Simulation of Eddy Current Non Destructive Testing using COMSOL® Multiphysics

A. Kyrgiazoglou*, T. Theodoulidis

Department of Mechanical Engineering, University of Western Macedonia, Greece
* Corresponding author: Bakola & Sialvera, 50132, Kozani, Greece, akyriazoglou@uowm.gr

Abstract

In this paper, we perform simulations of the most popular eddy current nondestructive testing Benchmark Problems. In all cases, we observe good or excellent results. The agreement between numerical calculations and experimental measurements verifies the correct application of the modeling method. Owing to the fact that the eddy current problem is a low frequency electromagnetic field problem the choice was the COMSOL ® Multiphysics AC/DC module, which validates its use as a very reliable tool for conducting realistic eddy current testing studies.

Keywords: Eddy current testing, numerical models, Benchmarks Problems, COMSOL ® Multiphysics, AC/DC module.

1 Introduction

Eddy current testing (ECT) is one of the oldest nondestructive testing (NDT) methods. The theory is based on the principles of electricity and magnetism, particularly on the inductive properties of alternating current [1]. According to Faraday's law, eddy currents are generated in an electrically conductive part by applying a time-varying magnetic field [2]. The ECT method uses a coil, which is excited with an alternating electrical current. This coil produces an alternating magnetic field around itself, which oscillates at the same frequency as the current running through it. When the coil approaches a conductive material, currents opposed to the ones in the coil are induced in the material. The equation defining the eddy current flow is derived from Maxwell's equation and is written in terms of the magnetic vector potential, **A**:

$$\nabla^2 \mathbf{A} - \mu\sigma \frac{\partial \mathbf{A}}{\partial t} = -\mu \mathbf{J}$$

Where μ is the magnetic permeability, σ is the conductivity of the medium and **J** is the source current. From **A** all electromagnetic field quantities are derived as well as the coil impedance.

The mathematical simulation of eddy current phenomenon and its applications in nondestructive testing, are valuable tools for designing probes and inspection procedures, for understanding the underlying physics phenomena, for training and education, for automatic detection and clarification of defect, for interpretation of results and for evaluation of Probability of Detection (POD) curves. Simulation refers to the process of using a model to study the behavior and performance of the system. In general, the numerical models needed to simulate the intricacies of interactions of test geometries are complex and computationally expensive. Examples of these difficult to model geometries include very thin discontinuities or complex discontinuities geometries. A standard procedure for verifying the correct application of the modeling method is the agreement between numerical calculations and experimental measurements. For that reason, we gathered the most popular eddy current Benchmark Problems and solved them using COMSOL ® Multiphysics software. All of these problems provide coil impedance measurements in order to identify the presence of a defect in a conductive test piece.

The representative Benchmark Problems that we gathered are shown in Table 1 [3-5, 7]. All of these Benchmark Problems consider harmonic excitation. In this paper we provide numerical results obtained with COMSOL ® Multiphysics, and compare them to experimental measurements presented in related publications. The results are encouraging, as excellent agreement between computations and measurements is observed for all the examined cases.

Table 1 ECT Benchmark Problems

WFNDEC EC Benchmark 2007, '11, '12, '13, '15
TEAM Workshop No. 8 and No. 15
COFREND Working Group Problems
DSTO Experimental Results No. 2, 3, 4, 5
Harrison et. al, JNDE, 1996

2 Simulation Models

The numerical model replicates the coil geometry and parameters, as those described in the Benchmark Problems. The simulations are performed in COMSOL ® Multiphysics (version 5.3), employing the AC/DC module. The selected studies are Frequency - Domain study and Material - Switch. All the Benchmark Problems entail a multi-turn coil moving above a conductive test piece, in order to detect the defect. The identification of the latter is accomplished by taking into account the changes in the coil impedance.

In all cases, we set the outer boundaries of the model area at a distance 10 times the outer coil radius. Moreover, we performed the simulation twice, first including the defect and then without it, exploiting the Parametric Solution via Material Switch Step. "Without the defect", means that the defect is present but assumes the host medium conductivity. Between these two cases the mesh remains the same. The difference between those two calculations gives the signal due to the defect, without mesh influence. The coil is set as a domain with external current-density parameter. In order to avoid moving the coil, which would require changing the external current density parameters, we chose to move the slot instead. Moreover, by this arrangement the coil is always placed at the center of the geometry away from the outer boundaries. In all cases we used tetrahedral quadratic elements.

