

SIMULATION OF NON DESTRUCTIVE TESTING PROCESS BY MESHLESS TECHNIQUE

Salim BENNOUD¹, Mourad ZERGOUG², Seif eddine GUERGOUR¹, Yacine BEHILIL¹

¹ University of Saad Dahlab-Blida 1-, Blida, Algeria

² center of welding and NDT control CSC Cheraga, Algeris, Algeria
bensalimen2006@yahoo.fr

Abstract. The non destructive testing objective is to check the integrity of a structure or a material without deteriorating them. Among the techniques most used in aeronautics, the eddy current method presents a remarkable interest.

The eddy current is not directly accessible by measurement, it can be observed only via the measurements on other physical parameters on which it acts.

In this context, simulation of the process of the non destructive testing by eddy current enables to study the interactions between the probe and the tested part and play an important role to include and understand the systems of control and to demonstrate their performances.

Recently, the interest is directed towards a new class of simulation techniques called meshless method.

The principal objective of this work is the development of a simulation of eddy current testing based on the meshless technique so-called EFGM.

The validation of results is carried out by a comparison with numerical results obtained by suitable codes and experimental results.

This study reveals factors and specimen parameters, such as geometrical form, used frequency, etc, that act on impedance variation of probe. It also shows some specific results, which are consistent with the use of the selected meshless technique.

1. Introduction

The eddy current method (EC) has been used as one of the most effective techniques for the detection and characterization of defects in conductive domains [1]. Numerical modeling, concerning non destructive testing by eddy current (NDT-EC), is a good way to understand and evaluate impedance responses due to various flaws, such as cracks and near surface voids or inclusions [2]. Over the past few years significant progress has been made in the computation of electromagnetic fields, including eddy currents.

The important challenge in this kind of numerical modeling is that sensitive impedance variations due to flaw and inspection process must be captured in an adaptive model. It is therefore important to use accurate and adequate numerical methods [3, 4].

Although finite element method (FEM) is widely employed and known as the most powerful numerical method in solving electromagnetic field problems such as eddy currents problems. Modeling and simulations of (NDT-EC) problem using the numerical models of the finite element method in order to establish codes able to solve Maxwell's equations have been developed in different papers, see for example [5, 6].

Contrary to all advantages presented by FEM method. A difficulty joined to the application of this method proceeds from the need of carrying out a regular mesh of the studied domain. This follows the significant deformations undergone by the matter of the studied domain. Another disadvantage of domain re-meshing is the need to project domain information, which was known at the different points of integration of the old mesh, towards the points of integration of the new mesh. So, a flexible method to add or remove meshes or nodes irrespective of the connectivity of existing meshes or nodes is well suitable. To surmount this obstacle, we can call upon the approaches known as meshless methods [7].

The meshless method has, in general, the same ingredients as the FEM method (approximation, integration, resolution of the linear equations system) but it is freed from the definition of the mesh; the discretization is based then on a cloud of nodes only.

At the beginning of the Nineties, various approaches of meshless approximations were developed to increase the numerical effectiveness of the modeling based on the meshless method, they are adapted to the numerical resolution of electromagnetic problems and many works have found this method very promising for the study of electromagnetics [8-10].

This paper exploits the discretization procedures and the associated discrete formulations of a meshless method so-called element-free Galerkin method (EFGM) based on the moving least square (MLS) approximant that are required when using meshless methods to study electromagnetic problems and the principal contributions of this paper is to validate EFGM method via comparison with an open source code based on FEM method formulation and in second fold is formulation and application of this technique to eddy current problems..

The EFGM method was successfully used and to validate the code, a set of thorough numerical values are presented and compared with those obtained from an experimental data and those given by the FEMM code.

2. Mathematical treatments

In this paper, the related direct problem consisting of modeling the impedance coil response over a specimen used in eddy current testing is treated.

