Direct and inverse electromagnetic methodologies: the proposal of MADEND project for ECT analysis

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Abstract

We present here some original methodologies for the solution of the direct and the inverse problems in Eddy Current Testing (ECT), developed or improved in the framework of the MADEND (Methods and Applications of Non-destructive Electromagnetic Diagnostic) research project partially funded by the Italian Research Ministry. Of the direct methods, the CARIDDI integral formulation has been tailored specifically for ECT problems, and an original discrete geometric approach of magneto-quasistatics has been developed. In order to validate and compare these formulations, a number of experimental benchmarks have been defined and set up with either inner or outer defects.

Methods and techniques for the solution of ill-conditioned inverse problems have also been developed, such as a new non-iterative inversion method for electrical resistance tomography, the transformation from a hyperbolic problem into a parabolic problem and innovative approaches to conductivity distribution identification. In addition, an estimation of the reliability of the ECT results has been performed and, to reduce the Probability of False Indication of the reconstruction, a new stochastic approach has been developed.

Methodologies for the solution of the direct problem and benchmarks

A fast and accurate solution of the forward problem is essential in view of the solution of the inverse problem. To this end, numerical methods, grouped into two different frameworks, have been developed.

The first group has been developed into the framework of an integral formulation based on the electric vector potential represented through edge-element shape functions (CARIDDI code). The computational cost to compute the fields has been reduced from $O(n^3)$ to $O(n \log(n))$ or $O(n)$ by means of the precorrected Fast Fourier Method [1] and the Fast Multipole Method [2]. Moreover, fast numerical methods for solving the forward problem due to resistivity changes in a small region of a conductor, have been implemented [3]. A magneto-optic inspection device (MOI) [4] and a Fluxset sensor [5] have been also modelled with this numerical method.

The second approach is an original alternative discrete method based on a geometric reinterpretation of the physical laws and the constitutive laws of magneto-quasi-statics, reformulated on a pair of interlocked meshes, each dual of the other [6], [7]. An algebraic formulation has been implemented, based on the circulation of the magnetic vector potential on edges and on a gauge function on the conductor nodes [8].

The proposed formulations can handle both volumetric and zero thickness defects. To validate and compare these approaches, a number of experimental benchmarks have been defined and realized, with either inner or outer defects. These benchmarks [9] are based on an inductive coil probe (400 turns, 10 mm in height, 12 mm inner diameter, 18 mm outer diameter) placed above an aluminium plate (4 mm thick) having 0.5 mm lift-off. The volumetric defect is a perfectly insulating cylinder 1mm in diameter, having its base on the bottom surface of the plate and different heights respectively of 4 mm (benchmark 1), 3 mm (benchmark 2) and 2 mm (benchmark 3). A bridge circuit is used to reveal the impedance variation due to the defect. An additional (identical) coil is placed in a defect free configuration to

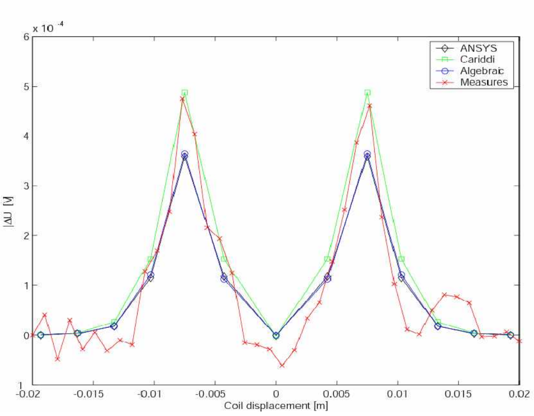

Figure 1. Voltage variation as a function of coil displacement computed with the described approaches and compared with the measured values (benchmark 1).

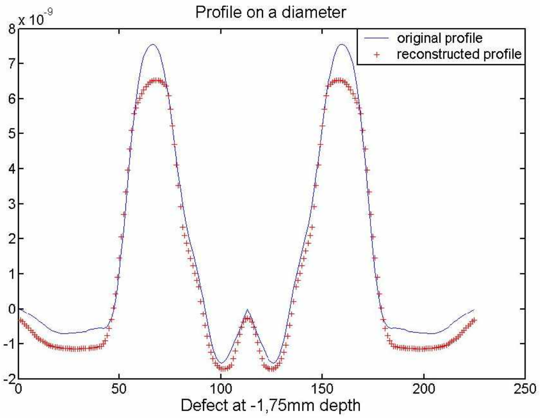

Figure 2. Reference and reconstructed conductivity profiles.

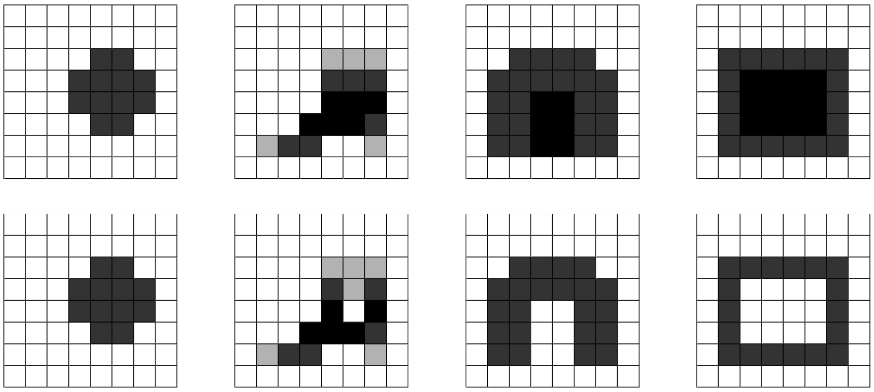

Figure 3: Results for a 16 electrodes ERT system, 0.01% multiplicative noise, 4 different anomaly profiles. White and dark grey: pixels correctly retrieved. Light grey: pixels of the anomaly but not retrieved. Black: pixels of the reconstruction that are not in the anomaly. Upper row: first step of the inversion algorithm, lower row: second step.

provide the reference impedance. In figure 1 we compare the numerically computed and the measured voltage variation on the bridge circuit corresponding, as discussed, to the variation of impedance between the defected and the flawless plate configurations. The results obtained from both approaches are in a good agreement with each other, with the experimental data and with the results from a commercial code, as follows from Figure 1 (benchmark 1).