2.1 Benchmark problem TEAM workshop No.15

The configuration of the first Benchmark Problem is shown in Figure 1.

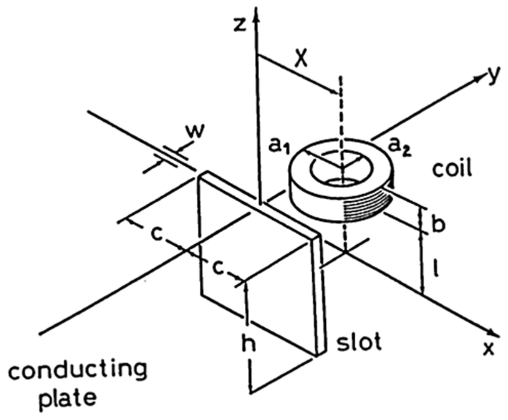

Figure 1: Schematic configuration for the measurement of the impedance change ΔZ due to a surface breaking slot [3].

A rectangular slot is located in a thick conductive plate and the coil moves above and along the slot. The excitation frequency is 7 kHz and the plate conductivity is 30.6 MS/m. The coil and slot parameters are shown in Table 2.

Note that the skin depth for the testing frequency is 1.09 mm. To ensure better results, we increase the mesh density near the defect area, as needed. The computation time on a standard PC for each coil position is about 1 minute.

Table 2 Coil and Slot Parameters

Coil	
Inner Radius	9.34 mm
Outer Radius	18.40 mm
Coil Height	9.00 mm
Number of Turns	408
Lift-off	2.03 mm
Slot	
Length	12.60 mm
Depth	5.00 mm
Width	0.28 mm

The comparison between experimental data and simulation results, regarding real and imaginary components of the coil-impedance change due to the defect, are shown in Figure 2, as a function of the distance between coil center and defect center. As seen, there is very good agreement for all coil positions. The average number of the elements for this Benchmark Problem is 31,700 and the number of degrees of freedom (DoF) is 248,500.

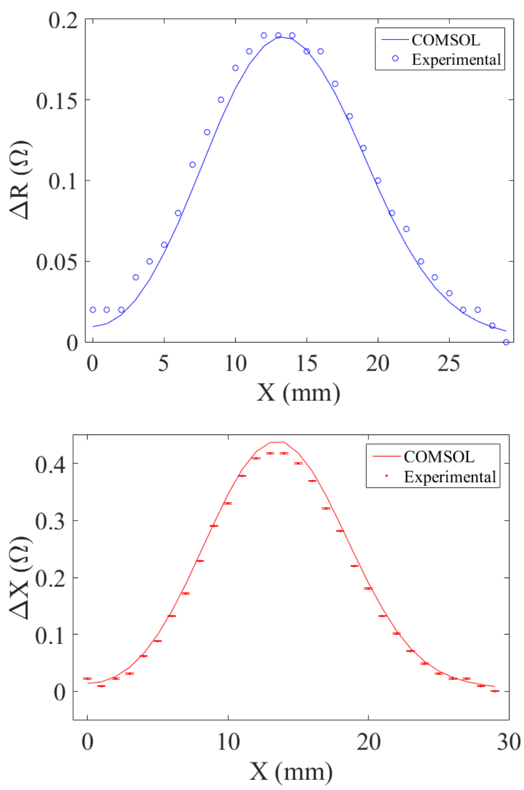

Figure 2: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of the distance between coil and slot centers.

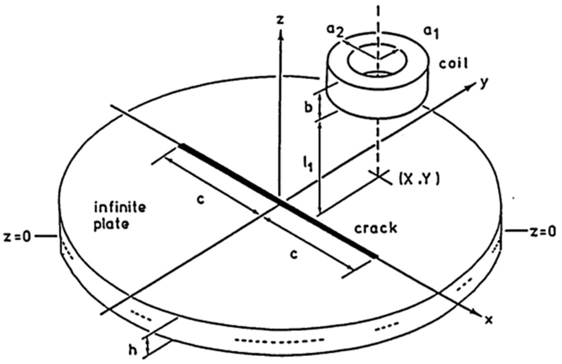

Figure 3: Eddy-current induction by a circular coil in an infinite plate containing a straight, through-thickness crack [4].

