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Modeling and Simulation for 3D Eddy Current Testing in Conducting Materials

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Abstract**—**The numerical simulation of electromagnetic interactions is still a challenging problem, especially in problems that result in fully three dimensional mathematical models.

The goal of this work is to use mathematical modeling to characterize the reliability and capacity of eddy current technique to detect and characterize defects embedded in aeronautical in-service pieces.

The finite element method is used for describing the eddy current technique in a mathematical model by the prediction of the eddy current interaction with defects. However, this model is an approximation of the full Maxwell equations.

In this study, the analysis of the problem is based on a three dimensional finite element model that computes directly the electromagnetic field distortions due to defects.

Keywords**—**Eddy current, Finite element method, Non destructive testing, Numerical simulations.

I. Introduction

EDDY current testing is one of the non destructive techniques (NDT) often used to detect defects and ensure total integrity of conducting materials. It is one of the most applied methods in aeronautical field. It is presently used in aeronautics and aerospace for over 50% of all applications for the detection of hidden defects in fuselage skins and multi-layers and to clarify the real condition of aircraft structure for appropriate repair and corrective action [1], [2].

Eddy current testing can be used for a variety of applications such as detection of cracks (discontinuities), measurement of metal thickness, detection of metal thinning due to corrosion and erosion, determination of coating thickness and the measurement of electrical conductivity and magnetic permeability. Eddy current technique is an excellent method for detecting surface and near surface defects when the probable defect location and orientation is well known [2]-[4].

Electromagnetics problems modeling is a good tool for understanding and analyzing impedance responses due to various defects in the non destructive techniques by eddy current. Small impedance variations due to defect and inspection process must be captured in the suggested model. It is therefore important to use accurate numerical methods adequate to these problems [5].

The modeling approach can be divided into analytical and numerical models with the ability to solve Maxwell‘s equations.

In this context, various techniques for modeling NDT problems are already available. In this study, an approach based on finite elements method is chosen.

Numerical modeling of the eddy current technique has been developed since the 60’s with the important contribution of Dodd’s works [6]. The axisymmetrical geometries were studied next and the various potential formulations were used since the 80’s [7].

The 3D finite element models used nodal elements were early developed and used by various authors, see [8] for example, but later also edge elements were exploited [9], [10].

Various advantages have been shown to favor the finite element approach for such studies, including ease of handling boundary conditions, ability to follow awkward boundary shapes, and relative economy of computer facilities usage. These factors are particularly relevant for the simulation of electromagnetic NDT techniques, and hence parallel developments have taken place in the use of finite element analysis for modeling eddy current and active and residual leakage field NDT phenomena [11]-[13].

The developed method is tested and compared to experimental data obtained from the sixth JSAEM benchmark problem.

The numerical model studied in this paper enables to predict and evaluate important parameters act directly on the impedance responses of eddy current testing.

In this paper, only, the defect length or depth effects are evaluated. Other parameters which act on the impedance responses values, such as probe type, permeability, conductivity, and frequencies rang can be studied in future works.

II. Mathematical Model

Modeling and simulation of eddy currents testing provide a good basis for allowing an early evaluation of part inspection.

The equations governing the general time varying fields in section include magnetic and conducting isotropic materials can be derived from the Maxwell equations:

$$\nabla \times H = \sigma E + \partial(\epsilon E)/\partial t \quad (1)$$

$$\nabla \times E = -\,\partial B/\partial t \quad (2)$$

$$\nabla .(\mu H) = 0 \quad (3)$$

$$\nabla . E = \rho/\epsilon \quad (4)$$

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where E and H are the electric and magnetic fields, and ρ, σ, ε, and μ are respectively the volume density of electric charges, conductivity, permittivity, and permeability of the medium. Conductivity ranges vary from zero in insulators to > 10^{6} (S/m) in metals. Permittivity ranges vary from the value ε_0 ($\varepsilon_0=10^{-9}/36\,\pi$ SI) in vacuum to up to 100 ε_0 in some dielectric materials. The range for permeability is from μ_0 ($\mu_0=4\,\pi\,10^{-7}$ SI) in vacuum to about 5000 μ_0 in soft iron.

