The Metrological Characterization And Optimization Of A Low Cost Measurement System For Inductance Tomography On Conductive Materials

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Abstract **–** The paper proposes the improvement and the metrological characterization of a measurement system for non-destructive testing on conductive materials. The limits showed by the previous realized prototype are discussed and overcome using a new hardware and software solution. The metrological characterization in terms of probe linearity, measurement uncertainty, and crack detection sensibility is reported. The experimental analysis carried out using the proposed system on specimens with known defects shows a good agreement between the estimated and expected results.

I. Introduction

Nowadays there are several applications that require, at the end of the manufacturing process or during the use as well, that the realized component do not have any superficial or internal defect that could affect its physical and mechanical properties. Examples can be found in nuclear, aerospace, biomedical and similar applications, where the quality and the integrity of components used are important in order to avoid unacceptable risks, also involving human lives. For these reasons both the industrial and scientific communities have placed their attention to the development of Non-Destructive Testing (NDT). NDT techniques are, by definition, methods used to evaluate the integrity of components and structures (both during the manufacturing and the active service) without harming them or affecting their performances. These methods are based on different measurement principles, as x-rays, ultrasonic, magnetic, Eddy Current (EC), thermography, and so on [1]-[10]. Many are the requirements that influence the choice of one of these methods: the cost, the measurement time and/or accuracy, the material under test. When NDT techniques are employed in industrial environments, a low cost and a brief measurement time become main aspects which drive the NDT method choice. With reference to inspection methods for conductive materials, the EC-based techniques grant these requirements and appear to be more attractive.

An EC-based inspection (see Fig. 1) usually is performed in three steps: (i) inducing EC in the specimen and sensing the reaction field by means of suitable coils (*excitation* and *pick-up*), (ii) measurement of the impedance variation $\Delta\dot{Z}=V_{pickup}/I_{excitation}$ due to the defect presence, and (iii) use of *ad hoc* elaboration algorithm to evaluate defect characteristics starting from $\Delta\dot{Z}$ values. It is here remarked that complex impedance $\dot{Z}$ provides information only for the little region of the specimen covered by the excitation/pick up set. In order to obtain information on the whole specimen, two different approaches can be adopted: (a) the use of a single excitation/pick up set, which has the advantage to have a simple probe and elaboration process but requires a moving system to cover all the specimen surface; (b) the use of a probe with multiple excitation/pick-up sets which cover all specimen

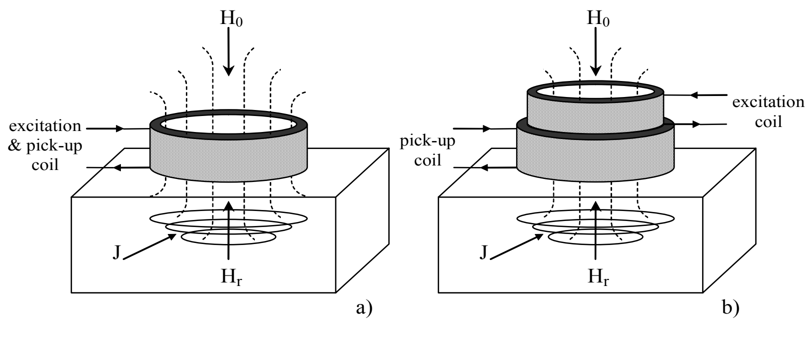

Figure 1. The operating principle of the eddy current method (H_0 = excitation filed; J = induced eddy currents; H_r = reaction field). a) single coil on the conductor specimen, to induce the excitation field and to detect the reaction field; b) two coils to induce and detect separately.

surface, allowing a more rapid inspection of the specimen under test without the use of a moving system. The advantages in (b) approach take research developments toward this solution even if the realization of multiple excitations and sensing probes entails more complex technological problems. In fact, from an hardware point-of-view, problems as cross talk interference and electromagnetic (EM) disturbances among supply and sensing lines are present, while from a numerical point-of-view it is necessary to take into account the interaction among the probe elements.

