Finite Element Computational Model for Defect Simulation and Detection by Eddy Currents Non Destructive Testing

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Abstract: - This paper presents numerical modelling of eddy currents non-destructive testing in bidimensionnal cylindrical plane. The magnetostatic and magnetodynamic model in term of magnetic vector potential is solved using the finite element method. The displacement of the probe operand in differential mode is simulated with the geometrical band technique based on the physical properties assignment and the impedance change at each position of the probe permit to keep the presence of defect and it influence on the eddy current distribution. A comparison of the results given by the implemented model with experimental ones is in good agreement.

Key-Words: – Finite element method, eddy current non-destructive testing, impedance calculating, geometrical band of movement.

1 Introduction

A variety of non-destructive testing (NDT) based on physical principles are available for detection and characterization of geometrical and physical anomalies in materials. One widely NDT technique for detection and evaluation of surface and sub-surface defects in electrically conducting materials is the eddy currents testing (ECT). This technique is employed in all types of engineering industries, aerospace, nuclear, defense, transport and petrochemical industries. The characteristics responsible for such popularity for the technique incluse simplicity, higth sensitive, non-contact operation, versatility, high speed testing, and scope for real time analysis. Nevertheless (ECT) present some disadvantages such as, a great sensitivity of the induced eddy currents compared to the lift-off, the materials to be controlled must be conductive and the exact knowledge of a defect (position, dimension) requires use several frequencies [1][2].

The eddy currents testing technique works on the principles of electromagnetic induction, it's consisted on the detection of the magnetic field due to the eddy currents induced on the tested specimen. The presence of the defect modifies the eddy currents pattern and hence gives rise to field perturbation closely related to the position and shape of the defects.

The distribution of the eddy current in the probes depends on the various parameters such as, excitation frequency, conductivity and permeability of the probe, and also the presence of material defect. The excitation field is carried out by using a coil fed by an alternating current and the changed impedance coil can be measured or computed to account the defect influence on the induced currents.

In the present work, numerical model based on the finite element method is implemented to understand interactions between fields and defects materials. Starting from the Maxwell's equation eddy current testing phenomenon can be expressed in the form partial derivative equation in term of magnetic vector potential and can be solved numerically for obtained the fields and eddy currents distributions in order to calculate the global quantities such as the impedance variation. The displacement of the probe is simulated using the geometrical band technique based on the physical property assignment.

2 Equations governing eddy current testing phenomenon

Eddy currants test phenomenon can be explained with the help of the Maxwell's equations with the absence of displacement currents [3]:

$$\nabla \times \vec{H} = \vec{J}_s + \vec{J}_e \tag{1}$$

$$\nabla \cdot \vec{B} = 0 \tag{2}$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{3}$$

Where the various quantities involved are the magnetic field $\vec{H}$, the applied source current density $\vec{J}_s$, the induced eddy current density $\vec{J}_e$, the electrical field intensity $\vec{E}$ and the magnetic flux density $\vec{B}$.

The above field's equations are supplemented by a constitutive relation that describes the behaviour of electromagnetic materials.

$$\vec{B} = \mu \, . \, \vec{H} \tag{4}$$

$$\vec{J}_e = \sigma \, E \tag{5}$$

Where μ and σ is the permeability and the conductivity of materials respectively.

The field's formulations present the disadvantage of discontinuity at the interfaces; to mitigate these problems the magnetic vector potential defined by the equation (2) is introduced.

$$\vec{B} = \nabla \times \vec{A} \tag{6}$$

Substituting equation (6) in equation (2), we get:

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \vec{\nabla} V \tag{7}$$

Considering a linear and isotropic homogeneous materials and substituting (6), (7), (4), (5) in the equation (1) the resulting partial derivative equations in term of the magnetic vector potential for such regions can be written:

$$\vec{\nabla} \times \left(\upsilon \cdot \left(\vec{\nabla} \times \vec{A} \right) \right) = \begin{cases} 0 & air \\ \vec{J}_s & probe \\ -j\sigma\omega\vec{A} & load \end{cases} \tag{8}$$

With $\vec{J}_s = \sigma \vec{\nabla} V$ the current density source relatively for voltage excitation.

