using a suitable probe and analyzed by means of a novel low cost non-iterative inversion algorithm. In particular, the probe is constituted by a set of coils arranged in a two-dimensional array: during a measurement session, the mutual impedance matrix is obtained exciting one coil at time and capturing the voltage at the terminals of the other coils on the probe, at different excitation current frequencies. In the paper, the probe design, the inversion algorithm, the architecture of a useful measurement station, and the preliminary results obtained carrying out measurement sessions on a specimen with known defects, are reported.

Keywords: non-destructive testing, eddy current testing, multi-sensor probe, digital signal processing, automatic measurement systems, inverse problems.

1. INTRODUCTION

The online quality control of conductive material is a very important task in many industrial processes. This is particularly true in the case of manufacturing of materials for nuclear, aerospace, and similar application. In fact, the presence of a defect on the final product can occur even if the industrial process was correctly designed and controlled, thus giving rise to unacceptable risks and costs. Therefore, a complete non-destructive inspection on the entire production during the manufacturing process is strongly required.

These reasons have lead to a rapid development of Non-Destructive Testing (NDT) techniques based on a number of different measurement principles, such as eddy current testing, magnetic particle testing, ultrasounds, thermo-graphy, radiography [1, 2]. Among these, electromagnetic techniques (E-NDT), and in particular Eddy Current (EC) based techniques, are still less widespread in industry, but are receiving a growing attention by the international scientific community thanks to their low cost.

EC-NDT techniques are based on the analysis of the magnetic field generated by eddy currents induced in the material under test, and perturbed by the presence of defects.

The authors are involved in this research field, realizing algorithms, measurement methods, probes and measurement systems [3-11]. In this paper, the design of a EC-NDT method using a two-dimensional probe and a new low-cost non-iterative algorithm is presented. In particular, the proposed method is based on the retrieval of the resistivity variations of the conductive material under test due to the presence of defects. To this aim, a probe constituted by a two-dimensional matrix of coils is realized to induce EC in the material under test and to pick-up the voltage signals due to the reaction field. Exciting one coil at time with a suitable excitation current and measuring the voltage signals at the terminal of other coils, and repeating this procedure for all the coils on the probe with different excitation current frequency values, it is possible to determine a particular parameter, the *mutual impedance matrix* [8,9], related to the resistivity spatial distribution on the material under test. A suitable algorithm is then adopted in order to reconstruct the defect characteristics starting from the mutual impedance matrix values measured during an investigation session. In the following, the principles of the proposed method are discussed, together with considerations carried out during the probe design phase. A preliminary sensitivity analysis, carried out in order to determine the probe characteristics able to assure a suitable defect identification also in presence of noise, is also detailed. Finally, with reference to a probe built-up on the basis of the achieved results, the architecture of a suitable measurement station is also reported.

2. THE MUTUAL IMPEDANCE MATRIX METHOD

The EC techniques are based on the generation of eddy currents in the material under test by an external magnetic field, generated by a suitable excitation coil. A reaction field is produced by EC (see Fig. 1), whose characteristics depend on the specimen material (i.e. spatial values of the resistivity and magnetic permeability), and modifications are related to the presence, position and geometry of defects (cracks). Suitable sensors and measurement methods are then required to measure the reaction field modifications and then to determine the defect characteristics. In particular, many solutions are based on the use of suitable pick-up coils capable of sense reaction field variations due to spatial resistivity modifications. In this way, the impedance value:

$$\dot{Z} = \frac{\overline{V}_{pick-up}}{\overline{I}_{excitation}}$$

is obtained. Suitable computation methods are then necessary in design and operating phases in order to, respectively: (i) determine the $\dot{Z}$ values starting from the measurement conditions and from the characteristics of the material under test and the used probe (*forward problem*), and (ii) to reconstruct the defect characteristics in the material starting from the $\dot{Z}$ values obtained at different excitation current frequencies (*inverse problem*).

Since the $\dot{Z}$ value is related to a punctual investigation, in order to obtain a defect map in overall the specimen, two different approach can be adopted: (i) the use of a single excitation/pick-up set together with a suitable automated mover, or (ii) the use of a probe with multiple excitation/pick-up sets, in order to cover all the investigation area without a positioning system. In this paper, the second solution has been adopted. In particular, a probe constituted by a two-dimensional matrix of excitation/pick-up coils was developed. During a measurement session, one single coil (excitation coil) is supplied by a suitable excitation current, whereas the other coils (pick-up coils) sense the voltage related to the reaction field. Repeating this procedure using as excitation and pick-up coils all the coils on the probe, it is possible to obtain the mutual impedance matrix $\mathbf{Z} = \{\dot{Z}_{ij}\}$, where each element is related to the *i*-th excitation coil and to *j*-th pick-up coil.

