EDDY CURRENT MODELLING FOR NONDESTRUCTIVE TESTING

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Abstract: Eddy current nondestructive evaluation is widely used to inspect conducting materials during manufacture or in service. In this context, modeling is a powerful tool for inspection improvements : it helps probe-coil designers to optimise sensors for each examination requirement, it gives better understanding of the involved physics, it helps operator training and it also increases defect analysis reliability. This contribution presents the recent progresses in developing models which have the capability to predict quickly the signal of an eddy current probe used in nondestructive testing. These codes form a part of the tools available in CIVA which is a multi-technique (ultrasonic, radiographic, electromagnetic) platform for NDT. It is shown how these models, included in the convivial user interface of CIVA, can be used in order to optimize the design of probe-coils and study various configurations of control. It is a powerful tool for implementation of industrial NDT methods (e.g. coil shape, frequencies) and evaluation of perturbation parameters (e.g. lift-off, tilt) by limiting the number of experimental tests. This paper tackles the various analytical and semi-analytical approaches used in these models. In particular, it presents simulations of the response of eddy current probes due to a 3D flaw located in a plate or in a tube, obtained with models based on dyadic Green function calculations in the framework of the volume integral formalism. The case of testing with a ferrite core probes is also detailed. All models developed and integrated in CIVA have been validated using experimental results.

Introduction: Eddy current nondestructive testing of conductive materials is of importance in many domains of industry: energy production (nuclear plants), transportation (aeronautic), workpiece manufacturing etc. This technique, based on the analysis of changes in the impedance of one or more coils placed near the workpiece to be tested, is used to detect and characterize possible flaw or anomalies in the workpiece. Typical testing configurations may consist of ferrite or air core bobbin probes which are placed above a planar (or at least locally planar) layered workpiece or inside or outside a tubular workpiece and which are operated in the time-harmonic regime. The probes can as well operate in absolute mode as in differential mode with additive or subtractive flux, or in transmit-receive mode.
This contribution presents the recent progresses in developing models mainly based on the volume integral method using the Green's dyadic formalism [1] which has the capability to predict quickly the signal of an eddy current probe used in nondestructive testing. These codes form a part of the tools available in CIVA which is a powerful multi-technique (ultrasonic, radiographic, electromagnetic) platform for industrial NDT applications including a convivial user interface.
All models developed and integrated in CIVA have been validated using experimental results.

Tools dedicated to the design of the probes: Before even simulating the response of a probe to the presence of a defect, it is often useful to study the way in which a probe excites the workpiece to be tested in order to optimise its design and to assess the impact of perturbation factors (e.g. lift-off, tilt). Two tools were designed for this purpose. The first of them makes it possible to calculate [2, 3, 4, 5, 6] and represent (figures 1 and 2) the incident field in the workpiece (i.e. the electric field in the absence of flaw). The second is dedicated to the study the probe performance which is usually assessed via the normalized impedance diagram (figure 3).