For a homogeneous extended conductor placed in a time-varying external magnetic field, with a frequency that is low enough that displacement currents and finite propagation velocity effects can be neglected. The mathematical model based on the resolution of the Maxwell's equations is used and these equations are as follows:

$$\nabla \times \mathbf{E} = - \partial \mathbf{B} / \partial t \text{ (Faraday's law)} \quad (1)$$

$$\nabla \cdot \mathbf{B} = 0 \text{ (law of conservation of magnetic flux)} \quad (2)$$

$$\nabla \times \mathbf{B} = \mu (\mathbf{J} + \partial \mathbf{D} / \partial t) \text{ (Ampere-Maxwell theorem)} \quad (3)$$

$$\nabla \cdot \mathbf{E} = \rho / \varepsilon \text{ (Gauss theorem)} \quad (4)$$

where \mathbf{B} is the magnetic induction, \mathbf{E} is the electric field intensity, \mathbf{D} is the electric displacement, \mathbf{J} is the current density, \mathbf{H} is the magnetic field intensity, μ and ε are respectively the permeability and the permittivity of the medium, ρ is the electric charges density.

The constitutive relations are given in the following forms:

$$\mathbf{B} = \mu \mathbf{H} \quad (5)$$

$$\mathbf{D} = \varepsilon \mathbf{E} \quad (6)$$

$$\mathbf{j} = \sigma \mathbf{E}. \quad (7)$$

where \mathbf{H} is the magnetic field and σ is the conductivity of the medium.

Using the formulation in potentials based on the introducing of two potentials, the magnetic vector potential \mathbf{A} and the electric scalar potential V , and including the implicit gauge condition, Maxwell equations for time-varying harmonic fields written in potential form are:

$$\nabla \cdot (\nabla \mathbf{A}) + \mu (\sigma (\nabla V + \partial \mathbf{A} / \partial t) = \mu \mathbf{J} \quad (8)$$

$$\nabla \cdot (-\nabla V - \partial \mathbf{A} / \partial t) = \rho / \varepsilon \quad (9)$$

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

$$\nabla^2 \mathbf{A} + K^2 \mathbf{A} = -\mu \mathbf{J}_{source} \quad (10)$$

where $K^2 = -j\omega\mu(\sigma + j\omega\varepsilon)$, ω is the angular frequency of the excitation current. And the gradient of V is implicit in \mathbf{J}_{source} .

Following the approach developed in [2, 4-6] for planar multilayer medium with constant electrical and magnetic properties, the numerical formulation of FEM is well established and the two main steps for establishing the model are determining the vector potential \mathbf{A} and then calculating the coil impedance \mathbf{Z} .

In the introduction part, authors mention that FEM method leads to some distinct disadvantages such as difficulties in the treatment of discontinuities when an underlying mesh is used and/or a domain re-meshing is required. For such problems, developing a numerical method that does not rely on mesh is advantageous.

The principal contributions of this paper is to validate the element free Galerkin method (EFGM) via comparison with an open source code FEMM based on FEM method formulation and in second fold is formulation and application of this technique to eddy current problems.

However, to implement the EFGM procedure, it is necessary to compute the integrals over the solution domain.

Consider a function $u(x)$ that is to be approximated. In MLS approximation, the interpolation $u^h(x)$ is given by:

$$u^h(\mathbf{x}) = \sum_{j=0}^m p_j(\mathbf{x}) a_j(\mathbf{x}) = \mathbf{p}^T(\mathbf{x}) \mathbf{a}(\mathbf{x}) \quad (11)$$

where m is the number of terms in the basis, $P_j(x)$ are monomial basis functions, and $a_j(x)$ are coefficients that depend on the position x .

After some mathematical treatments, the MLS approximation can be written as:

$$u^h(\mathbf{x}) = \sum_{j=1}^m \Phi_j(\mathbf{x}) u_j \quad (12)$$

where shape function Φ_i are given by

$$\Phi_j(\mathbf{x}) = \sum_{i=0}^m p_i(\mathbf{x}) (\mathbf{A}^{-1}(\mathbf{x}) \mathbf{B}(\mathbf{x}))_{ij} = \mathbf{p}^T \mathbf{A}^{-1} \mathbf{B}_j \quad (13)$$

where:

$\mathbf{A} = \mathbf{P}^T \mathbf{W}(\mathbf{x}) \mathbf{P}$, $\mathbf{B} = \mathbf{P}^T \mathbf{W}(\mathbf{x})$ and

$$\mathbf{W}(\mathbf{x}) = \begin{bmatrix} w(\mathbf{x} - \mathbf{x}_1) & & & 0 \\ & w(\mathbf{x} - \mathbf{x}_2) & & \\ & & \ddots & \\ 0 & & & w(\mathbf{x} - \mathbf{x}_n) \end{bmatrix}$$

The solution domain is covered by domain of influence of each node; while the choice of shape of this domain is arbitrary.