With reference to the described probe, a suitable computation algorithm is then necessary to solve the inverse problem.

3. THE INVERSION ALGORITHM

The non-linear inversion of eddy current measurement data is the most critical part of any reconstruction procedure. The problem is usually formulated as the minimization of an error functional related to the distance between measured and numerically computed field values. Minimization is a difficult task, which is often affected by local minima and characterized by heavy computational costs. This problem is often tackled by deterministic procedures based on the knowledge of the error functional's gradient. In this case, the risk of being trapped by local minima is the main problem but this risk can be reduced by a suitable choice of the number of parameters associated to the unknown. On the other hand, the application of global minimization procedures, such as genetic algorithms or simulated annealing, may provide a suitable alternative in the presence of a limited number of unknowns. In all cases, the number of error functional evaluations, which strongly affects the computational time, increases more than linearly with the number of unknowns. Therefore, non-iterative methods appear to be an interesting alternative to iterative methods based on the minimization of an error functional.

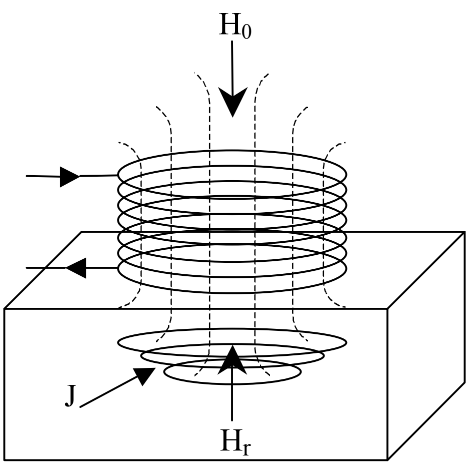

Fig. 1. The operating principle of the eddy current method (H_0 = excitation filed; H_r = reaction field; J = induced eddy currents).

The non-iterative method on which relies the measurement station has been first proposed for Electrical Resistance Tomography [8, 9] and then extended to Eddy Current Non-Destructive Testing [10, 11]. This method is based on the monotonicity property [10, 11]:

$$\eta_1(\mathbf{x}) \geq \eta_2(\mathbf{x}) \text{ in } V_c \Rightarrow \mathbf{P}_1^{(2)} \geq \mathbf{P}_2^{(2)} \quad (1)$$

where V_c is the conductive domain, η_1 and η_2 are two different resistivity profiles and $\mathbf{P}_k^{(2)}$ (k=1, 2) is the lowest order non-vanishing moment of the real part of the impedance variation due to the conductor with resistivity η_k. Specifically, $\mathbf{P}_k^{(2)}$ is defined through:

$$\text{Re}\{\mathbf{Z}_0(j\omega) - \mathbf{Z}_{\eta_k}(j\omega)\} = \omega^2 \mathbf{P}_k^{(2)} + O(\omega^4), \ \omega \to 0 \quad (2)$$

where ω is the angular frequency, $\mathbf{Z}_0(j\omega)$ is the impedance matrix when the conductor is removed and $\mathbf{Z}_{\eta_k}(j\omega)$ is the impedance matrix corresponding to η_k.

It is possible to show that $\mathbf{P}_k^{(2)}$ is a symmetric matrix and we recall that **A**≥**B** implies that **A**–**B** is a positive semi-definite matrix.

Here some of the derivation of the inversion algorithm are recalled for the sake of thoroughness.