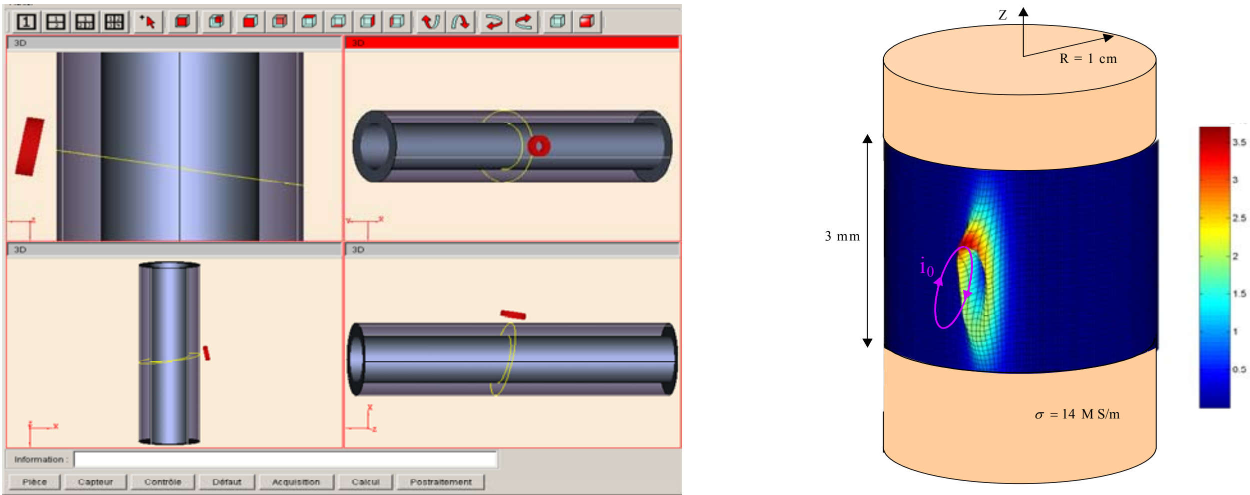

Figure 1: CIVA user interface (left) and distribution of eddy current induced on cylinder by a coil for a tilt of 10° (right).

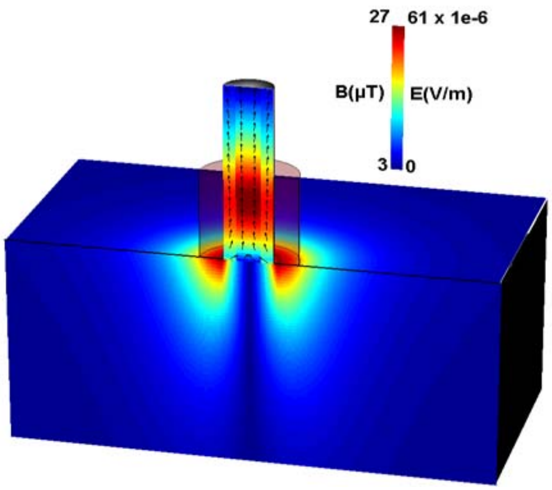

Figure 2: Magnetic field inside the ferrite core (cylindrical shape) of the probe and electric field induced by the probe inside a planar workpiece.

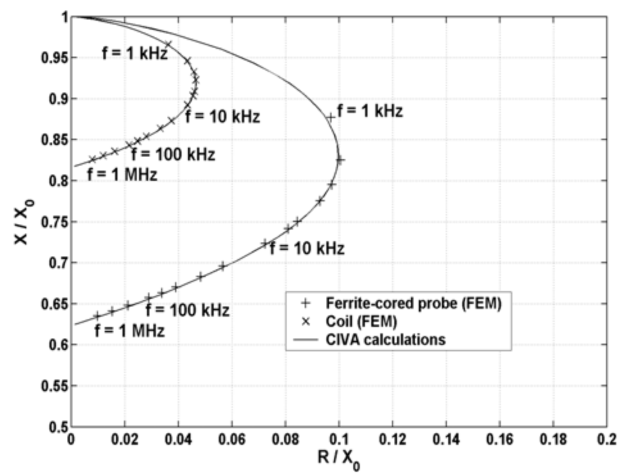

Figure 3: Normalized impedance diagram of the cylindrical ferrite-cored probe and of the coil alone computed with CIVA and compared with finite element calculations.

Tools to simulate the response due to a 3D flaw: In the framework of the volume integral approach based on the Green's dyadic formalism, 3D flaws are described as a local variation of conductivity which may vary by the shape, the size and the place in the workpiece (figure 4).

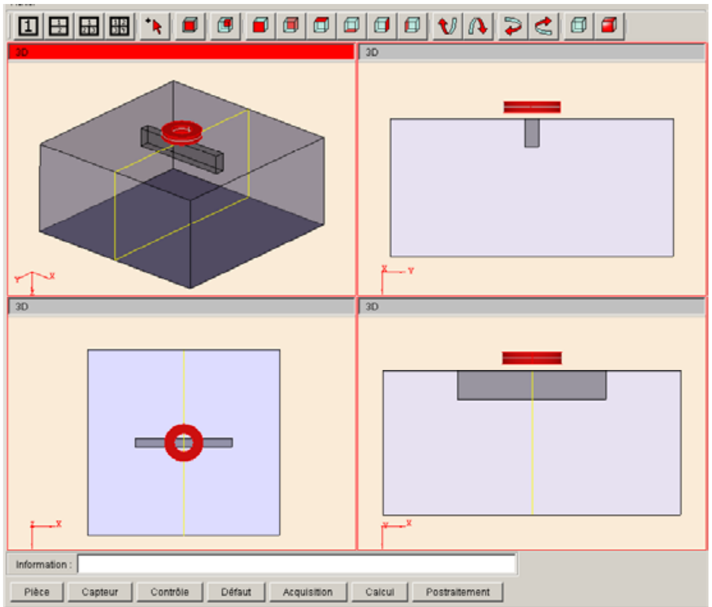

Figure 4: Representation of the eddy current testing configuration in the CIVA user interface for a bobbin coil placed above a conducting plate affected by a parallepipedic flaw