Potentials must be introduced as usual in 3D eddy current finite element formulations. Thus, the flaw field can be constructed by introducing two potentials, the magnetic vector potential A and the electric scalar potential Φ:

- The magnetic vector potential A is linked with the magnetic flux density B by:

$$\mathrm{B} = \nabla \times A \tag{5}$$

- The relation between the electric field and the magnetic vector potential can be derived as:

$$E = -\nabla\Phi - \partial A/\partial t \tag{6}$$

Substituting (5) and (6) in (1) and (4), and using the constitutive relation (B= μ H), (1) becomes:

$$\nabla \times \nabla \times \mathrm{A} = \mu\,\sigma\left(-\nabla\Phi - \frac{\partial \mathrm{A}}{\partial \mathrm{t}}\right) + \mu\,\epsilon\left(\frac{\partial\left(-\nabla\Phi - \frac{\partial \mathrm{A}}{\partial \mathrm{t}}\right)}{\partial \mathrm{t}}\right) \tag{7}$$

After simplification by the curl-curl relationship (i.e: $\nabla \times (\nabla \times \mathrm{A}) = -\nabla\,.\,(\nabla\,\mathrm{A}) + \nabla\,(\nabla\,.\,\mathrm{A})$). Equation (8) is given by:

$$-\nabla\,.\,(\nabla\mathrm{A}) + \nabla(\nabla\,.\,\mathrm{A}) - \mu\,\sigma\left(-\nabla\Phi - \frac{\partial \mathrm{A}}{\partial \mathrm{t}}\right) = \mu\,\epsilon\left(\frac{\partial\left(-\nabla\Phi - \frac{\partial \mathrm{A}}{\partial \mathrm{t}}\right)}{\partial \mathrm{t}}\right) \tag{8}$$

Using the Coulomb gauge ($\nabla.\,\mathrm{A} = 0$) and the relation $\nabla\,\Phi = 0$ (there is no gradient of a scalar potential in (8) if there is no initial static charge on the medium). Equation (8) is written as:

$$-\nabla^2\,\mathrm{A} + \mu\,\sigma\left(\frac{\partial \mathrm{A}}{\partial \mathrm{t}}\right) = \mu\,\epsilon\left(\frac{\partial\left(-\nabla\Phi - \frac{\partial \mathrm{A}}{\partial \mathrm{t}}\right)}{\partial \mathrm{t}}\right) \tag{9}$$

or

$$\nabla^2\,\mathrm{A} = \mu\,\sigma\left(\frac{\partial \mathrm{A}}{\partial \mathrm{t}}\right) - \mu\,\mathrm{J}_{\mathrm{source}} \tag{10}$$

The gradient of Φ is implicit in Jsource.

The eddy current problem can be described mathematically by the following equation in terms of the magnetic vector potential:

$$\nabla^2\,\mathrm{A} + \mathrm{K}^2\mathrm{A} = -\mu\,\mathrm{J}_{\mathrm{source}} \tag{11}$$

where A represents the magnetic vector potential, μ is the magnetic permeability, Jsource is the excitation current density, $K^2=-\omega\mu(j\sigma+\omega\varepsilon)$, ω is the angular frequency of the excitation current (rad).

The magnetic vector potential can be found by solving (10) with appropriate boundary conditions attached to the studied configuration, and once this potential is given, other physical parameters can be deduced from it.

Indeed, the complexity of the geometries of the studied problems induced that the analytical solution exists only for limited simple cases, and obviously, our interest is directed towards the search for the approximate numerical solutions.

Based on the Galerkin's method, the finite element formulation of (10) can be developed. The studied configuration is discretized into a number of tetrahedrons and the nodal shape functions defined on this mesh are the basis functions. The vector and scalar functions are approximated by the sets of these basis functions, as:

$$A = \sum_{i=1}^{K} N_i\,A_i \tag{12}$$

where k is the number of nodal points in the element (in this case K= 4), Ni and Ai: are the nodal interpolation functions and the value of potential function corresponding to the i^{th} node respectively of the element.