With reference to the shape identification problem for a two phase conductor, (1) can be recast in a different form. Specifically, let D_α and D_β be subset of V_c, and let η_i the resistivity of the inclusion hosted in a conducting material (the background conductor) of resistivity η_b. We assume that the resistivity of the inclusion is greater than the resistivity of the background conductor, i.e. $\eta_i > \eta_b$. Let η_α and η_β be the following functions:

$$\eta_\alpha(\mathbf{x}) = \begin{cases} \eta_i & \text{for } \mathbf{x} \in D_\alpha \\ \eta_b & \text{for } \mathbf{x} \in V_c \setminus D_\alpha \end{cases}; \ \eta_\beta(\mathbf{x}) = \begin{cases} \eta_i & \text{for } \mathbf{x} \in D_\beta \\ \eta_b & \text{for } \mathbf{x} \in V_c \setminus D_\beta \end{cases} \quad (3)$$

it follows that $D_\beta \subseteq D_\alpha \Rightarrow \eta_\alpha(\mathbf{x}) \geq \eta_\beta(\mathbf{x})$ in V_c. Therefore, by taking into account (1), we obtain:

$$D_\beta \subseteq D_\alpha \Rightarrow \mathbf{P}_\alpha^{(2)} - \mathbf{P}_\beta^{(2)} \text{ is positive semi-definite}. \quad (4)$$

The monotonicity property (4) is the basis for the inversion algorithm. Specifically, equation (4) is used as sufficient condition to exclude that a set is contained within another one. For instance, if the matrix $\mathbf{P}_\alpha^{(2)} - \mathbf{P}_\beta^{(2)}$ is not positive semi-definite than $D_\beta \subseteq D_\alpha$ is false.

The first step of the inversion algorithm is the extraction of $\widetilde{\mathbf{P}}^{(2)}$, an estimate of the second order moment of, $\mathbf{R}^*_{coil}(j\omega) = \mathrm{Re}\{\mathbf{Z}_0(j\omega) - \mathbf{Z}(j\omega)\}$, by noisy measurements of $\tilde{\mathbf{R}}^*_{coil}$ collected at different frequencies. Specifically, from (2) we interpolate $\tilde{\mathbf{R}}^*_{coil}$ as $\tilde{\mathbf{R}}^*_{coil}(j\omega) = \tilde{\mathbf{P}}^{(2)}\omega^2 + \tilde{\mathbf{P}}^{(4)}\omega^4$ and we compute the elements $\tilde{\mathbf{P}}^{(2)}_{ij}$ and $\tilde{\mathbf{P}}^{(4)}_{ij}$ by minimizing:

$$\Psi_{ij}(p_2, p_4) = \sum_k \omega_k^{-np}\left[\left(\widetilde{\mathbf{R}}^*_{coil}(j\omega_k)\right)_{ij} - p_2\omega_k^2 - p_4\omega_k^4\right]^2 \quad (5)$$

where ω_k is the k-th measurement angular frequency and np is a small integer (usually not greater than 10) used to weight the measurements collected at different frequencies. We found by means of numerical simulations, that for a geometry consisting of a conductive slab, the fourth order interpolation of $\tilde{\mathbf{R}}^*_{coil}$ holds if the skin depth at any ω_k's is not smaller than the thickness of the slab.

Once that $\widetilde{\mathbf{P}}^{(2)}$ has been extracted from the measurements, it is processed as follows.

Let $V \subseteq V_c$ the unknown region containing the anomaly, and let the conductive domain V_c be divided into S "small" non-overlapped parts $\Omega_1,\ldots,\Omega_S$. Let us temporarily assume that V is union of some Ω_k's and that the estimate $\widetilde{\mathbf{P}}^{(2)}$ is error free, i.e. $\tilde{\mathbf{P}}^{(2)} = \mathbf{P}^{(2)}$ where $\mathbf{P}^{(2)}$ is the second order moment corresponding to a defect in V.

Following (4), we set the estimate $\widetilde{V}$ of V as the union of those Ω_k such that $\widetilde{\mathbf{P}}^{(2)} - \mathbf{P}^{(2)}_k$ is positive semi-definite where $\mathbf{P}^{(2)}_k$ is the second order moment related to $\eta_k(\mathbf{x})$ defined as:

$$\eta_k(\mathbf{x}) = \begin{cases} \eta_i & \text{for } \mathbf{x} \in \Omega_k \\ \eta_b & \text{for } \mathbf{x} \in V_c \setminus \Omega_k \end{cases}, \quad (6)$$

i.e. $\eta_k(\mathbf{x})$ corresponds to a defect in Ω_k. It is worth noting that $V \subseteq \widetilde{V}$ as it follows from (4), thus the reconstruction is equal to or contains the defect.