The eddy current signal is calculated at different positions corresponding to the motion of the probe which differs according to the testing configuration (planar surface riding configuration, tubing inspection).
The inspection of heat exchanger tubes is usually carried out with eddy current non destructive testing. For this application, eddy current testing methods are based on the analysis of changes in the impedance of bobbin coils placed inside the tube. A 3D model has been developed [7] to predict quickly the probe response as the probe moves along the tube. This model has been validated with experimental data for 2D and 3D flaws. For 2D flaws (i.e. circumferential groove), the results obtained with the 3D model has been also compared with data obtained with a previous 2D computer modelling tool [8] already integrated into CIVA (figures 5 and 6).

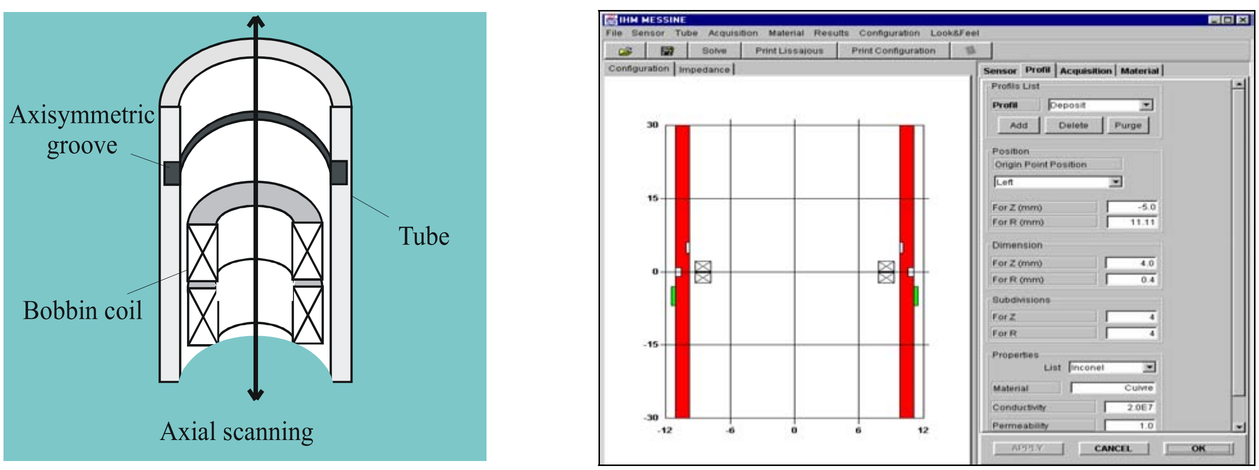

Figure 5: 2D model for tubing inspection : User interface representing a configuration with a circumferential inner groove, a circumferential outer groove and also a circumferential conductive deposit.

