Simulation of Cracks Detection in Tubes by Eddy Current Testing

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ABSTRACT
The eddy current testing can be used such as a perfect tool to characterize defects in conducting materials. However, in the latest years, an important progress was made in the development of software for the eddy current testing simulations. Evaluation of the non-destructive testing (NDT) modeling tools is the principal goal of this study. Main concerns of the aeronautical industry and the potential contribution of modeling are discussed and illustrated. The objective of this work is the development of a code for efficient resolution of an electromagnetic problem modeling. Simulation based on finite element method was realized with the aim to calculate the electromagnetic energy that enables to deduce the impedance response changes. The obtained results converge quickly towards the solution given by the (FEMM) code with an average error of 0.018 for real parts of impedance and 0.004 for imaginary parts. The presented results in this work serve to illustrate that the proposed method is practical and they are also of some intrinsic interest especially in the control of aluminum tubes used in aeronautic.

1. INTRODUCTION

The need to control complex parts leads to design increasingly advanced appropriate methods. Cracks in aeronautical tubes can occur due to a diversity of mechanisms such as stress-corrosion cracking, fatigue cracks or inter-granular attack. They can initiate from the inter-section of tube or the outer-section of tube and can be axial, circumferential or branching.

The non-destructive testing by eddy current (NDT-EC) is an electromagnetic technique largely employed to inspect conducting materials. It is frequently used in the field of aeronautic and aerospace to examine the metallic parts (dishes, sheets, tubes, stems and bars), for the detection and the classification of cracks, corrosion and other discontinuities in material during manufacture as in service [1, 2].

The eddy current testing can be used for various applications such as the detection of cracks, measurement of piece thickness, detection of metal thinning due to corrosion and erosion, determination of coating thickness and the measurement of electrical conductivity and magnetic permeability [2].

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The eddy current control is a good tool to detect defects when the eventual defect location and orientation are well known [3]. It can be used such as perfect tool to characterize defects in materials [4]. However, the sensitivity of the characterization process is highly dependent on the probe choice and the operation frequency [5].

An important aspect to comprehend (NDT-EC) technique is the capability to simulate performances of probe-piece interaction. Numerical modeling of electromagnetic fields can present important approaching into the analysis of probe responses and the design of new systems of (NDT-EC).

The modeling approach can be divided on analytical and numerical models. Finite element methods have been used in this context to numerically compute the different fields associated with physical problems and enable the analysis of their parameters [6].

The modeling and the simulations of (NDT-EC) using the numerical models of the finite element method (FEM) to establish codes able to solve Maxwell's equations have been developed in different papers in the latest years [7-10].

Early, Dodd's works present the known general model for axisymmetric problems [11]. The conductor can have any number of layers and the studied geometries fall into two major categories: planar and coaxial cylindrical layers.

This theoretical model, presented by Dodd for eddy current testing of long cylindrical tubes with constant properties of a conducting medium (the electric conductivity and magnetic permeability), is widely used. And analytical solutions for the problems where the properties are constant or no can be found in the literature (see, for example (Koliskina and Volodko [12], Fan et al [13], Skarlatos and Theodoulidis, [14]).

The detection of axial cracks in tubes continues to be a major challenge in various industrial applications [15-17] especially in aeronautic.

Based on eddy current (EC) technique principle, it is essential that eddy current field penetrates on either side of the tube wall. Defects can be detected by means of impedance variations due to inhomogeneities caused by the defect presence.

A simple model, applied to detected cracks by eddy current testing in aluminum tubes used in aeronautic, is used to calculate the optimum values of impedance change due to the presence of cracks in different depths of tested parts.

The general idea is to provide a theoretical and computational framework for the efficient and approximate treatment of three-dimensional electromagnetic problem, i.e. the simulation of cracks in the presence of an eddy-current probe of arbitrary configuration.

FEM method has been used in this context to numerically compute the electromagnetic fields on the surface of a conductor of cylindrical shape attached to eddy current probe.

The validation of developed code was made. The obtained results converge quickly towards the solution given by the (FEMM) code.

The presented results in this work serve to illustrate that the proposed method is practical and that it's also of some intrinsic interest especially in the control of aluminum tubes used in aeronautic.

2 PROBLEM MODELING AND NUMERICAL TREATMENT

In this study, the problem consists from a full conductor of cylindrical shape attached to eddy current probe (see figure 1). The sample is a long cylindrical tube with constant properties.

The formulations by FEM method for axisymmetric problems of eddy currents phenomena can be easily got from the literature.

In the field of the NDT-EC, the studied physical phenomenon enables to work by a mathematical models that return directly to the resolution of the Maxwell's equations.