The local discontinuities of a metallic specimen subject to plastic deformations, have also been investigated by using eddy currents. If discontinuities are present in the sample, they cause local modifications in both the electric and the magnetic properties of the specimen itself, consequently modifying the equilibrium condition corresponding to the absence of defects. The path of the eddy currents is thus disturbed, and a variation of the total magnetic field is produced. In the FLUXSET ® probe used, this implies a phase shifting in the voltage across a pick-up coil [10].

Identification methodologies for the solution of the inverse problem

Recently, a new non-iterative inversion method [11], [12] for electrical resistance tomography has been proposed (numerical results are shown in Figure 3). The relevant advantage of this method is that it requires the solution of a number of direct problems increasing linearly with the number of pixels (voxels) used to represent the unknown. This method is based on a monotonicity property of the unknown-data mapping. The method has also been extended to eddy current testing [26]. Another class of methods is based on the Q-transform [12], [14], an operator that transforms the solution of a proper hyperbolic problem into the solution of a given parabolic problem. Exploiting this relationship between different types of problem makes it possible to introduce, within certain limits, the time-of-flight for problems governed by the diffusion equation. Consequently, under proper conditions, it is possible to solve an inverse problem for the diffusion equation by using methods originally developed for wave-propagation problems. The presence of a defect can also be detected from the spatial discontinuity of the conductance profile. This problem can be represented as the inversion of a model which returns the distribution of the differential impedance from the profile of conductivity. The reference profiles of the electrical resistance impedance have been computed by means of the FEM approach. The identified conductivity profile has been obtained by means a recursive maximum likelihood inversion technique [15]. In its simplest form, the model needs to be linearized at each iteration around the current solution, and so the Jacobian of the non-linear model must be repeatedly computed. In order to overcome the problem of studying the electromagnetic interaction between the probe and the specimen, in this work we propose to approximate it, along with its linearization, through a neural network trained by means of a set of conductance/impedance patterns. The good approximation capability of a Multilayer Perceptron [16] is shown in Figure 2, where the approximated real part of the differential impedance profile for a small cubic defect (edge 0.5 mm) is depicted.

The modelling and simulation of the time evolution of degenerative processes in the fine structure of solder-points (Au-Al contacts) inside power integrated circuits has also been developed. The solid diffusion of one metal into the other, with impressed current, determines the growth of an intermetallic layer at the interface, with a strong dependence on temperature. As a result, the electric resistance of the contact increases while its mechanical strength decreases [17], [18], [19], [20], [21]. In the studied case, the direct problem requires both coupled (electro-thermal) and time-varying formulation, as well as non-linearity in the constitutive law of materials. In order to identify the electrical conductivity of a material layer characterized by diffusive growth, minimal-order optimisers belonging to both deterministic and evolutionary categories have been considered. This formulation has been applied to minimise the deviation between measured and simulated thickness of the diffusive layer at various time instants with the final goal of retrieving the distribution of conductivity inside the contact. The identified conductivity is about $5.5\ 10^5\ \Omega^{-1}\mathrm{m}^{-1}$ with this value, the maximum thickness of the compound along the profile grows to a first order proportionally to the square root of time up to the measured value of 75 μm after 2 hours.

Impact of uncertainties on the solution of the inverse problem

The goal of an Eddy Current Testing (ECT) process is to provide accurate and reliable reconstructions of defects in conductive structures, [22], [23], [24], [25]. The inevitable uncertainties, both systematic (e.g. inaccuracies in the knowledge of measurement system parameters) and random (e.g. measurement noise), have an impact on the reliability of the ECT reconstruction that can be quantified in terms of the *Probability Of Detection* (POD) and the *Probability of False Indication* (PFI). Apart from the measurement noise, the signal from ECT probes is usually calibrated before the flaw detection by acquiring the field map of flawless parts and removing possible offsets; the quality of the reconstruction is highly dependent on the accuracy of this calibration. The reliability of the ECT reconstruction also depends on the precision of the geometrical data, the accuracy of the material modelling and the precision of both the direct and the inverse procedures used in the reconstruction process. Therefore an estimation of the reliability of the ECT results is required. The introduction of the average process and the presence of multiple minima call for considerable computational power. Therefore the inverse ECT problem is solved by a Parallel global model Genetic Algorithm (PGA) while the direct solver is a finite edge-element integral code based on an electric vector potential formulation. The PGA individuals are described by bit-valued chromosomes, where, in the framework of a finite element approach, a bit 1 indicates a material element while a bit 0 indicates a crack element; a special definition of the individuals has been adopted to avoid a checker board solution with not simply connected crack geometries. A concurrent stochastic model has been implemented on a parallel distributed computing environment built onto a Beowulf-class cluster of processors to achieve the needed performance levels. The developed software framework comprises a parallel GA library and MPI for message passing together with Matlab for graphics and for the user friendly interface. The PGA achieves a global parallel strategy for the evaluation of the individual fitness by adopting a task farming model with a master-slave structure. In addition, to prevent new evaluations of already calculated configurations, a data base of already computed trial cracks is built and updated during the inverse resolution process. The presented model has been tested with good results against a benchmark problem: a square plate with a hole and a rectangular crack.

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