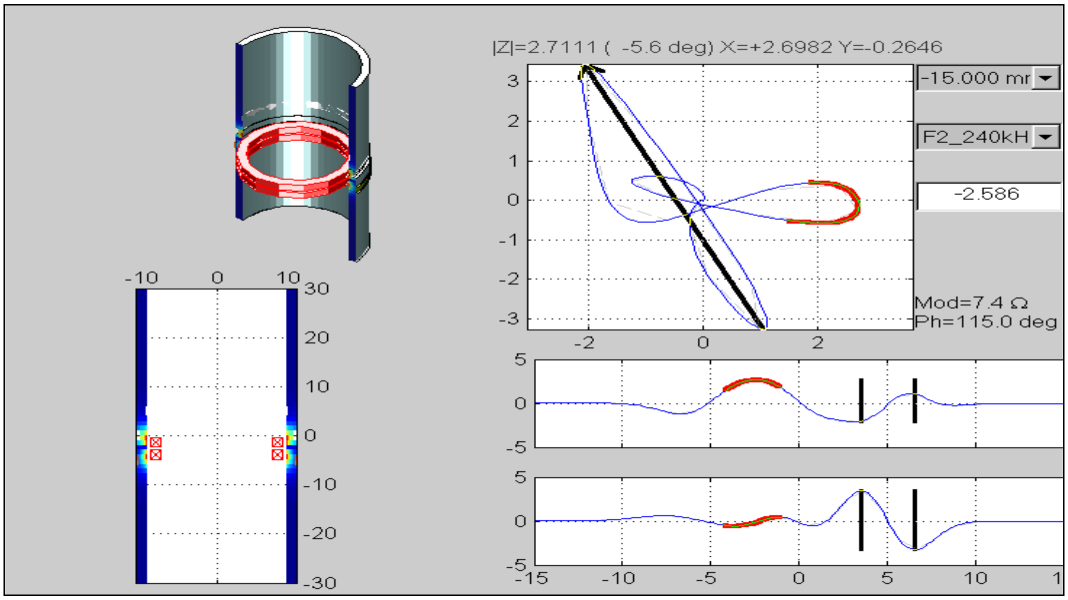

Figure 6: Eddy current distribution inside the tube and signal obtained with the 2D model for the configuration described in figure 5.

To illustrate the work which has been done to validate the 3D model dedicated to tubing inspection, the figures 7, 8, 9 and 10 give the configuration studied (left) and the results of validation (right). The tube, made of inconel 600 (conductivity of 1 MS/m), has an inner radius of 9.84 mm and a thickness of 1.27 mm. The probe consists of two identical coils excited with a time harmonic drive current in phase in both coils (additive flux mode). The inner radius of the coils is 7.83 mm, the outer radius is 8.5 mm, the height is 2 mm, the number of turns is 70, the gap between the coils is 0.5 mm.

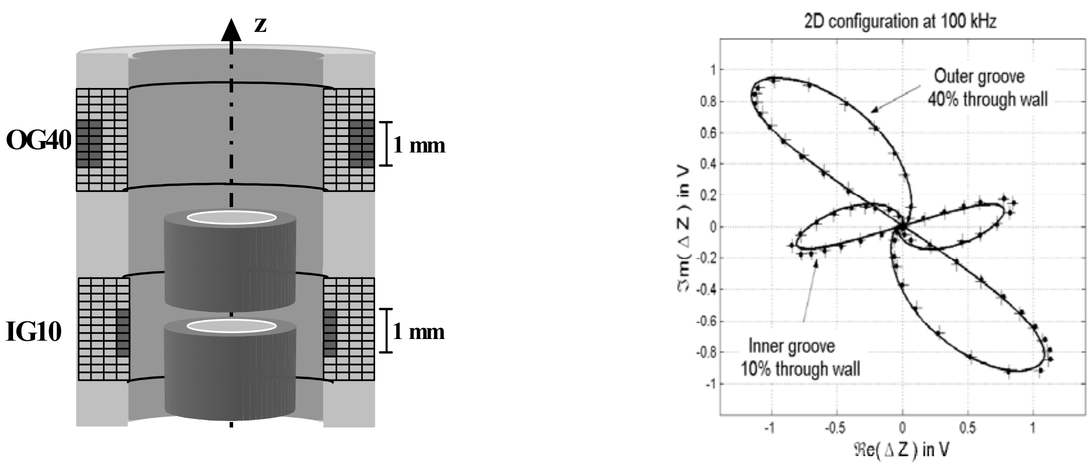

Figure 7: Case of circumferential outer groove and inner groove. Configuration scheme and EC signal for a probe operating in differential mode ('—' experimental data, '•' 2D model, '+' 3D model).