These equations are giving by:

$$\nabla \times B = \mu (J + \frac{\partial D}{\partial t}) \tag{1}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{2}$$

$$\nabla . B = 0 \tag{3}$$

$$\nabla . E = \frac{\rho}{\varepsilon} \tag{4}$$

where: μ and ε are respectively the permeability and permittivity of studied domain, ρ represents the electric charges density, E is the electric field, B is the magnetic induction, j is the conduction current density and D is the electric induction.

The constitutive relations are given in the following forms:

$$B = \mu H \tag{5}$$

$$D = \varepsilon E \tag{6}$$

$$j = \sigma E \tag{7}$$

H is the magnetic field and σ is the conductivity of the domain.

The electromagnetic field can be constructed by introducing two potentials, the magnetic vector potential A and the electric scalar potential V.

The magnetic flux density B and the electric field E can be defined in terms of the magnetic vector potential A and the electric scalar potential V as:

$$B = \nabla \times A \tag{8}$$

$$E = -\nabla V - \frac{\partial A}{\partial t} \tag{9}$$

For axisymmetric structures with current passing only in the angular direction such as problems treated in this work, the problem is formulated by considering only the A_θ component of the magnetic potential vector and electric field is present only in the azimuthally direction.

The studied problem is described and giving by the following equation (using cylindrical coordinates, magnetic potential vector A and potential formulation named electric formulation A-V):

$$-\frac{\partial}{\partial r}\left(\frac{1}{\mu}\frac{\partial A_\theta}{\partial r}\right)-\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A_\theta}{\partial z}\right)+j\omega\sigma A_\theta = J_s \tag{10}$$

where A is a complex magnetic potential vector and Js is a current source in probe regions.

The boundary conditions used for the electromagnetic induction are:

(1) Axial symmetry at r = 0.
(2) Magnetic insulation at the domain boundaries (A_θ = 0).
(3) Continuity of magnetic fields at the interior boundaries (n×(H1 − H2) = 0).

Solving equation (10) with appropriate boundary conditions for a selected geometry, the magnetic vector potential A can be found. This equation can be solved directly when the geometry forms are simple. If they are complex, it is essential to transform this domain to new smaller domains adapted to the borders and in which the application of the boundary conditions becomes much simpler that requires the use of various numerical methods for solving these equations.

A numerical model is useful tool to control the capability of the model to visualize electromagnetic fields around the probe and in tested part. FEM method has been used in this research to numerically compute the electromagnetic fields on the surface of a conductor of cylindrical shape attached to eddy current probe. The mathematical approach is integrated in code. The resolution of the obtained system is realized in two steps. First, the Maxwell's equations are solved by using the input data. The nodal values of the potential functions (e.g. magnetic potential) are considered as main or primary unknowns must be calculated. Then, their derivatives (e.g., flux density) are the secondary unknowns must be deduced.

The FEM is one of the methods most used nowadays to indeed solve these equations. It is applied successfully since it adapts for any chosen section.

The mesh generation is an important part to use the FEM. The studied domain is discretized into a large number of linear triangular elements. In each element, three nodal points are defined at which the magnetic vector potential is found. The value of A within each element is assumed to be a linear combination of the nodal values A_i:

$$A=\frac{1}{\Delta}\sum_{i=1}^{3}(a_i+b_i r+c_i z)A_i \tag{11}$$

where Δ is the area of the triangular element and A_i are the nodal values of the magnetic vector potential. This approximation is extended throughout the solution domain resulting in N nodal points and therefore in N unknown values of A.

$$A = \sum_{k=1}^{TNE} \sum_{i=1}^{nn} N_i \, A_i \tag{12}$$

where N_i and A_i: are the nodal interpolation functions and the value of potential function corresponding to the ith node respectively of the element e, nn is the number of nodes in the element and TNE is the total number of elements in the studied domain.

By applying the Galerkin weighted residual treatment and the local boundary conditions; the standard finite element equation for an element 'e', after discretization of equation (10), can be written in the matrix form as:

$$\mathbf{[[R^e]+}i\mathbf{[S^e]]\ \{A^e\}=\{b^e\}\ or\ [k^e].\{A^e\}=\{b^e\}} \tag{13}$$

[R^e] is the (nn x nn) real part of the elemental matrix consisting of geometrical quantities of the mesh (r and z values of the dement vertices, the area of the element and permeability). **[S^e]** is the (nn × nn) imaginary part of the matrix represents the term ($j\omega\sigma A_\theta$) in equation (10). **{b^e}** is the (nn×1) vector of contributions at the nodes of the element from the impressed current densities (J_S), and **{A^e}** is the (nn × 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 using equation (13) and summed into a global system of equations. The global system to solve is given by:

$$\mathbf{[k].\{A\}=\{b\}} \tag{14}$$

where **[k]** is the (N × N) banded symmetric complex global matrix, and **{b}** and **{A}** are the (N x 1) complex source vector and the (N × 1) complex vector of unknowns (N is the total number of nodes in the studied domain).