2.2 Benchmark Problem No.3

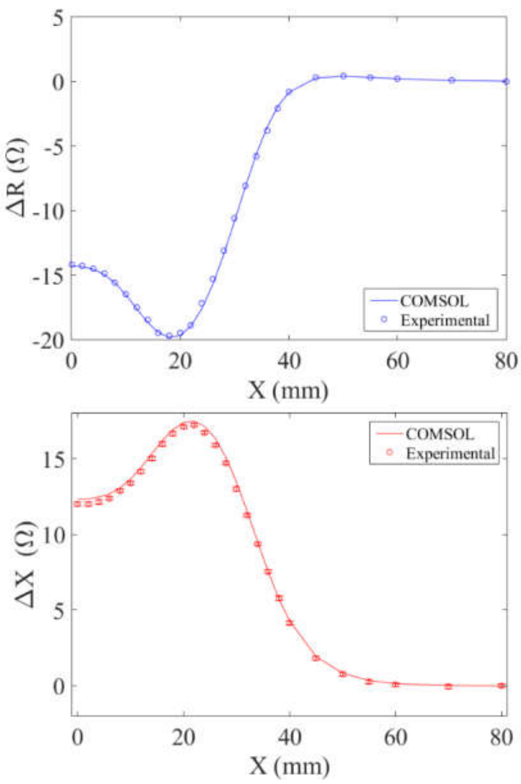

Figure 4: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of distance between coil and slot centers.

The geometry for the second ECT Benchmark Problem is taken from [4] and is shown in Figure 3. Now, the case of a through-crack in a thin brass plate is investigated, and comparison between experimental and simulation results is performed for two distinct cases. The first one involves a line scan of the coil along the crack at a constant frequency of 1 kHz, while the second one considers a frequency scan, with the coil centered on the crack and a range of frequencies 110 Hz-10 kHz. The conductivity of the brass plate is 16.5 MS/m. The coil and defect parameters can be found in [4].

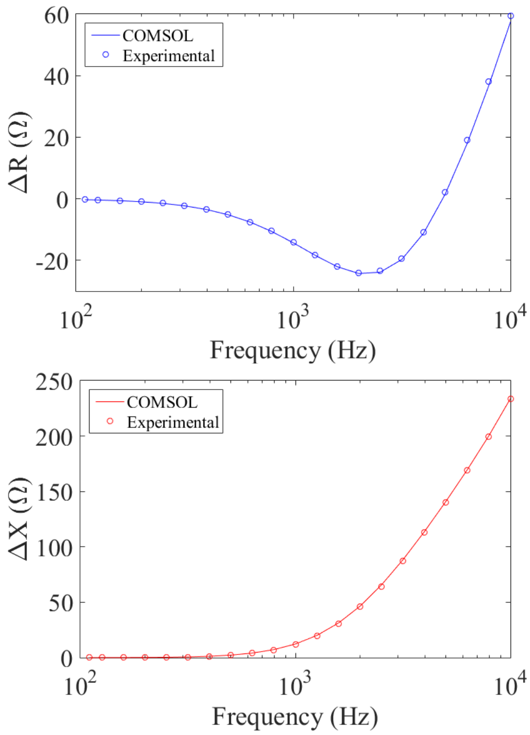

Figure 5: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of frequency.

In this problem the skin depth at 1 kHz is 3.91 mm. The number of elements and the DoF is different between two cases of this Benchmark Problem, but the average numbers are 123,500 and about 1,000,000 respectively.

The results from the aforementioned cases are shown in Figures 4 and 5, respectively. The agreement between calculations and measurements is excellent.

2.3 Benchmark Problem No. 5

This Benchmark Problem concerns a tangent coil geometry [4], which is depicted in Figure 6.