The authors are involved in this research field, in order to detect superficial and inner cracks together with the evaluation of their geometrical characteristics as shape, length, width, depth, etc. To this aim, using the EC NDT approach, algorithms, measurement methods, probes and automated measurement systems have been realized [11]-[24]. In particular, the authors have designed and developed a prototypal low-cost EC measurement system (see Figure 2) based on the inductance tomography [23]. The core of the proposed system is an innovative imaging procedure that estimates the impedance variation of the conductive material under test due to the presence of defects [18]-[21]. The inspection procedure can be divided in two steps: (i) the estimation of the mutual impedance matrix **Z** that represents an electromagnetic map of the cracked specimen under test, and (ii) the reconstruction of the defect characteristics in the material. The first step is realized using a probe constituted by a two-dimensional matrix of coils that induces EC in the material under test and senses the voltage signals due to the reaction field, while the latter is performed using a suitable imaging algorithm that processes the obtained **Z** values at different excitation current frequencies *(inverse problem)* [18]-[21].

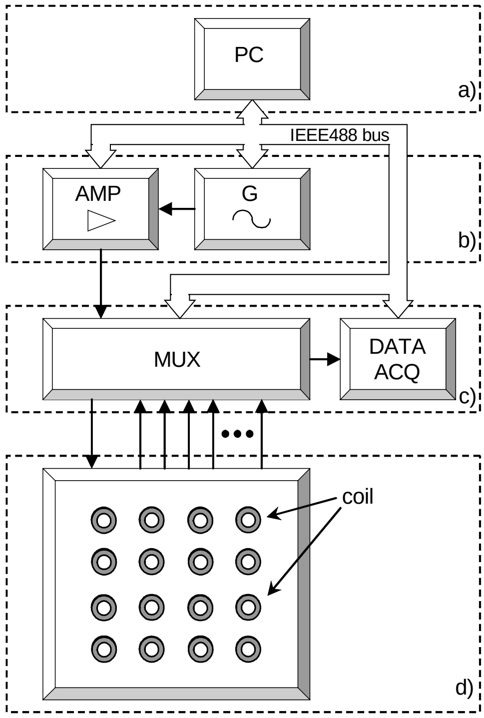

Figure 2. The developed measurement system: a) digital signal processing unit; b) generation unit; c) acquisition and measurement unit; d) the probe.

During the previous research activity, the processing algorithm of the realized system was accurately characterized and a first probe prototype was realized. This one had the aim to show the goodness and the suitability of the proposed measurement method, but was not optimized to solve problems linked to the optimum sensitivity and accuracy in the measurement of the required electromagnetic quantities. In particular, the response of the realized prototype was too much dependent from environmental EM noise that, in many cases, made the crack detection and/or reconstruction almost impossible. In fact, the evaluation of crack characteristics, based on an inversion algorithm, is a very critical task, ever since a small uncertainty on the direct measures can give rise to a great uncertainty in the identification of crack geometrical characteristics (*ill posed problem)*. For these reasons, this paper proposes an optimization and characterization of the previous realized system in order to overcome all these problems.

II. The improved probe prototype

In order to correctly evaluate the crack geometrical characteristics, two strategies could be adopted: (i) to use a black box model tuned with a great number of experiments; (ii) to adopt a numerical model of the EC problem very close to the actual measurements. The second way requires a less number of experiments to tune the model output, can give more precise measurements thanks the

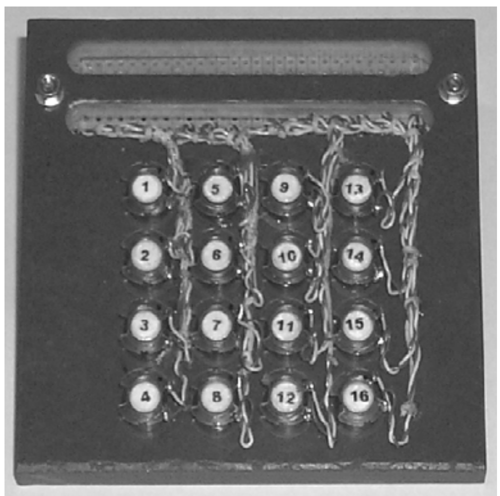

Figure 3. The previous realized probe.

possibility of modeling the crack accurately, and can be easily implemented in a control system to take decisions depending from the obtained results. For these reasons, it has been adopted in the proposed method. Obviously this strategy requires very good similarity between expected and modeled data thus requiring a good experimental apparatus able to give small measurement uncertainties. In addition, a relevant computational capability is required for properly modeling the probe-specimen interactions; this capability increases with the geometrical complexity and/or in presence of non linearity. For these reasons, in order to exploit simply the direct and inverse problem modeling, the previous prototype probe was composed by a 4x4 matrix of air wounded coils (see Figure 3). Nevertheless, this solution has lead to several troubles in the probe operating, showing sometime anomalous behaviors also in normal operating conditions. In particular, during several tests carried out for different specimen, defect geometry and location, it was noted that, also adopting the maximum supply current in the probe, the prototype frequently leads to bad or missing detections.