The approximation for the magnetic vector potential in (12) is substituted into the Galerkin weighted residual technique to set up the finite element equations. After some usual mathematical manipulations, the approximation of nodal values results in equations which in matrix form can be written as:

$$([S^e] + j\,[R^e])\,\{A^e\} = \{Q^e\}\} \tag{13}$$

$[S^e]$ is the k x k real part of the elemental matrix, $[R^e]$ is the k x k imaginary part, $\{Q^e\}$ is the k×1 vector of contributions at the nodes of the dement from the current densities, and $\{A^e\}$ is the k × 1 vector of unknown values of the magnetic vector potential at the nodes of the element.

The elemental contributions of the solution can be calculated and summed into a global system of equations:

$$[K]\,\{A\} = \{Q\} \tag{14}$$

where [K] is the N×N banded symmetric complex global matrix (N is the total number of nodes), and {Q} and {A} are respectively the Nx1 complex source matrix and the N×1 complex vector of unknowns.

The system is solved using a developed code. Special techniques are used to the storage of the global matrix elements by the elimination of zero elements and storage of nonzero elements as a 1D array. And the Gauss elimination method is chosen like method of resolution.

After calculating the potentials, the flaw impedances can be evaluated.

III. Applications and Results

The studied problem is presented in Fig. 1. It deals with a pancake coil, placed above a plate of conducting material with a crack. The probe coil moves parallel to the chosen axis, placed along the crack length direction.

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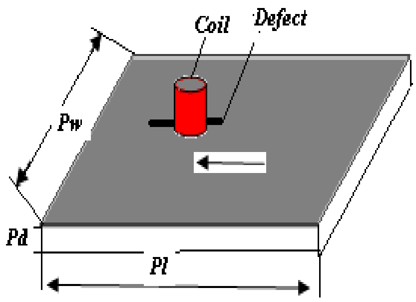
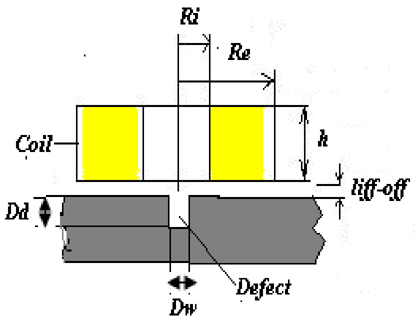
The magnetic vector potential can be found by solving (10) with appropriate boundary conditions attached to the studied configuration, and once this potential is given, other physical parameters can be deduced from it.



(a) Studied configuration



(b) Parameters

Fig. 1 Description of the configuration geometry (plate, probe, defect)

Fig. 2 shows the mesh in three dimensional with 2000 tetrahedron elements and 2662 nodes.

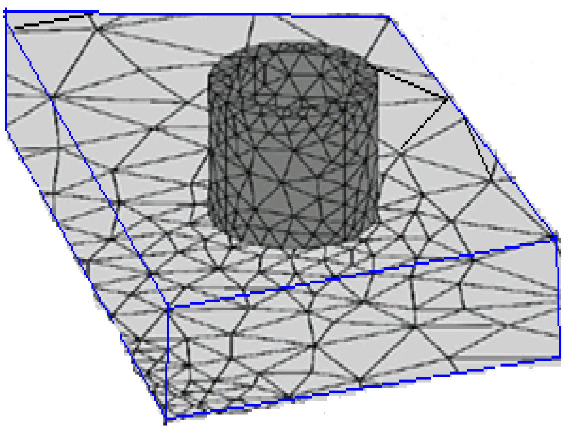


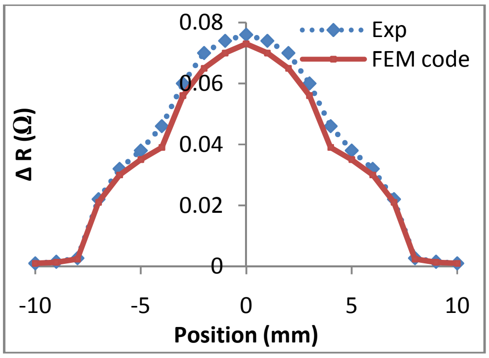
Fig. 2 Three dimensional meshes for the studied problem and for the probe coil

The suggested case will first be discussed and compared to an experimental model obtained from the sixth JSAEM benchmark problem (the parameters for this test are listed in Table I). The knowledge from this model is then used in the set up and analysis of the more complex case.