NDT-EC problems generally involve multiply connected regions where interfaces lie between different materials. So, the derivatives of the shape function or the shape function itself should be discontinuous at the interface.

3. Application and results

In this section we present the validation of EFGM method and compare their solutions to those obtained from an experimental data and those given by the FEMM code using traditional FEM.

The procedure of NDT-EC was applied to some plated samples (copper, aluminum). In the case of this study, a sample with external cracks of various depths was used.

The problem geometry and dimensions are described in (Figure.1). The eddy current test procedure was made using an EC instrument (LCR-GMBH System) attached to a personal computer with a good possibility of execution for data acquisition, storage and analysis (Figure.1). A representation in two dimensions crack was used.

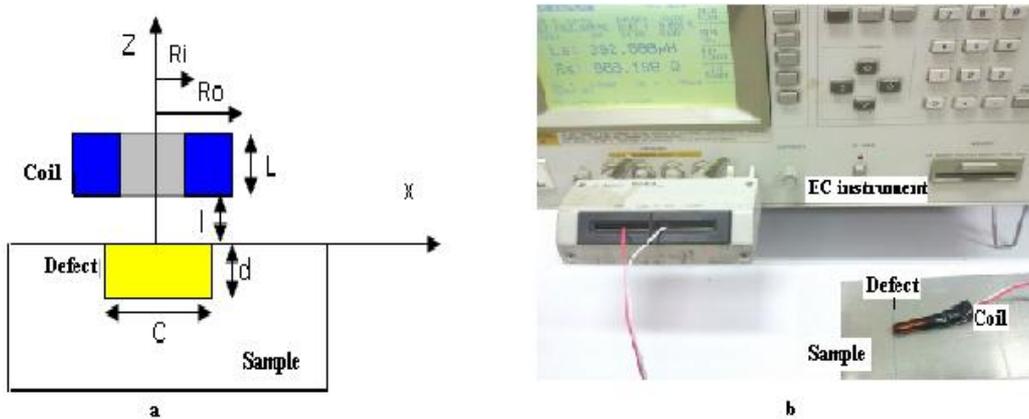


Figure 1. Typical model of eddy current problem and testing. (a) Studied configuration, (b) Experimental materials: sample and probe connected to EC instrument

The parameters for this test are listed in Table 1.

Table 1: Parameters of Studied case

The coil	
Inner radius (R_i)	3.65mm
Outer radius (R_o)	4.50 mm
Length (L)	9.80 mm
Number of turns (N)	170
Lift-off (l)	0.1. mm
Conductivity	5.8 MS/m
Permeability	1
The test plate	
Thickness	2.00mm
Length	100 mm
Width	50 mm
Conductivity	3.5 MS/m
Permeability	1
Crack is in the first lower plate	
Length (c)	10. mm
Depth (d)	1. mm
Width (w)	0.2. mm
Other parameters	
Frequency	20000 Hz

No-uniform mesh of 250 nodes is used with 4x4 Gaussian quadratic in each cell. EFGM with linear bases are used in the study, results are compared with those obtained from an experimental data and those given by the FEMM code based on linear FEM formulation with 4483 nodes and 8623 triangular elements.

Figure (2) presents comparison between experimental data, code values and FEMM values for the studied configuration. It displays variation of impedance according to the displacement trough the line of chosen scan.