The system is solved using in-house code developed by the authors. The Gauss elimination algorithm is applied to this system of equations to find A values at the nodes of the finite element mesh. From the magnetic vector potential other quantities can be deduced and calculated.

3 APPLICATIONS AND RESULTS

Standard with the external cracks of various depths is used. The material specifications of the standard must be similar to those used in related industry. The widths of the cracks are 2 millimeters and the depths are for 2 millimeters to 4 millimeters.

The design of the studied problem is mentioned in figure 1. For simplicity, one axisymmetric problem is studied. The parts of this problem are: a full aluminum tube with conductivity σ = 20 MS/m, relative permeability μr= 1 and diameter of 5 millimeters where the crack (external crack) can be localized and a differential probe made up of two coils. The two coils are indistinguishable, the dimensions of each coil are 5x5 millimeters and the distance between them is 10 millimeters. The coils are provided with an alternating current (AC) of density equal to 1 MA/m2.The number of turns of coil 1 is 900 and 900 for the second coil. Dimensions of the studied cracks are of 2x2 millimeters.

For the chosen cases, the widths of the cracks are 2 millimeters; the depths of the cracks are from 1 millimeter to 2 millimeters. The frequencies vary from 4 to 30 KHz.

The tube is tested by the differential technique, which is ideal for detecting local defects; it can decrease the effects of geometry differences and probe motion.

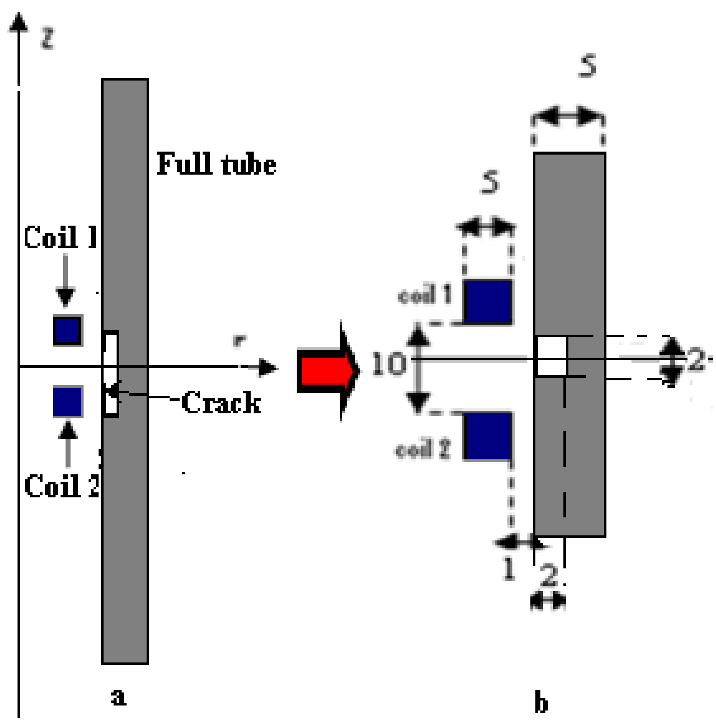


Figure 1: Problem description. (a): studied configuration, (b): geometrical dimensions (given in millimeters).

An alternating current is impressed across a differential probe. The magnetic field developed by this current flow in the probe causes eddy currents to flow in the tube wall. The corresponding magnetic field caused by eddy current flow in the tube wall is out of phase with the field developed by the current in the probe. Materials properties of the studied tube such as permeability and conductivity affect the flow of eddy currents. The probe current has direct relationship with the conductivity of tube material. If the conductivity decreases, due to a defect presence in the tube wall, the probe current increases.

Figure 2 shows the problem mesh with 4084 nodes and 7895 triangular elements. To ensure the suitable modeling of the skin effect in the tube, the density of mesh should take account of the employed frequency in the analysis. For that, frequencies between 5 and 20 Khz are used. The equivalent skin depths effects for these frequencies are between 4 millimeters and 1 millimeter respectively.