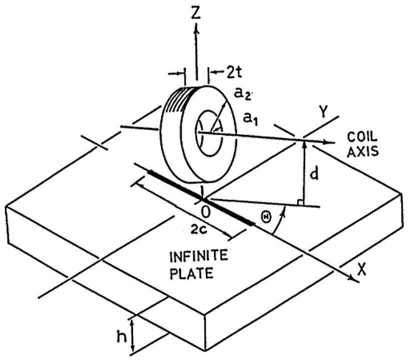

Figure 6: Schematic configuration for the measurement of the impedance change ΔZ due a through-crack in a plate using the tangent coil geometry [4].

The problem description in [4] examines three different cases, with dependence on coil position, excitation frequency and angle dependence. We modeled all of them and present the case with coil axis orientation Θ, at the frequency of 2 kHz.

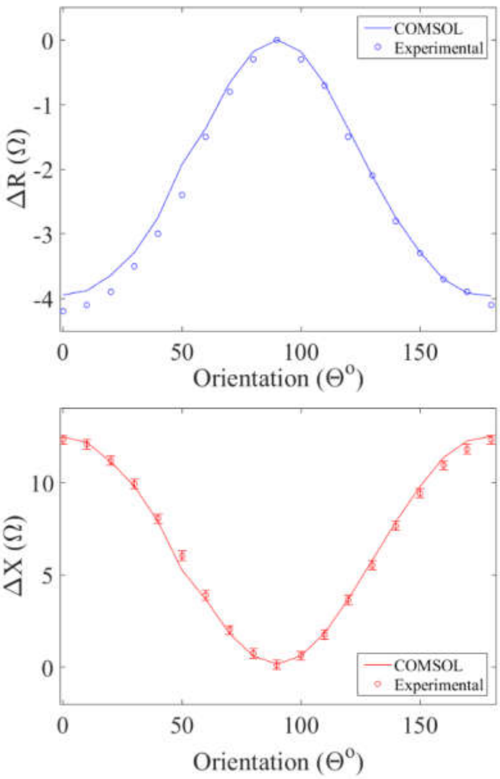

Figure 7: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of coil orientation.

The range of Θ is 0°-180°. The other cases consider a parallel to the slot movement at 2 kHz and a coil impedance measurement within a frequency range 0.25-10 kHz. The test specimen is a thin brass plate with conductivity of 16.4 MS/m, and the skin depth at 2 kHz is 2.77 mm. The average element in this Benchmark Problem is about 65,000 and the DoF is about 500,000. The corresponding curves are plotted in Figure 7, where once again the agreement is very good for all coil orientations.

2.4 WFNDEC EC Benchmark 2013

Next we analyze a more complex Benchmark problem, which concerns a crack at the edge of a hole in a conductive plate as shown in Figure 8. This problem consists of four different cases. The first case (I) is a conducting plate with a hole and a defect at the edge, the second one (II) and the third (III) include two plates with holes centered and the crack on the top and on the bottom plate respectively. The last one (IV) includes a plate with a hole without defect.

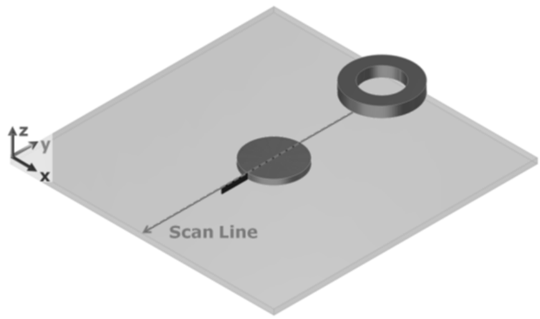

Figure 8: Schematic configuration for the measurement of the impedance change ΔZ due a hole and crack in a conductive plate [6].

The exact geometric dimensions of the problem are provided in [6]. The conductivity of the test specimen is 17.34 MS/m, and the test frequencies are 1 and 5 kHz. The comparison between simulation and measurements values of first case is provided at Figure 9 and Figure 10 and for second case in Figure 11 and Figure 12. It becomes evident that, due to the presence of the hole, the change in the impedance's components exhibit completely different behavior, compared to all other test cases. Nevertheless, the numerical data reproduce the measurement curves in a very reliable fashion.