The matrices $\mathbf{P}^{(2)}_k$ can be pre-computed and, in addition, easily stored since their dimensions are $n\times n$ where n is equal to the number of coils that, usually, is not greater than few dozens. Moreover, to check if $\widetilde{\mathbf{P}}^{(2)} - \mathbf{P}^{(2)}_k$ is positive semi-definite, it is required to compute the eigenvalues of $\widetilde{\mathbf{P}}^{(2)} - \mathbf{P}^{(2)}_k$ for each k. The computational cost for computing the eigenvalues (for a fixed k) grows as $O(n^3)$ but n is "small" as already highlighted.

In the general case where V is not union of some Ω_k's and the data are affected by noise, $\widetilde{\mathbf{P}}^{(2)}$ is also affected by noise. Therefore, the noise affecting $\widetilde{\mathbf{P}}^{(2)}$ corrupts the eigenvalues of $\widetilde{\mathbf{P}}^{(2)} - \mathbf{P}^{(2)}_k$.

To tackle this situation we compute a sign index s_k related to Ω_k and defined as:

$$s_k = \left(\sum_j \lambda_{k,j}\right)\left(\sum_j |\lambda_{k,j}|\right)^{-1} \quad (7)$$

where $\lambda_{k,j}$ is the j-th eigenvalue of the matrix $\widetilde{\mathbf{P}}^{(2)} - \mathbf{P}^{(2)}_k$. For noise free data, the sign index s_k is equal to –1 when $V \subseteq \Omega_k$ and to +1 when $\Omega_k \subseteq V$.

Then, we introduce the reconstruction with threshold ε that is the set defined as $V_\varepsilon \hat{=} \bigcup_{k|s_k>\varepsilon} \Omega_k$. Finally, to select the most appropriate value for the threshold ε we solve the one parameter minimization problem:

$$\min_\varepsilon \left\|\widetilde{\mathbf{P}}^{(2)} - \mathbf{P}^{(2)}_\varepsilon\right\|^2 \quad (8)$$

where the matrix $\mathbf{P}^{(2)}_\varepsilon$ is related to V_ε and $\|\cdot\|$ is a suitable matrix norm as the Frobenius norm.

Finally, notice that the inversion method entails to solve the inverse problem by solving a number of forward problems that increases linearly with the number of parameters representing the unknowns resistivity S.

4. THE PROBE DESIGN

The proposed method presents two critical aspects from a measurement point-of-view:

a) the very small amplitude of the induced voltage signal at the coil terminals;
b) the little difference between the elements of the **Z** matrix calculated in absence and presence of a defect.

As far as the (a) point is concerned, the method imposes to obtain induced voltage signals high enough to overcome the mask effect caused by environmental noise, while the (b) point imposes to find the better measurement conditions that enhance the mutual impedance matrix variations caused by the defect presence.

To optimize these aspects, an exhaustive sensitivity analysis regarding:

i) the number of coils in the probe;
ii) the coil geometric dimension;
iii) the number and the thickness of coil turns;
iv) the distance between coils;
v) the distance between the probe and the specimen;
vi) the excitation current amplitude;
vii) the excitation current frequency values;
viii) the maximum acceptable noise levels on the current and voltage acquired signals;

should be performed. To this aim, a simulated approach is strongly preferable, in order to avoid the construction of a great number of probes and the realization of a great number of measurement sessions.

Nevertheless, even an exhaustive simulation analysis proves to be very cumbersome for the large number of parameters to be optimized. For these reasons, a simplified approach was followed: having fixed, on the basis of Authors' experience, the (i), (iii), (iv), (v), and (vi) characteristics, a set of simulations has been performed in order to investigate the (ii), (vii) and (viii) aspects. Then, an experimental phase will be carried out in order to validate the overall approach.

In particular, simulated tests have been carried out considering a probe formed by a matrix of 4x4 equally spaced coils on a diamagnetic support. The distance between the coil centers is fixed at 14 mm. Each coil is supposed to be realized winding up 80 turns of a 0.05 mm^2 copper wire, in order to allow an exciting current equal to 1 A. A 8 cm x 8 cm x 2 mm Al conductive specimen is considered, with a defect (hole) of 4 mm x 4 mm x 2 mm located at the center. The specimen resistivity is assumed equal to $\eta=2.825\cdot10^{-8}$ Ωm, while the defect resistivity is assumed 1000 times higher. The probe is located at 1 mm above the specimen.