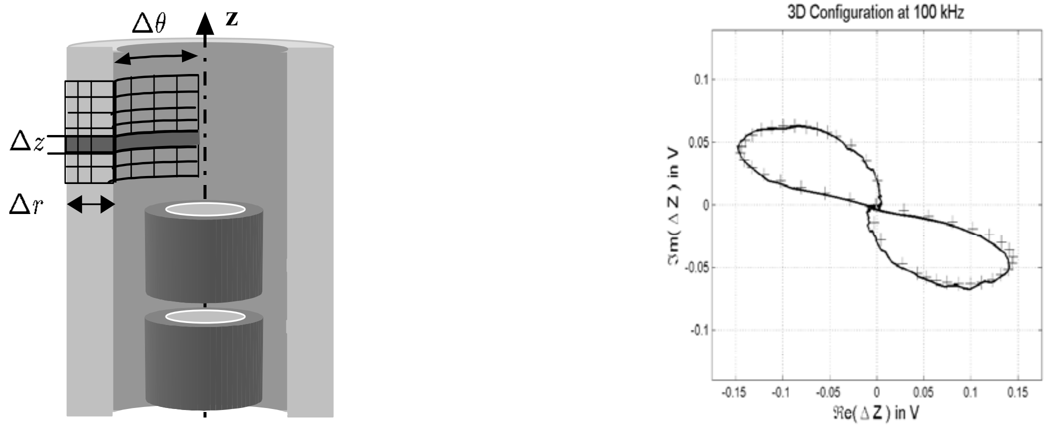

Figure 8: Case of transversal notch. Configuration scheme and EC signal for a probe operating in differential mode ('—' experimental data, '+' 3D model). This notch is a 100% through wall flaw ($\Delta r = 1.27$ mm) of 0.1 mm length ($\Delta z = 0.1$ mm) and of 82° angular extension ($\Delta\theta = 82^o$).

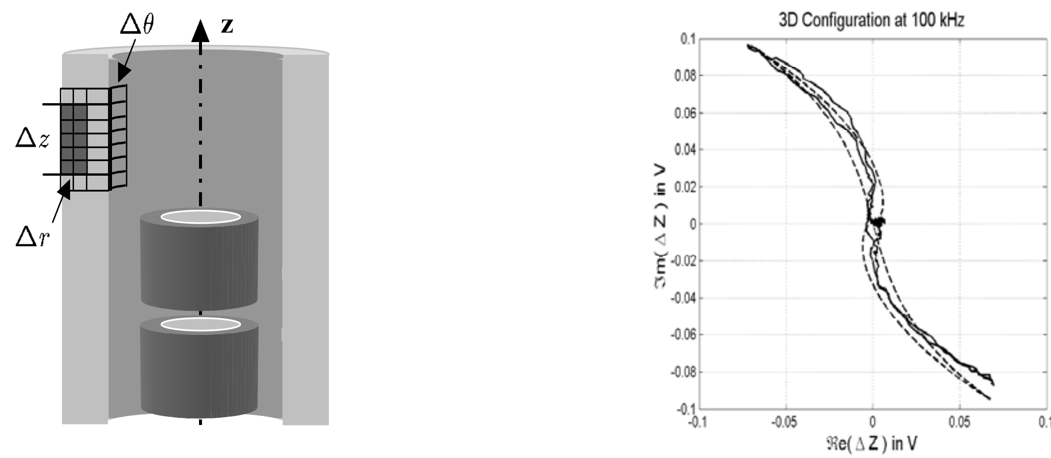

Figure 9: Case of longitudinal notch. Configuration scheme and EC signal for a probe operating in differential mode ('—' experimental data, '- -' 3D model). This notch is a 54% through wall outer flaw ($\Delta r = 0.7$ mm) of 10 mm length ($\Delta z = 10$ mm) and of 0.6° opening ($\Delta\theta = 0.6^o \Leftrightarrow \Delta l = 0.1mm$).

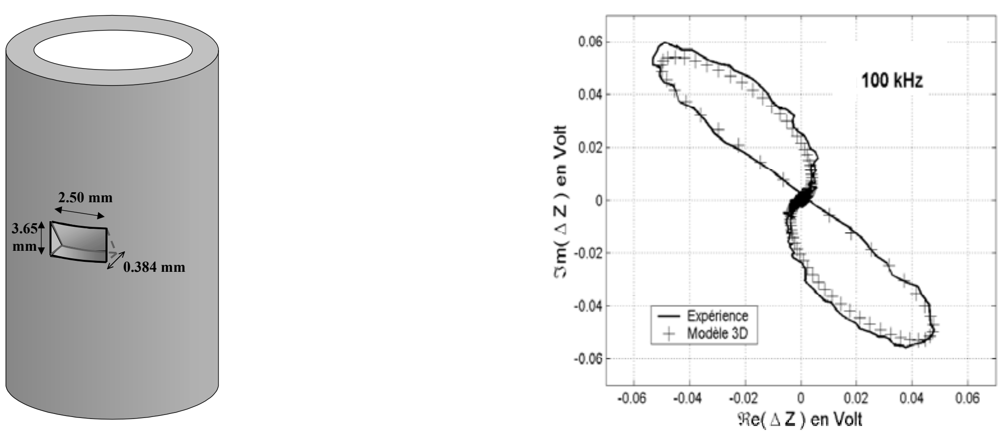

Figure 10: Case of a complex outer flaw. Configuration scheme and EC signal for a probe operating in differential mode ('—' experimental data, '+' 3D model).