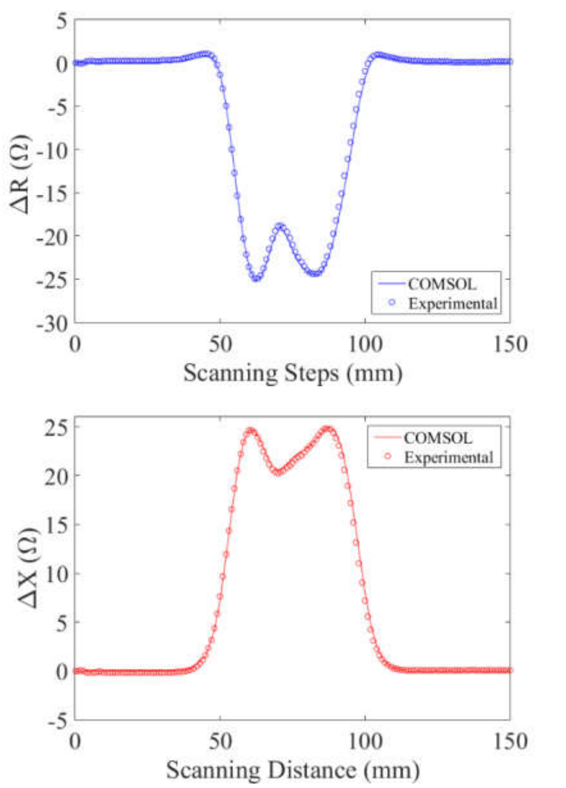

Figure 9: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of scanning steps at 1 kHz, case (I).

The number of the elements in cases (I) and (III) is less than the other two cases because of the geometry complexity. The average number of elements is 200,000 and the DoF is about 1,000,000.

In the cases (II) and (III) a thin gap exists between the plates. We chose to use swept meshing to avoid the large number of elements between plates that entails a long computational time. Swept meshing is a geometry discretization technique for specific types of geometries, including thin geometries, geometries with bends, and models with little or no variation in a specific direction. A swept mesh starts at a source boundary and sweeps along to a specified destination boundary. The swept mesh creates hexahedral (default) or prismatic mesh elements, which can still effectively handle the disproportional dimension sizes, with far less elements. Including this parameter the computational time is 20 min. per each coil position. Without swept meshing the computational time is an order of magnitude larger.

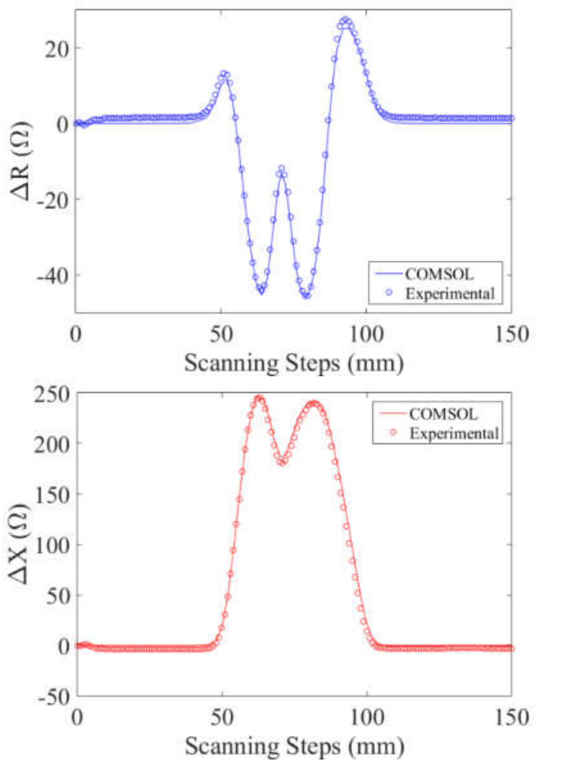

Figure 10: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of scanning steps at 5 kHz, case (I).