The tests were carried out: (i) varying the internal coil radius from 2 mm to 3 mm, with 0.1 mm step, and adopting a coil height equal to 5 mm, 10 mm, and 15 mm; (ii) using five excitation current frequencies (250 Hz, 500 Hz, 750 Hz, 1000 Hz, and 1250 Hz), corresponding, for the considered specimen, to skin-depth values of 5.35 mm, 3.78 mm, 3.09 mm, 2.68 mm, and 2.39 mm, respectively. It is noticed that the maximum frequency of the excitation current is limited by considering that the skin depth must be greater than the specimen thickness.

An original software capable of solve the forward problem was adopted [11]. In particular, fixed the above mentioned parameters, the software is able to compute the mutual matrix impedance variation $\Delta\mathbf{Z}_\eta=\mathbf{Z}_\eta-\mathbf{Z}_0$, where $\mathbf{Z}_0$ is obtained assuming the coils in the free space (air) [12], and $\mathbf{Z}_\eta$ is related to the spatial resistivity η of the considered specimen.

In order to evaluate the overall method sensitivity, the following index:

$$D = \left\| \Delta\mathbf{Z}_\eta \right\|_F ,$$

computed as the Frobenius norm, has been adopted.

Fig. 2 shows the results obtained in simulation sessions conducted as above mentioned. It is possible to notice that: (i) the D values show a great variation depending on the coil internal radius and height; in particular, the larger is the internal radius and the smaller is the height, the higher is the D value; (ii) D assumes higher values when the excitation current frequency increases.

A second simulation phase has been performed, in order to investigate the reconstruction capability of the probe respect to the noise level. In particular, a multiplicative noise with different amplitudes has been considered. Fig. 3 shows the results obtained for the adopted probe geometry (Fig. 3.a). The partition of the conductive domain V_c is made with a regular grid of 20x20x1 Ω_k elements (Fig 3.b). The measurement noise has been modeled as a uniformly distributed multiplicative noise affecting the **Z** element values. In Fig. 3.c, the square gray point located at the center of the specimen represents the imposed defect, while Figs. 3.d, 3.e, and 3.f show the reconstruction results obtained with noise level of 0.5 %, 1 %, 1.5 %, 2 % and 5 %, respectively.

Some consideration can be made on the obtained results. Tests carried out with noise level up to 2% show a correct defect detection, also if at noise levels equal to 1.5% and 2% a wrong further defect was identified (black square point in Fig. 3.e). Growing the noise level up to 5 %, the defect detection prove to be wrong (Fig. 3.f), confirming the necessity to use high performance measuring systems and useful noise limiting tricks. Moreover, the light gray border

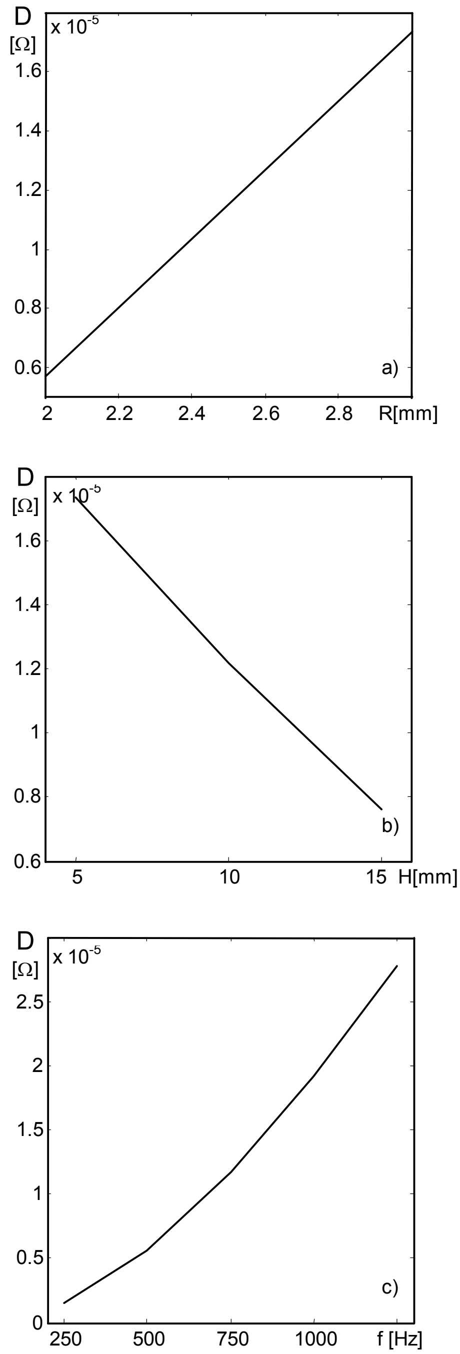

Fig. 2. Sensitivity index D computed varying: (a) the coil internal radius; (b) the coil height; (c) the excitation current frequency.

elements in the Figs 3.d, 3.e and 3.f highlight magnetic field boundary effects. In order to avoid a wrong defect identification, these elements have to be excluded from the defect reconstruction process and assumed as no defect zone.