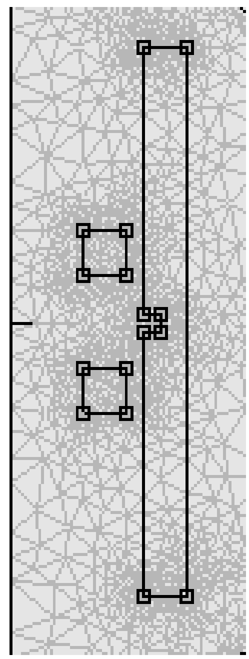


Figure 2: Triangular mesh used in problem simulations.

To ensure maximum symmetry, the differential probe is located at the center of the analyzed medium (figure 2). The problem is performed using the FEM method. First, the magnetic potential vector is calculated. After analyzing of electromagnetic field distribution, the electromagnetic energy is calculated and the real and imaginary components of the probe impedance are deduced in order to carry out the simulation of the NDT -EC of the studied system (figure 3).

In all cases, stored energy and power loss are integrated in model simulations to predict the variation of the reactance and resistance in order to calculate the impedance variation (the resistance is defined from power loss, while the reactance is defined from stored energy of the whole system and the impedance is as the square root of resistance square and reactance square, the amplitude scaling indicates the magnitude of signal detected by the probe).

For the validation, it is critical that computational schemes for electromagnetic field problems should be validated by inter-comparison and by reference to analytical methods.

The obtained code values are compared with the results given by the FEMM code.

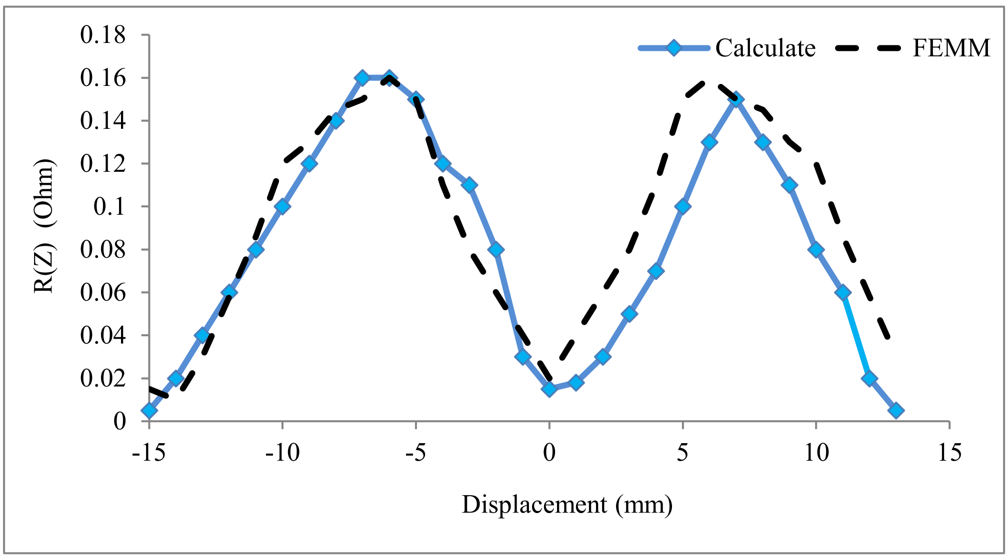
The results of the developed code approach towards the FEMM solution with an average error of 0.018 for real parts of impedance and 0.004 for imaginary parts.

After the validation, simulations can be carried out for the various input data.

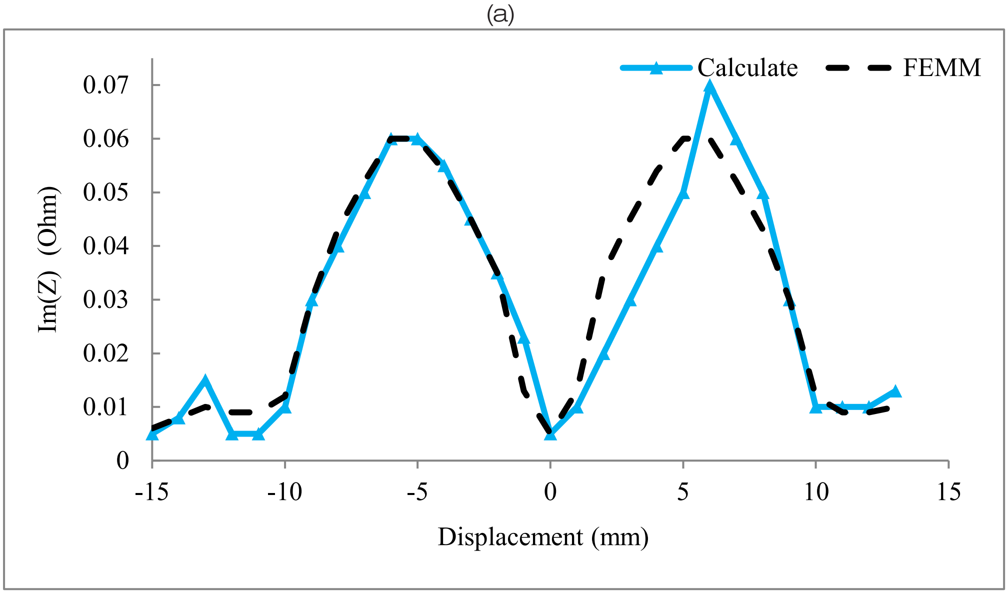
The impedance value can be affected by the defect depth, the defect length, and the area of the tested part.