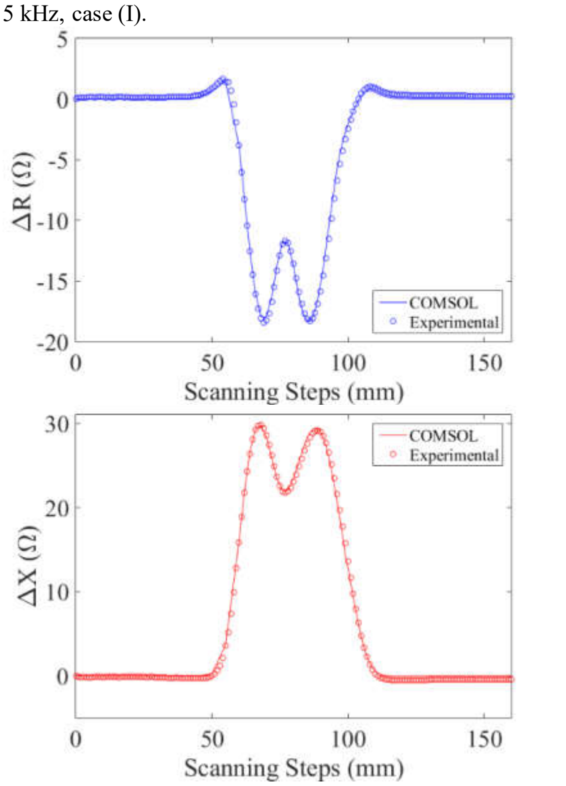

Figure 11: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of scanning steps at 1 kHz, case (II).

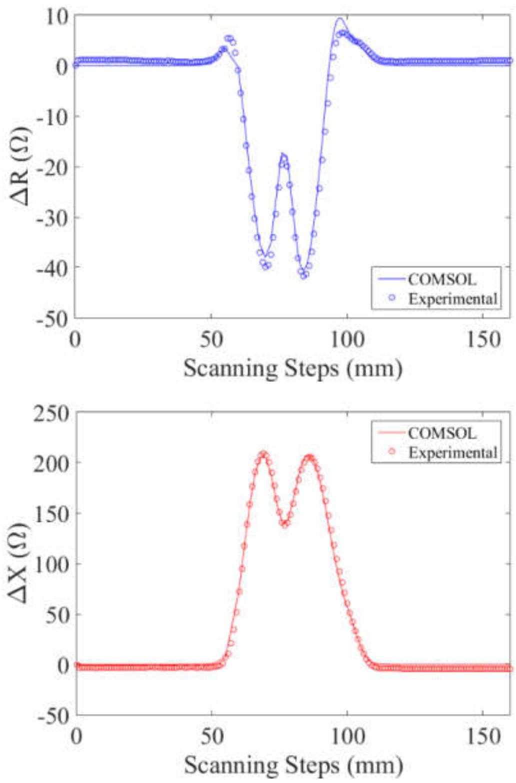

Figure 12: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of scanning steps at 5 kHz, case (II).

2.5 Benchmark Problem Harrison et. al, JNDE, 1996

With this Benchmark Problem, we investigate the solver's potential in cases with different defect sizes and shapes [7]. A representative geometry is provided in Figure 13.

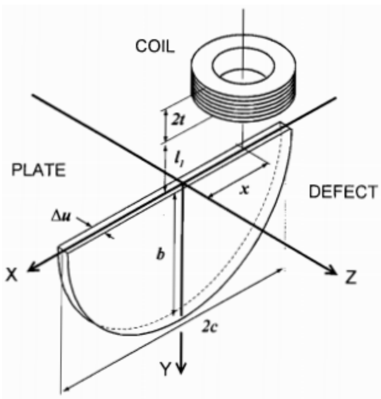

Figure 13: Geometry of Benchmark problem for defect size and shape determination [7].

The plate's conductivity is 22.15 MS/m. The configuration of the coil and four different defects are described in [7]. Two defect shapes, denoted as D1 and D2, are shown in Figure 14.