5. THE REALIZED MEASUREMENT STATION

In order to build up an automatic measurement system able to provide the inducing current, to acquire the coils voltage signals, to build-up efficiently the mutual impedance matrix, and finally to process the measurement data, suitable

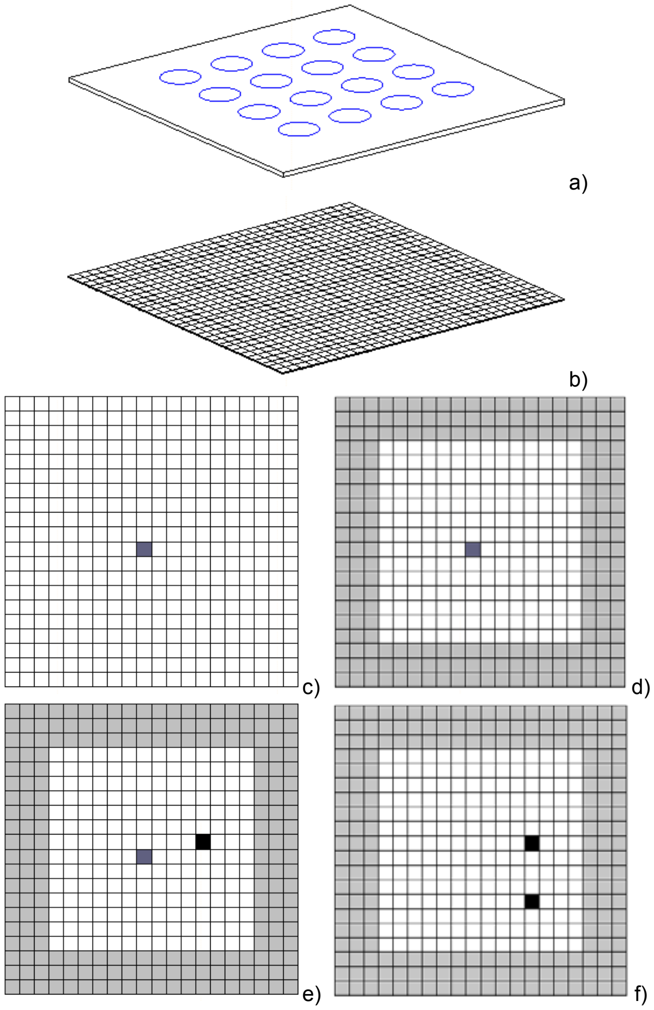

Fig. 3. Experimental results obtained during the set-up phase. (a) reference geometry; (b) the Ω_k's partitioning the specimen; (c) imposed defect; (d) detected defect with 0.5% and 1% noise levels; (e) detected defect with 1.5% and 2% noise levels; (e) detected defect with 5% noise level.

hardware architecture and software procedures were set up.

The accuracy required from the proposed method, together with the low amplitude of the acquired voltage signals, impose the use of a measurement system characterized by good accuracy in acquisition and elaboration devices. To this aim, a Personal Computer (PC), equipped with a standard IEEE488 interface board, controls the whole measurement system built up using high performance instruments.

A block diagram of the proposed measurement system is reported in Fig. 4. It can be divided in four parts: the probe, the generation unit, the acquisition and measurement unit, and the digital processing unit.

