32ND RESEARCH SYMPOSIUM
ASNT | EVENTS.

Presented At: ASNT Research Symposium:
25 – 28 June 2024
Pittsburgh, Pennsylvania, USA

Evaluating Eddy Current Simulation Tools: A Comparative Analysis with Benchmark Cases

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ABSTRACT

Eddy current modeling is a crucial tool in diverse industrial and scientific applications, playing a pivotal role in nondestructive evaluation (NDE), electromagnetic compatibility analysis, and the design of various electromagnetic devices. This paper comprehensively explores the analysis of eddy current response using two commercial software packages – VIC-3D® (4.3.9) and COMSOL Multiphysics® (5.6). By leveraging advanced commercial tools, the modeling process involves discretizing complex geometries, selecting appropriate solvers, and optimizing parameters to simulate eddy current phenomena accurately. Furthermore, this investigation examines the validation of simulated results against experimental data, emphasizing the software's capability to predict and replicate real-world scenarios.

KEYWORDS: Eddy Current, Nondestructive Evaluation, Numerical Solution, Skin Depth, Discretization

INTRODUCTION

NDE modeling with simulation software has become increasingly popular in recent years, particularly for industrial Eddy Current Testing (ECT). Benefits of this shift toward digital modeling include enhanced comprehension of physical phenomena, better interpretation of inspection results, support for the design of inspection benches and probes, qualification of NDE methods, and support in interpreting signals from inspections of intricate configurations. Furthermore, there is a discernible trend toward the incorporation of simulation into models for defect reconstruction, optimizing performance, and minimizing the requirement for extensive testing. In ECT, the alternating current in a wire loop generates a time-varying magnetic field, which induces electric currents in a nearby conductive component (e.g., a plate), known as eddy currents (EC). The current mirrors the applied current in the wire loop but flows in the opposite direction. The eddy currents circulating in the metal are also subject to variations over time, generating a corresponding magnetic field. In the presence of a defect or an anomaly in the conducting material, the flow of EC gets disrupted, leading to a detectable change of the signal in the pickup coil.

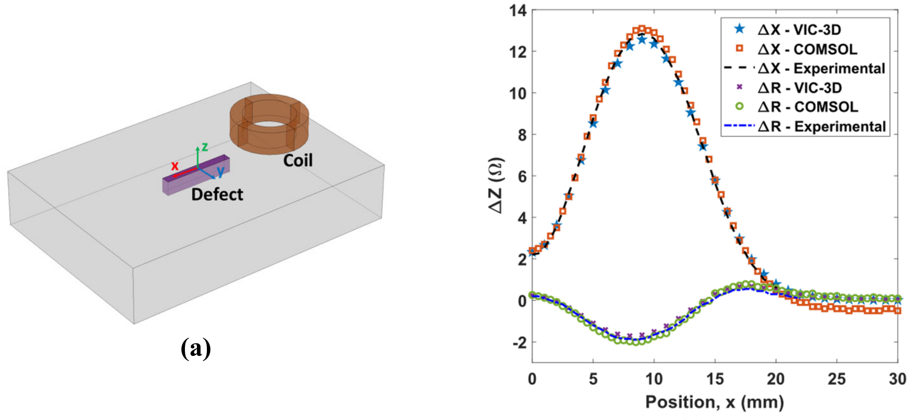
This work enlisted four benchmark cases with numerical findings using the mentioned software. VIC-3D® adopts a mathematical approach that determines the distribution of currents [1] in a workpiece by employing Green's function, known as the volume-integral method (VIM). On the other hand, COMSOL® uses the finite element method (FEM) to solve a set of partial differential equations at specified nodes on a mesh element representing a geometric shape [2]. The Magnetic Fields interface (AC/DC module) in COMSOL facilitates electric and magnetic fields study for static and low-frequency systems. For the numerical study, we mainly evaluated the impedance change due to the presence of the defect, where the coil scans the sample along the defect length. All the simulations have been performed in a DELL Precision (Intel Xeon R) workstation with dual quad-core processors at 3.5 GHz and 16 GB of RAM.

NUMERICAL MODELS AND RESULTS

The VIM can consider an infinite surrounding; however, the results still depend on the cell grid resolution in the region of the flaw. For the FEM tools, domain truncation to an extent is necessary for which results are still reliable. A good practice is keeping the air boundary ten times the coil's maximum dimension [3]. Element type and size are crucial factors in reforming the geometrical shape of the domain and attaining accurate simulation results. Since eddy currents are predominantly limited to the first three standard penetration depths (skin depth $\delta = \sqrt{1/(\pi f \mu \sigma)}$, f = frequency of the source current, μ = magnetic permeability, σ = electric conductivity of the medium.), addressing induced currents within the 3δ is pivotal. This section will describe the benchmark cases, including associated numerical results to compare against the experimental data. The experimental data is collected from the related references of the listed benchmark specifications.