Factors such as the type of material, the surface finish and material condition, the probe design and many other factors can affect the sensitivity of the inspection (figure (4) presents the influence of skin effect and frequencies).

It has been shown that the coil model parameter adjustment is very important to performing quantitative analysis or inversion. For example, the signal for 20 kHz is very weak (due to skin effect).



(a)



(b)

Figure 3: Impedance variation according to the current of 5 Khz. (a) real components and (b) imaginary components

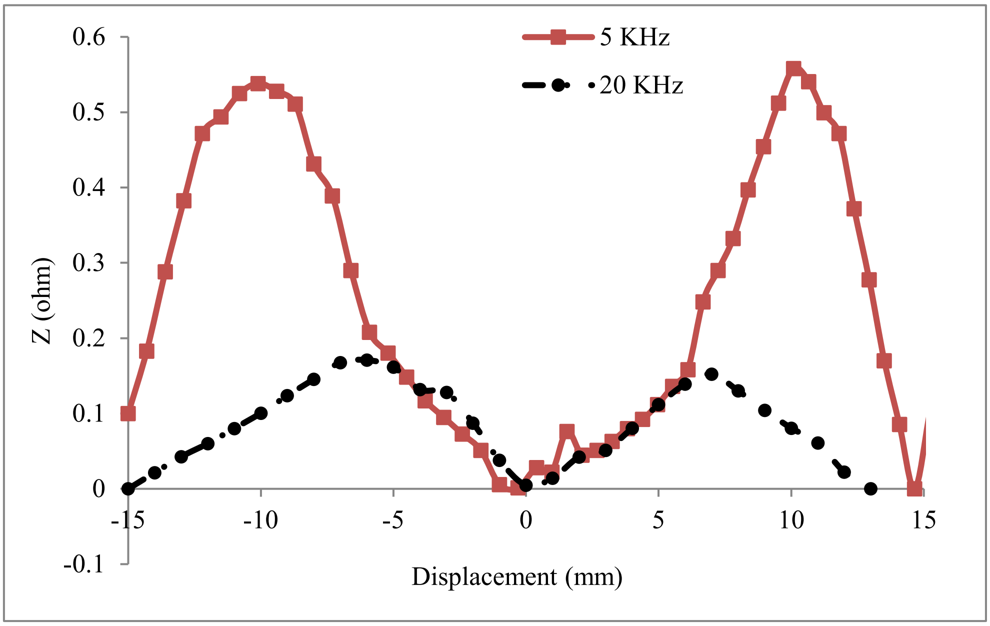


Figure 4: Probe impedance and influence of some factors.

4. CONCLUSION

The development of new probes and techniques for rapid and accurate inspection of tubes is of considerable interest to various industries.

The NDT by eddy currents is largely employed to inspect conducting materials. In this context, the tools for simulation enable to study the interactions (probe-part) and play an important role to conceive the systems of control and to show their performances.

The NDT–EC problems and Maxwell's equations allow to obtaining the evolution of the electric and magnetic fields in the continuous field.

The objective of this work is to use the finite element method to modeling the NDT–EC to provide a theoretical and computational framework for the efficient and approximate treatment of this electromagnetic problem.

The resolution of the problem is performed by FEM method where the magnetic potential vector A is found. After the electromagnetic field distribution analysis, the electromagnetic energy is calculated.

From the calculated energy, we deduce the real and imaginary components of the probe impedance that enable to determine the existence and effects of a crack under various frequencies applied on aluminum tubes.

The code validation is made with results given by FEMM code. The obtained results converge quickly towards the solution given by FEMM code with an average error of 0.018 for real parts of impedance and 0.004 for imaginary parts. That enables to use the code to carry out simulations for various similar cases with different input data. The code carried out allows the calculation of the eddy current field in various cases, the magnetic flux and the probe responses.

The suggested methodology can be applied to various probes and for various materials.

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