For planar configuration, the probe scans the surface during its motion and a cartography may be obtained (figure 11).

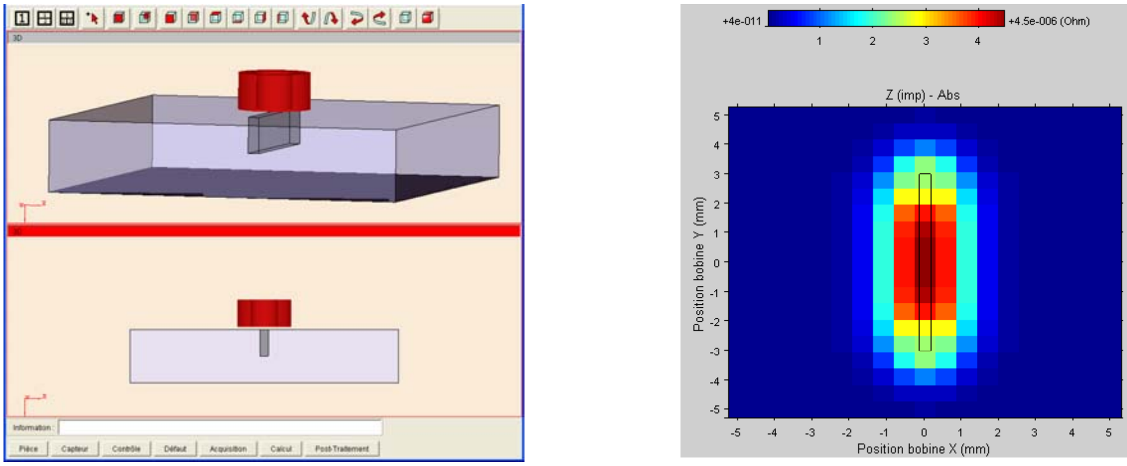

Figure 11: User interface (left) representing the planar configuration and impedance cartography (right) obtained when the probe has scanned the plate to be tested in the X and Y directions.

The case of probes with ferrite core has also been developed. The figure 12 gives the various shapes of ferrite cores which may be introduced in a probe.

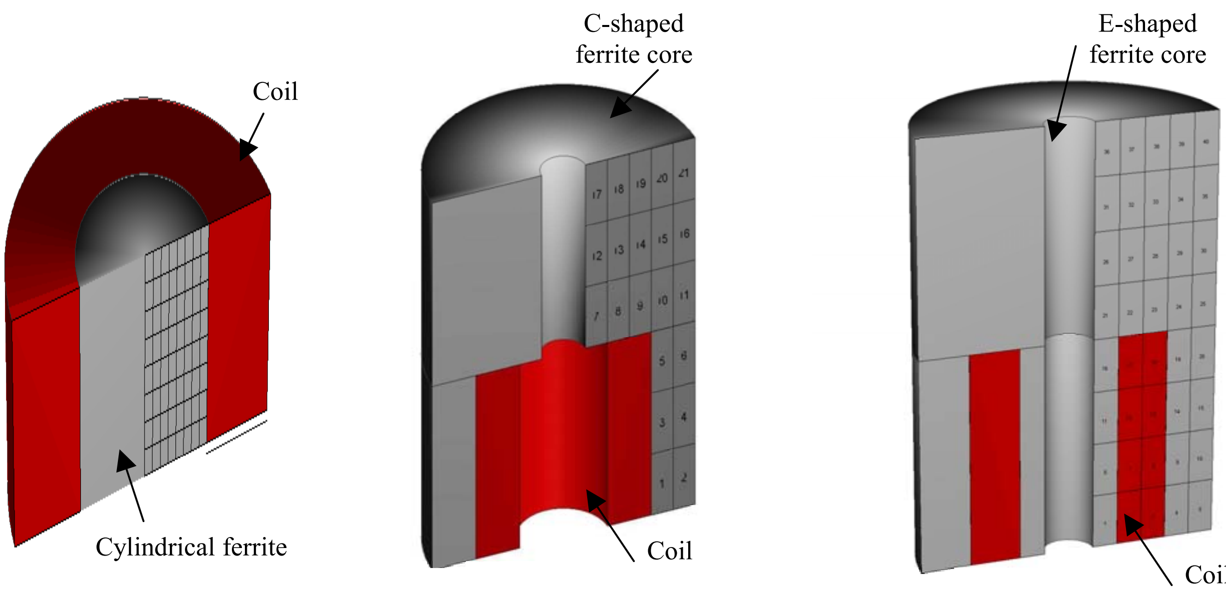

Figure 12: Various shapes of ferrite cores available : cylindrical shaped core (left), C-shaped core (center), E-shaped core (right)