With reference to the simulations carried out, a probe formed by a diamagnetic support (Plexiglas) with a matrix of 4x4 equally spaced coils (3.0 mm internal radius, 5 mm height, and 80 x 0.05 mm^2 copper wire turns) was realized (see Fig. 5). The coils are placed with their axes perpendicular respect to the support lower surface and are perfectly parallel among them. Moreover, in order to assure a easy connection to the measurement system and to reduce

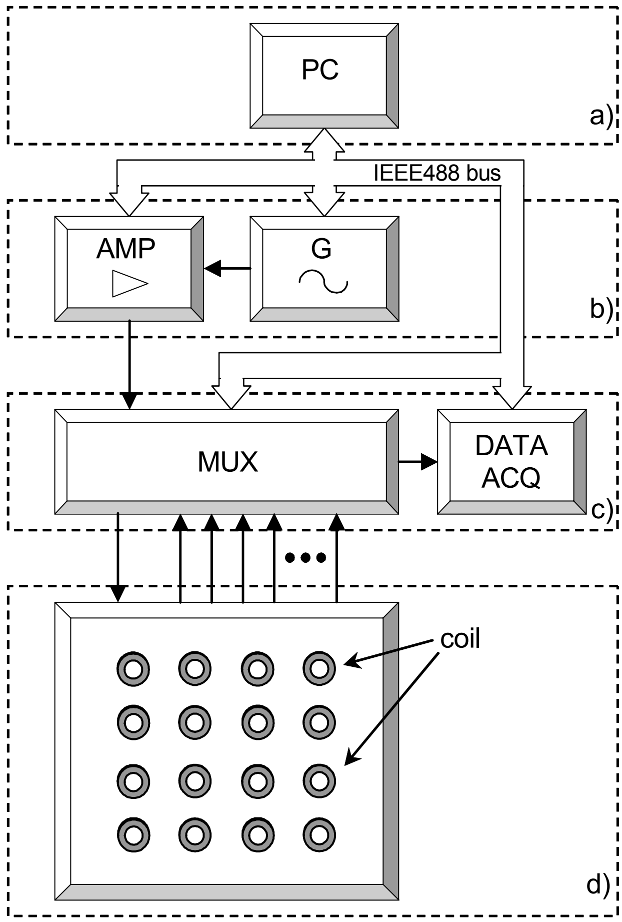

Fig. 4. The developed measurement system; a) digital signal processing unit; b) generation unit; c) acquisition and measurement unit; d) probe.

as much as possible the electromagnetic interference and coupling, each coil is connected to a useful terminal using a couple of twisted wires.

The generation unit is constituted by a 20-20 Kepko Bipolar Operational Amplifier (AMP) fed by a HP 33120A frequency generator (G).

The acquisition and measurement unit is essentially composed by a TEKTRONIX TDS520 digital oscilloscope and a Keythley 7200 6.5 digits multimeter, equipped with a switch matrix card (MUX) able to connect the probe to the generation and acquisition units. The switch matrix, driven by a suitable software, allows to connect one coil to the generation unit and any of the other coils to the acquisition and measurement unit. These operations are repeated in sequence for all the coils in the probe. The oscilloscope is employed essentially to compute the phase difference between a signal dependent from the impressed current and the measured voltage, using a frequency (FFT) approach, while the multimeter measures the RMS values of the impressed current and measured voltage. In this way, the mutual impedance matrix can be computed.

The digital processing unit is composed by a PC with a Borland C++ Builder 5.0 based software that: (i) manages the measurement devices via IEEE 488 bus, (ii) collects and organizes data transmitted from the acquisition unit, and (iii) performs the inversion procedure.

6. CONCLUSIONS

The paper presents a measurement system to identify defects in conductive materials using a EC-NDT approach. In particular, using a suitable probe and an original computation algorithm, it is possible to reconstruct the defect characteristics starting from the analysis of a useful quantity, the mutual impedance matrix. The preliminary analysis carried out in a simulated environment shows a good skill of whole set-up method in identify the defect position and geometry also in presence of noise. Further research activity are still in progress, with the objective of to test the method in a real environment. The related results will object of a future paper.

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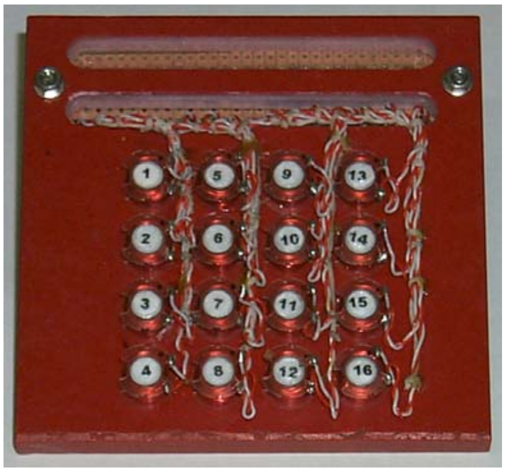

Fig. 5. The realized probe.

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