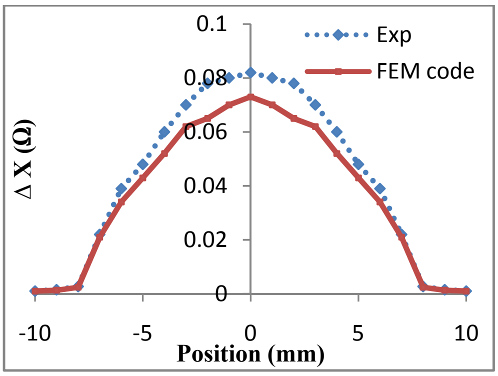
TABLE I
PARAMETERS OF STUDIED CASE

The coil	
Inner radius *(Ri)*	0.6 mm
Outer radius *(Ro)*	1.6 mm
Length *(h)*	0.8 mm
Number of turns (*N*)	140
Lift-off *(l)*	1. mm
The test plate	
Length (*Pl*)	140 mm
Depth *(Pd)*	1.25 mm
Width *(Pw)*	140 mm
Conductivity (σ)	1 10^6S/m
Permeability (μ_r)	1
Crack is in the first lower plate	
Length (*Dl*)	10. mm
Depth *(Dd)*	0.75 mm
Width *(Dw)*	0.2. mm
Other parameters	
Frequency	150KHz

Fig. 3 shows that the values of the resistive part (real part) of the impedance are always of the same form of those obtained by the experimental measurements. The same remark can be seen for the reactive part (imaginary part).



(a) Real part



(b) Imaginary part

Fig. 3 Impedance changes

It has seen in Fig. 3 that the experimental values of the impedance are always higher than the calculated ones and the accuracy of the calculation is in general satisfactory.

The developed code can be used to study the influence of certain parameters. In the example presented in Fig. 4, the parameters of test are fixed (the same parameters quoted in Table I), and the defect length is modified.

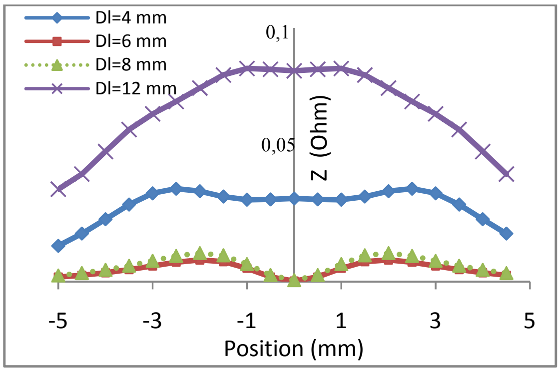


Fig. 4 Impedance variation due to the influence of defect length

To interpret the obtained results, it is significant to recall that the value of the skin effect for the studied configuration is 3.6mm.

The maximum impedance value is at the corner of the defect.

The defect sizes and positions are related to the penetration depth. Fig. 4 shows that the developed model gives good approximations if the defect length is less than 2.5 skin effect value ($Dl < 2.5\ \delta$). It can be seen, in the case Dl=12, that the impedance has higher values and its maximum value is not at the corner of the defect.

The increase in length is causing a decrease in impedance values.

IV. Conclusion

One of the important benefits of finite element method is that complex geometries can be studied. In the field of modeling and simulation of eddy current technique this feature enables the study of impedance responses on complex parts as well as using defects and probes with complex shapes. There are also possibilities to implement complex material properties in 3D finite element models.

The finite element method was applied successfully since it adapts for any chosen section.

The numerical model studied in this paper enables to predict and evaluate important parameters act directly on the impedance responses of eddy current testing.

Factors such as the type of material, surface finish and condition of the material, the design of the probe, and many other factors can affect the sensitivity of the inspection.

Further investigations have to be done in order to verify: the detection of defects, the influence of the various parameters on the control of the impedance responses and the increasing of analysis, which enables to minimize errors and benefit more of the performance of the finite element analysis.

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