The results obtained with the 3D model have been also validated when a ferrite core probe is used to test a planar workpiece affected by a flaw (figure 13).

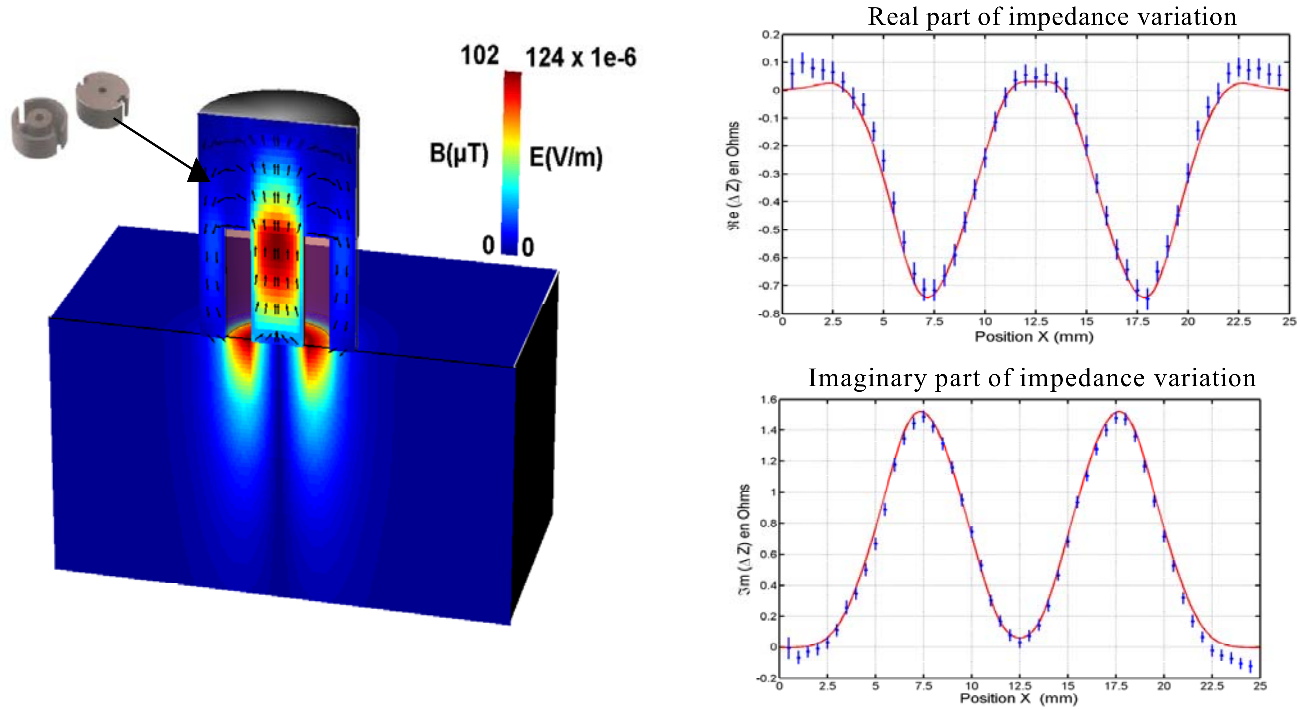

Figure 13: Magnetic field inside the ferrite core (E-shaped core) and electric field induced by the probe inside a planar workpiece (left); eddy current signal (right) obtained when the probe crosses a notch ('•' : experimental data, '—' 3D model).

Post-processing tool: In order to analyse the eddy current signals, a post-processing tool is used. This module, fully dedicated to treatment of eddy current signals, makes it possible to read files, to compare experimental and simulated data, to plot cartographies, to extract data, to represent impedance plane diagrams, to calibrate data, to make eddy current amplitude and phase measurements, to filter data etc. Figure 14 gives an example of the post-processing tool.