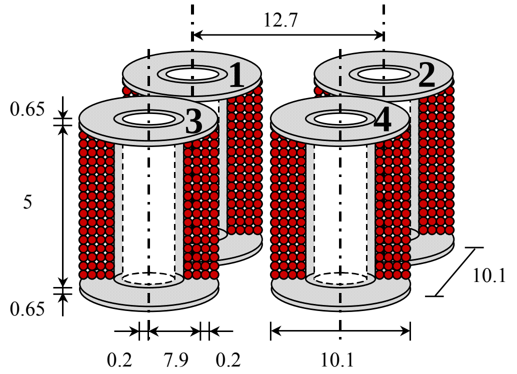

Figure 4. The realized air wounded test probe (dimensions are expressed in mm); the diamagnetic support is not sketched.

Table I. Comparison between the measured and calculated L11 (auto-inductance of coil #1) and M13 (mutual inductance between coils #1 and #3) values for the probe of Figure 4.

	Expected [μH]	Estimated	
		Mean Value [μH]	Rel. Unc. [%]
L11	82.3	94.9	1.9
M13	5.824	6.124	0.35

In order to quantify this phenomenon, an ad hoc air wounded test probe, composed by four cylindrical coils with 111 turns of 0.018mm^2 copper wire (see Figure 4) was realized. Several tests were carried out to estimate the influence of the environmental EM noise respect to the measured signals. In particular, the realized air wounded test probe was placed in different noisy environment with disturbances related to personal computers, power supplies, motors, switching circuits, that represents the common industrial EM pollution. The analysis of the carried out tests have highlighted that the obtained signal/noise ratio was not adequate to assure the measurement uncertainties required by the elaboration algorithm. As an example, Tab. I shows the obtained results for a test carried out in presence of EM noise related to the switching power supplies of PCs and measurement instruments. It is possible to notice that the expected and the estimated impedance values are very dissimilar, and the measured uncertainty make the estimated impedances not compatible with the expected one. In these conditions, is not possible to identify a mathematical model of the EC problem which matches the actual measurements. In order to overcome this problem, improvements were realized both in the measurement probe and in the processing algorithm.

A. The Measurement probe improvements

Aim of the measurement probe improvements was both to increase the measured signal values and to reduce the measurement uncertainty and bias. After a preliminary simulation phase, these tasks were performed both using a ferromagnetic core material and realizing an ad-hoc probe geometry. As far as the first aspect is concerned, after a preliminary analysis among ferromagnetic materials available on the market, a very low cost material that could be easily modeled in the processing software was chosen. In particular, a N27 ferrite with a flux density of 500mT at 25°C, an initial permeability μi=2000 was used. Regards the improved test probe geometry, a rectangular transformer shape was adopted. In this way, the specimen under test acts as the lower plate of the transformer while the upper plate is realized from the probe, allowing a less spread magnetic flux and increasing the sensibility. In its first

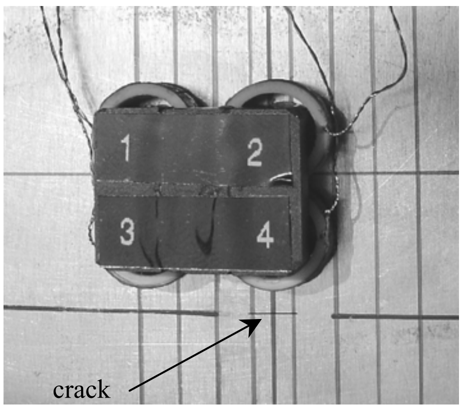

Figure 5. The improved test probe.

realization, the probe has realized by using a suitable ferromagnetic core in which the probe of Figure 4 can be inserted (see Figure 5).