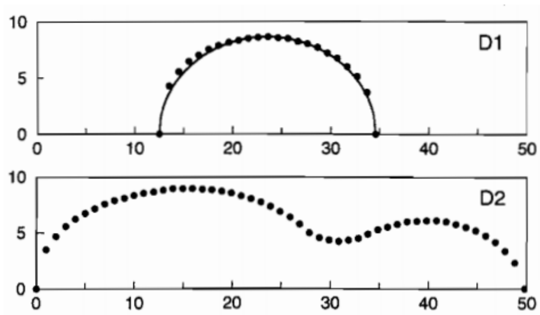

Figure 14: D1 (top) semi-ellipse profile defect and D2 (bottom) epicyclic defect [7].

In this work, we present simulations for a 250 Hz testing frequency in Figure 15 and Figure 16. Despite the more complicated crack configurations, the finite-element follow very closely the measurement ones. The number of elements and the DoF are different between two cases of this Benchmark Problem, but the average number is 42,000 and about 350,000 DoF.

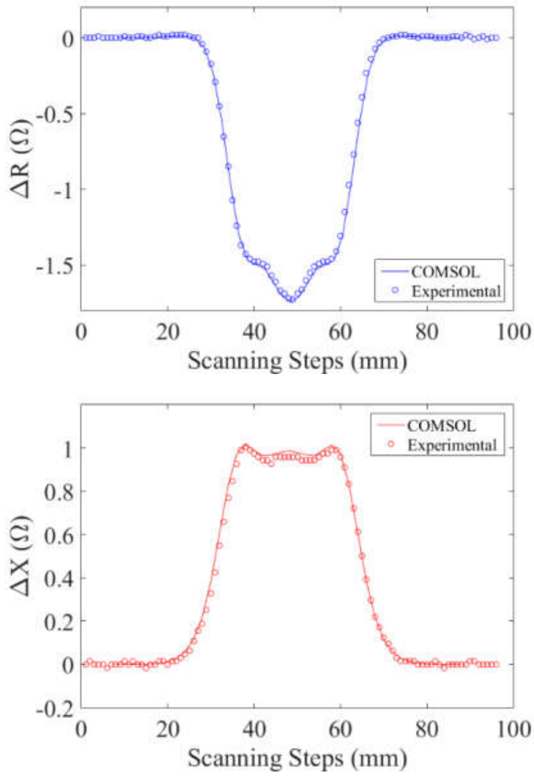

Figure 15: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of scanning steps for the D1 defect.

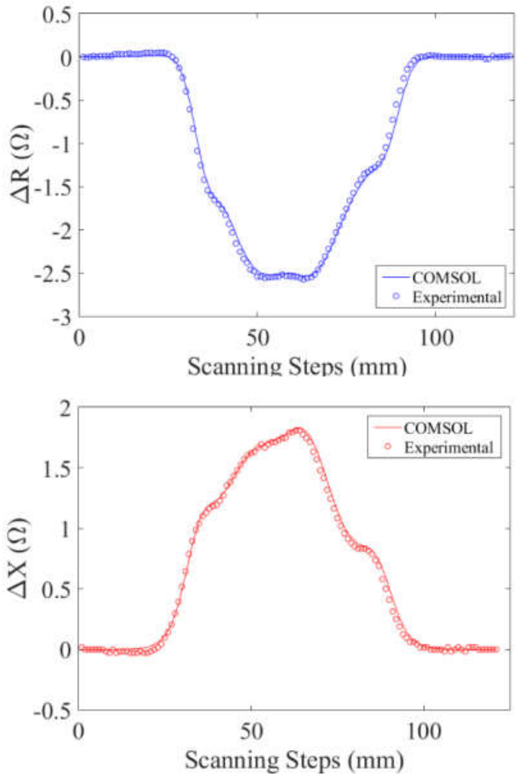

Figure 16: Real (top) and imaginary (bottom) components of coil impedance change ΔZ as a function of scanning steps for the D2 defect.

Conclusions

In this paper, we test the capability of the COMSOL ® Multiphysics software for efficiently simulating eddy current nondestructive testing configuration. Some good practice steps are provided along with these simulations with COMSOL ® Multiphysics software. We verified that the computational implementation of the ECT method in COMSOL ® Multiphysics software accomplishes very reliable results, when compared to published measurement data. The importance of this conclusion is further supported by the fact that all the test cases were taken from accepted Benchmark Problems.

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