Conclusions: This paper has presented the recent progresses in developing models which have the capability to predict quickly the signal of an eddy current probe used in nondestructive testing. These codes are integrated in the CIVA platform.

These models are helpful to optimize the design of probe and study various configurations of control. It is a powerful tool for implementation of industrial NDT methods (e.g. coil shape, frequencies) and are particularly useful to assess the impact of perturbation factors (e.g. lift-off) by limiting the number of experimental tests.

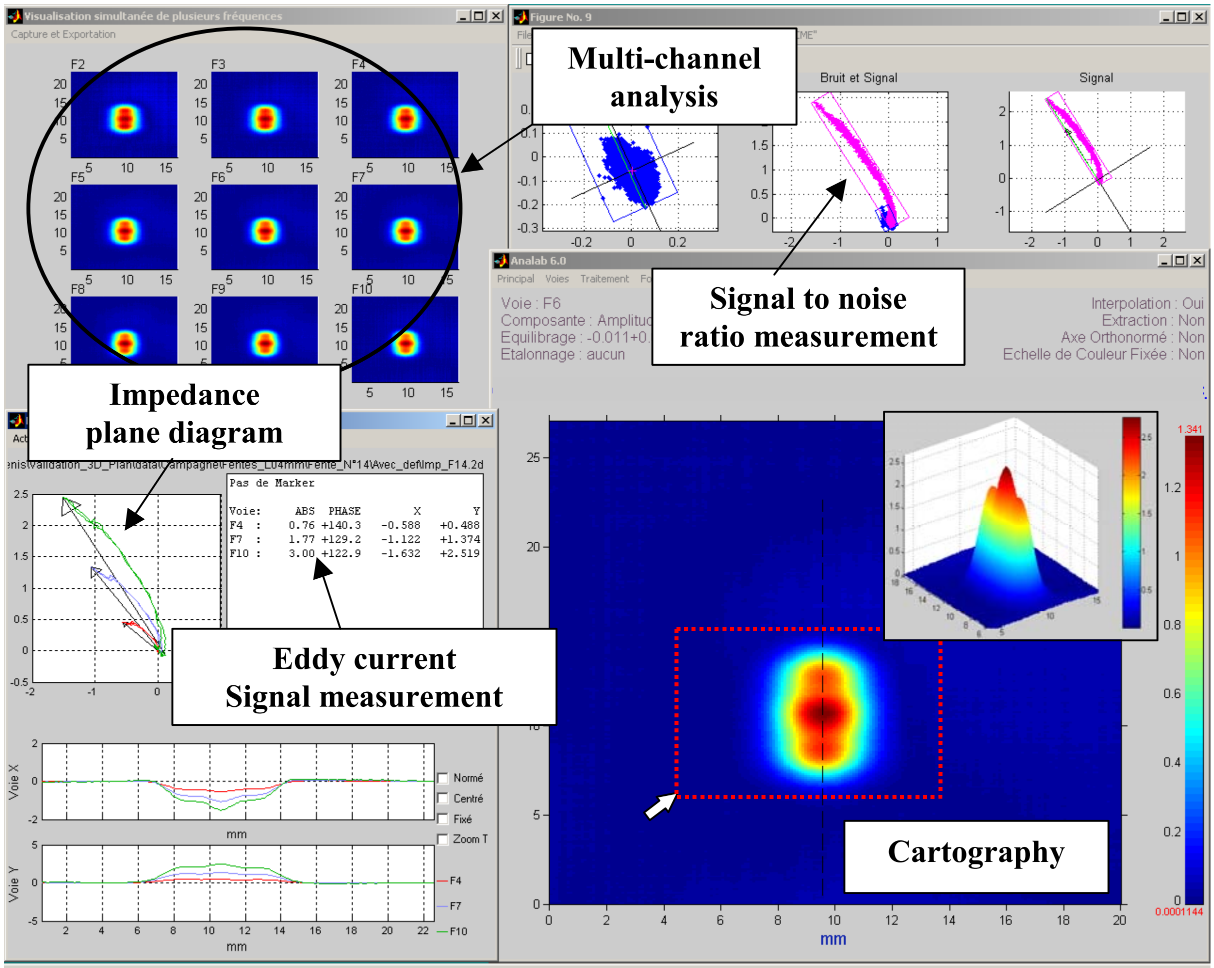

Figure 14: Example of the post-processing tool used to analyse eddy current signals

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