B. The processing software improvements

Taking into account that for this kind of NDT applications the magnetic field is usually so low that the ferromagnetic material exhibit a linear behaviour, and that the frequencies vary in a range where the properties of the magnetic materials are almost independent on the working frequency, it is possible to extend the EC approach also for probes with ferromagnetic cores. The numerical modeling of EC in presence of magnetic materials has been discussed in [25] (in [24] with explicit reference to EC testing). Here we briefly recall the related integral formulation. The basic unknown of the formulation is the two-component vector potential **T** defined in the conducting region V_c (where the current density **J** is given by its curl: **J**=∇×**T**) and the magnetization vector **M** defined in the magnetic region V_f. The numerical formulation is an integral formulation. Integral formulation are advantageous because they allow to discretize only the conductive and magnetic materials and regularity conditions at infinity are automatically taken into account. The disadvantage is that they yield full matrices systems but the number of unknowns needed to get a required accuracy is relatively small. The electric vector potential **T** is expanded in terms of co-tree edge-element basis functions $\mathbf{T}_k$, $\left(\mathbf{J}(\mathbf{x},t)=\sum_k I_k(t)\nabla\times\mathbf{T}_k\right)$, the gauge is imposed by means of a tree-cotree decomposition of the finite element mesh and the boundary condition $\mathbf{J}\cdot\mathbf{n}=0$ on ∂V_c can be easily imposed for a simply connected domain V_c by using the tree-cotree decomposition. The magnetization vector is instead piecewise constant: $\mathbf{M}(\mathbf{x},t)=\sum_k M_k(t)\mathbf{P}_k$ where $\mathbf{P}_k$'s are unit vector pulse functions obtained by multiplying the unit vectors along the coordinate axes by the usual scalar unit pulse functions, which are different from zero only in a single finite element of V_f. The electric field **E** and the divergence-free magnetic vector potential **A** can be expressed as functions of **J** and **M** as:

$$\mathbf{E} = -\partial\mathbf{A}/\partial t - \nabla\varphi \tag{1}$$

$$\mathbf{A}(\mathbf{x},t)=\frac{\mu_0}{4\pi}\int_{V_c}\frac{\mathbf{J}(\mathbf{x}',t)}{|\mathbf{x}-\mathbf{x}'|}dV'+\frac{\mu_0}{4\pi}\int_{V_f}\frac{\mathbf{M}(\mathbf{x}',t)\times(\mathbf{x}-\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|^3}dV'+\mathbf{A}_0(\mathbf{x},t) \tag{2}$$

where φ is the scalar electric potential, μ_0 is the magnetic permeability of the vacuum and $\mathbf{A}_0$ is the contribution of the external current density. The numerical formulation is then obtained by replacing **J** and **M** with their discrete representations and imposing the constitutive relationship by the Galerkin approach:

$$\int_{V_c}\nabla\times\mathbf{T}_k\cdot(\eta\mathbf{J}+\partial\mathbf{A}/\partial \mathrm{t})dV=0,\ \forall k \tag{3}$$

$$\int_{V_f}\mathbf{P}_k\cdot[\mathbf{M}-\frac{\chi_m}{\mu_0(1+\chi_m)}\mathbf{B}]dV=0,\ \forall k \tag{4}$$

where χ_m is the magnetic susceptivity and η is the resistivity (**B** is obtained from **J** and **M** via Biot-Savart law). The above modifications have affected the imaging algorithm that is now able to treat ECT problems in the presence of magnetic materials. Another modification to the imaging algorithm has been the possibility to process not the measured impedance matrix (in the presence of the defect) but the difference between the measured impedance matrix and the impedance matrix measured for the defect free configuration. This has a relevant impact because from the experimental viewpoint is more accurate to measure directly the difference rather than compute the difference between two measured (noisy) matrices.

III. The improved prototype characterization

Several tests were executed in order to estimate measurement system performances in terms of: (i) measurement probe linearity; (ii) increment in the measured Z values and improvements in Z uncertainty; (iii) agreement between the estimated and expected Z values; (iv) crack detection sensibility.

(i) The improved test probe input–output characteristic has been estimated for several working frequencies in the 100 Hz to 2kHz range. For each frequency, the probe has been supplied by a sinusoidal current in the 50mA to 500 mA range using a 50 mA step, and the inducted voltage signals have been measured. The execution of a regressive test has confirmed the good linear behaviour of the ferromagnetic material, for the above specified ranges, with a determination coefficient of 0.998, in the worst case.

(ii) A test was executed disposing the air wounded test probe and the improved test probe over an aluminum specimen, supplying the coil #1 and measuring the Z matrix according to the processing algorithm [23]. Tab. II shows the estimated Z mean values and the relative uncertainty values obtained after 50 consecutive measurements. It can be highlighted that the mean values of the mutual impedance estimated with the improved test probe are one order higher than the ones estimated with the air wounded test probe; analogously, a significant improvement in the estimated uncertainty have found.

Table II. Increment in the measured Z values and improvements in Z uncertainty.