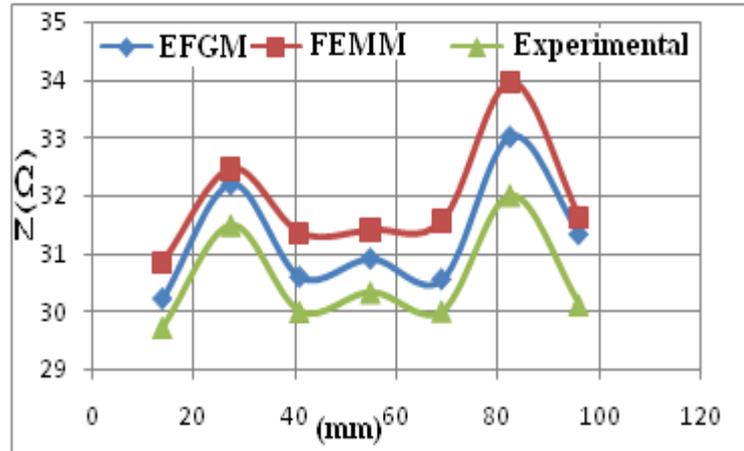


Figure 2. Comparison between the experimental, the code values and FEMM values

It can be observed that the convergence rate of EFGM depends on the scaling factor. The convergence rate of EFGM method is higher than that of linear FEM formulation used by the FEMM code, whose convergence rate to experimental data is 0.042. The convergence rate of EFGM is 0.019.

Through these applications, results confirm that EFGM method can be successfully applied to the NDT-EC problems and can obtain the same accuracy with a reduction of the execution time and the memory space reserving to data storage.

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

4. Conclusion

A meshless method, the element free Galerkin method (EFGM), for studying crack detection of eddy current problems is proposed. The developed method enables users to have the flexibility to add nodes in some specific regions without the need to consider their connectivity in the numerical implementation.

The accuracy and feasibility of the chosen approach are validated by comparing the numerical results with those obtained from an experimental data and those given by the FEMM code. The convergence rate of FEMM code to experimental data is 0.042. The convergence rate of EFGM is 0.019. This makes the chosen EFGM method ideally appropriate for pieces control in non destructive testing by eddy current.

References

- [1] Correia, J.P.M., M.A. Siddiqui, S. Ahzi, S. Belouettar and R. Davies, 2008. A simple model to simulate electromagnetic sheet free bulging process, *International Journal of Mechanical Sciences*, 50: 1466-1475.
- [2] Bennoud S, Zergoug M and Allali A, 2014, Numerical simulation for cracks detection using the finite elements method, *International Journal of Multiphysics (IJM)*. 8(1), 1-10.
- [3] Rosell, A., Gert Persson, 2012. Finite element modelling of closed cracks in eddy current testing, *International Journal of Fatigue*, 41: 30-38.
- [4] Bennoud S, Zergoug M, 2015, Modeling and simulation of defects inspection in conductive multi-layered pieces by the eddy current technique, *Journal of Physics: Conference Series*, J. Phys.: Conf. Ser. Vol 574, 012095. DIO: 10.1088/1742-6596/574/1/012095.
- [5] Kogl M, Hurlebaus S, Gaul L. 2004. Finite element simulation of non-destructive damage detection with higher harmonics. *NDT&E International*. 37: 195-205.
- [6] Liu Xu-dong, Yang Xiao-dong, Zhu Miao-yong et al. 2007. Finite element analysis of 3-D electromagnetic field in bloom continuous casting mold. *Journal of Iron and Steel Research*. 14(3): 06-12.
- [6] Bennoud S and Zergoug M, 2014, Modeling and simulation of defects due to corrosion in turbine blades of turbojet, 6th International Symposium on NDT in Aerospace, 12-14th November 2014, Madrid, Spain.
- [7] S. L. Ho, Shiyong Yang, Guangzheng Ni, H. C. Wong, and Yuhuai Wang, 2004, Numerical analysis of thin skin depths of 3-d eddy-current problems using a combination of finite element and meshless methods, *IEEE Trans. Magn*, vol. 40, no. 2.
- [8] V. Cingoski, N. Miyamoto, and H. Yamashita, 1998, Element-free Galerkin method for electromagnetic field computations, *IEEE Trans. Magn.*, vol. 34, no. 5, pp. 3236–3239.
- [9] C. Herault and Y. Marechal, 1999, Boundary and interface conditions in meshless methods, *IEEE Trans. Magn.*, vol. 35, no. 3, pp. 1450–1453.
- [10] S. A. Viana and R. C. Mesquita, 1999, Moving least square reproducing Kernel method for electromagnetic field computation, *IEEE Trans. Magn.*, vol. 35, no. 3, pp. 1372–1375.