Benchmark Case 1

The first standard benchmark consists of a conductive plate (σ = 30.6 MS/m, 12.6 mm thick) with a rectangular slot above which the coil moves. The coil is absolute, and the excitation frequency is 900 Hz. At this testing frequency, the δ is 3.04 mm. The representative geometry is in Figure 1(a), with detailed specifications in [4] Team Workshop 15. The numerical results obtained from both tools, shown in Figure 1(b), match the experimental data [4] very well.



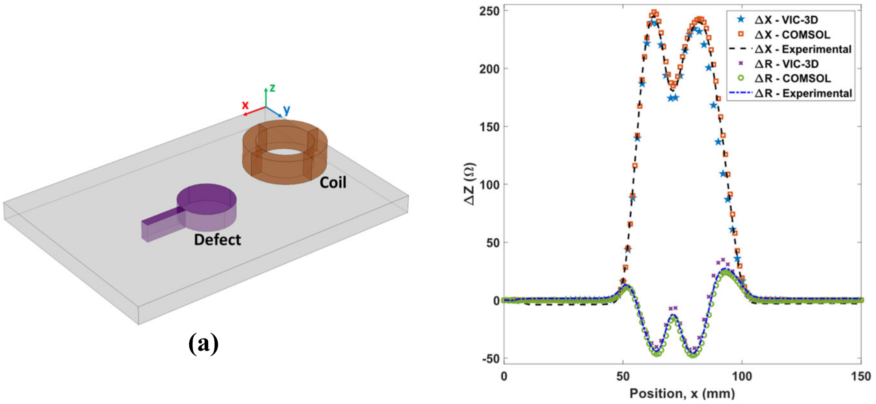
(a)

(b)

Figure 1: (a) Surface breaking rectangular notch, (b) impedance change (ΔZ) as a function of the relative coil's position from the notch center (at [(x,y) = (0,0) mm]). ΔR and ΔX are changes in the real and imaginary parts of the impedance.

Benchmark Case 2

We then examine a more difficult benchmark problem, depicted in Figure 2, which contains a notch at the edge of a through hole in a conductive plate. The first case is analyzed here for 5 kHz driving frequency. The geometric dimensions are provided in [5]. Since the hole-to-notch ratio is almost 20 times, both COMSOL and VIC-3D required dense meshes to reform the shape and took almost the same execution time. Nevertheless, the numerical data reproduce the measurement curves [5] in a very reliable fashion.



(a)

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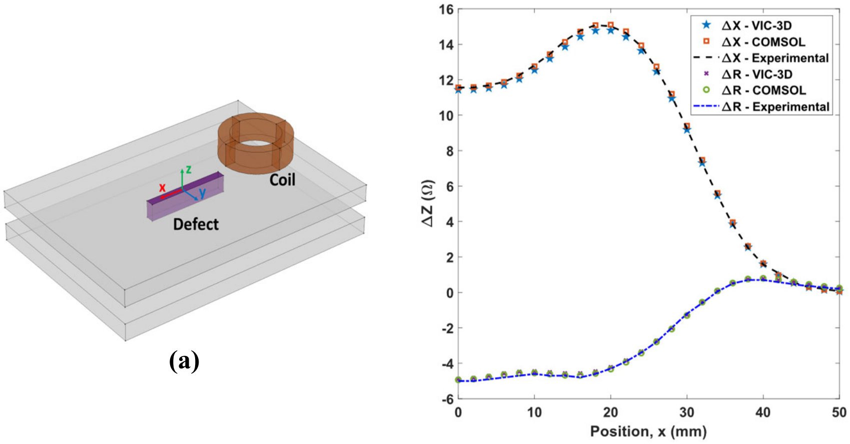
Figure 2: (a) Schematic for a sample with hole and edge notch (the hole center is at [x = 70.8 mm and y = 0 mm]), (b) impedance change (ΔZ) as a function of the relative location of the coil along the x-axis. ΔR and ΔX are changes in the real and imaginary parts of the impedance.