	Air wounded test probe		Improved test probe	
	Mean Value [mΩ]	Relative Uncertainty [%]	Mean Value [mΩ]	Relative Uncertainty [%]
Z11	3517.7	0.21	4437.4	0.18
Z12	27.688	0.25	411.9993	0.09
Z13	45.289	0.17	611.3091	0.09
Z14	11.210	0.54	123.7244	0.11

(iii) The Z values obtained using the improved test probe have been compared with those achieved by the processing software. Results are reported in Tab. III for some auto and mutual inductances. Is now possible to see that the measured and calculated Z values are now much closely.

Table III. Comparison between the measured and calculated L11 (auto-inductance of coil #1) and M13 (mutual inductance between coils #1 and #3) values for the probe of Figure 5.

	Expected	Estimated	
	[μH]	[μH]	Relative Uncertainty [%]
L11	363	368	0.4
M13	118	134	0.18

(iv) A scan on an aluminum specimen with a known crack (5 mm long, 2 mm depth, and about 0.01 mm width) was performed. The scan was conducted both with the air wounded and improved test probes using only two adjacent coils. Figure 6 shows the realized scan path together with the absolute values of the obtained **Z** matrix of the auto and mutual impedances both for the air wounded and the improved test probes. As it is possible to see, for the improved test probe the mutual-impedance value clearly shows a behavior with a maximum in correspondence to the crack position, while the auto-impedance value shows a minimum. As far as the air wounded test probe is concerned, it is possible to find a similar behavior, but with a noise level that make difficult to correctly evaluate the measurement results and identify the crack size and position.

IV. Conclusions

In the paper, an improvement of a measurement system for the execution of non destructive tests on conductive materials is presented. Starting from the analysis of the previous measurement system, a

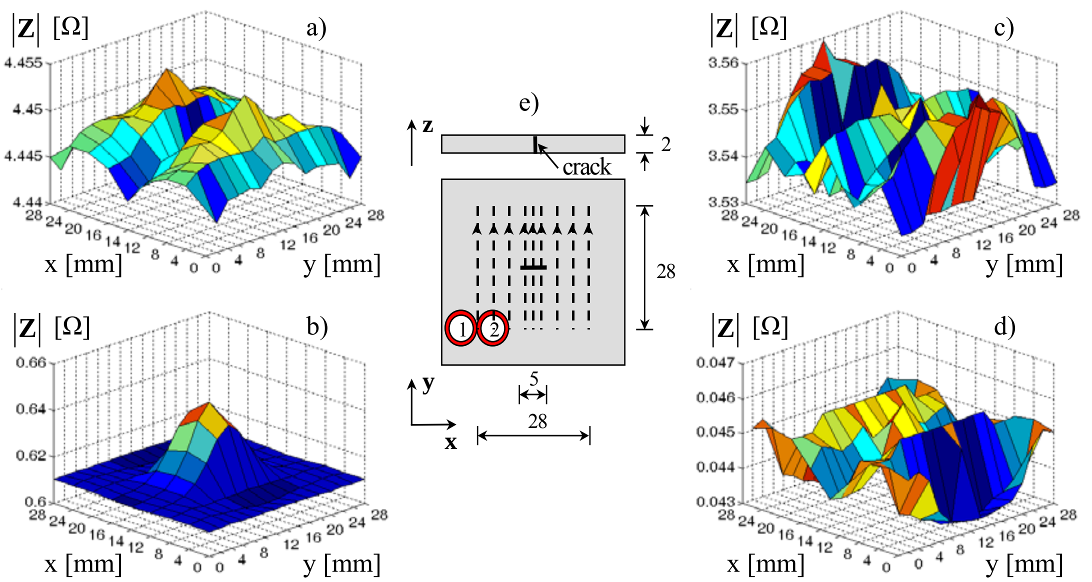

Figure 6. Results of the sensitivity analysis: a) auto and b) mutual absolute value of the impedance for the improved test probe; c) auto and d) mutual absolute value of the impedance for the air wounded test probe; e) the realized scan path (dimensions are expressed in mm).

new measurement hardware and software solution was realized, overcoming the problems that restricted the old measurement system performance. The improved solution has been characterized in terms of the linearity, accuracy and repeatability. A number of experimental test shows a good agreement between the measured and expected characteristic quantities. An exhaustive experimental tests are now in progress, in order to estimate the measurement performance in terms of defect detection capability and crack geometrical dimensions estimation. These tests are conducted on different specimen with different crack and different noisy environments, and will be object of a next paper.

The Authors would like to thank prof. Antonello Tamburrino for his helpful contribution in the paper development.

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