Benchmark Case 3

Figure 3 (a) displays the geometry for benchmark test 4 from [6]. The case involving a through-notch in the top layer of a two-layered conductive plate (σ = 16.4 MS/m, each plate 0.9 mm thick) with an air gap (0.19 mm) in between is examined at 1 kHz frequency. The outcomes of the two simulation findings are compared with experimental results [6] in Figure 3 (b), which are reasonable. Since each conductive layer is almost five times thicker than the air gap, distinguishing the narrow air region between the plates by mesh discretization was a modeling challenge.



(a)

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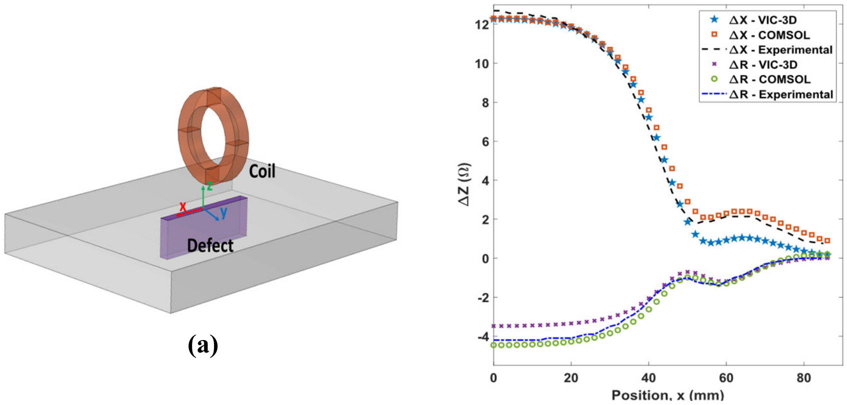
Figure 3: (a) Defect in the top layer of a double-layer medium with air gap in between, (b) impedance change (ΔZ) as a function of the relative coil's position from the notch center (at [(x,y) = (0,0) mm]). ΔR and ΔX are changes in the real and imaginary parts of the impedance.

Benchmark Case 4

The problem description is benchmark test 5 from [6], which examines three scenarios with dependence on coil position, frequency, and angle dependence. Here, we only worked on the case for coil position with a test frequency of 2 kHz. The test specimen is a thin plate with (σ = 16.4 MS/m), and the skin depth is 2.77 mm. It is an absolute coil, but in contrast to other cases, the coil axis is parallel (tangential coil) to the surface, as depicted in Figure 4(a). The COMSOL results from Figure 4(b) show good agreement with experimental results [6], whereas the VIC-3D results are inconsistent in some portions of the scanning region. The probable reason can be that VIC-3D solves the tangential coil domain numerically, whereas in other cases (e.g., a coil axis perpendicular to the surface), it implements the analytical solution of the coil.



(a)

(b)

Figure 4: (a) Tangential coil over sample, (b) impedance change (ΔZ) as a function of the coil's relative position from the notch center (at [(x,y) = (0,0) mm]). ΔR and ΔX are changes in the real and imaginary parts of the ΔZ.

Table 1 compares the computation cost in terms of discretized elements, memory requirement, and execution time by the two tools. It is noticeable that VIC-3D needs less computation requirement compared to COMSOL since it solves integral equations over flaw region only. However, for Case 2, to define the defect shape, the cell counts (cells along x,y, and z-axis) in VIC-3D are much higher than in other cases, making the execution time same as the COMSOL.

Table 1: Computational requirement by the simulation tools.

Benchmark Case	VIC-3D (VIM)				COMSOL (FEM)		
	Cell Counts	Unknowns	Memory	CPU Time	No. of Elements	Memory	CPU Time
1	64×2×16	5k	197 MB	4 min	118k	3.5 GB	1.5 min/position
2	128×64×4	89k	207 MB	4 min/position	248k	7.6 GB	3 min/position
3	128×2×4	2.3k	42 MB	2 min	113k	4.5 GB	2 min/position
4	156×2×4	2.8k	63 MB	2 min	434k	9.3 GB	3.5 min/position

CONCLUSIONS

The study explores two software tools for simulating ECT configurations. While the VIM tool is efficient on smaller computers with less pre-processing time, it has limitations with simple geometric shapes. FEM software, though time-consuming for complex models, excels in meshing irregular surfaces and parameterizing variables. The findings of experiments and numerical calculations accord very well with both tools. This computational success implies that similar approaches can be applied with confidence for real-world scenarios, which makes it a helpful tool for customized probe design, model-based inverse problems, and model-assisted probability of detection.

ACKNOWLEDGEMENT: This work was supported in part by a grant from the CNDE Membership Fund at ISU.

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