In most practical eddy current test situation the object geometry and probe are rotationally symmetric and can be simplified for modelling purposes to 2D radial/axial plane of the cylindrical coordinate system. In rotationally symmetrical geometry with (r, φ, z) coordinates, the current in the excitation coil flows in the φ direction. In such a configuration, the magnetic vector potential A has only one component A_φ, with introducing the modified magnetic potential $A = r \cdot A_\varphi$ the equations (8) takes the following form in the (r, z) plane:

$$\frac{\partial}{\partial r}\left(\frac{\upsilon}{r} \frac{\partial A}{\partial r} \right) + \frac{\partial}{\partial z}\left(\frac{\sigma}{r} \frac{\partial A}{\partial z} \right) = \begin{cases} 0 & air \\ -J_{s\varphi} & probe \\ j\frac{\sigma}{r}\omega A & load \end{cases} \tag{9}$$

3 Finite element formulation and the calculating impedance variations

3.1 Finite element formulation

The modified magnetic vector potential is finite element approached by interpolation functions α_j such as:

$$A = \sum_j \alpha_j (r, z) A_j$$

A_j : Nodal potential values

The space discretisations of the magnetodynamic equation using Galerkin's finite element method and the substitution of natural boundary conditions lead to the following equation: the solution is obtained at discrete nodes in the solution region by applying the weighted residual method.

$$\sum_{j=1}^{n} \left(\int_{\Omega} \upsilon \nabla(\alpha_i) \nabla(\alpha_j A_j) \frac{drdz}{r} \right) + \sum_{j=1}^{n} \left(\int_{\Omega} j\sigma\omega \, \alpha_i (\alpha_j A_j) \frac{drdz}{r} \right) = \sum_{j=1}^{n} \int_{\Omega} \left(\alpha_i J_{s\varphi} \right) drdz \tag{12}$$

When writing (12) for all nodes in such region, one obtains the following algebraic equations.

$$[M + L].[A] = [K]$$

With: $M_{ij} = \int_{\Omega^e} \upsilon \nabla(\alpha_i) \nabla(\alpha_j) \frac{drdz}{r}$

$$L_{ij} = \int_{\Omega^e} j\sigma\omega \, (\alpha_i)(\alpha_j) \frac{drdz}{r}$$

$$K_i = \int_{\Omega^e} \left(\alpha_i \, J_{s\varphi} \right) drdz$$

The magnetic vector potential is obtained after solving the algebraic equation and the other physical quantities such as the magnetic flux, the induced eddy current density and the impedance probe can be deduced.

3.2 Calculating of impedance probe

The detection of defect presence and effect on load specimen passes by the measurement of impedance variation in term of resistance and reactance [4].

3.2.1 Method based on the magnetic energy and eddy current losses

The probe resistance R depending on eddy currents losses P and the probe reactance X depending on magnetic energy W, are calculated by the following expressions:

$$R = \frac{P}{I^2} = \frac{1}{I^2} \int_{\Omega} J_{s\varphi} E^* d\Omega$$

$$X = \omega \frac{W}{I^2} = \frac{1}{2} \frac{\omega}{I^2} \cdot \int_{\Omega} H B^* d\Omega$$

With I is the current source intensity and E^*, B^* the complex conjugate electric field and magnetic induction density respectively

3.2.2 Method based on the magnetic vector potential

Using the magnetic flux crosses elementary area dS of probe of coil and assuming the electromotive force function of the magnetic flux, we obtained the real and imaginary part of the impedance probe variation:

$$\begin{cases} R = real(Z) = -\dfrac{N^2}{J_s \cdot S} \cdot 2\pi f \cdot \int_S 2\pi r \left(A_{imag}\right) dS \\ X = imag(Z) = \dfrac{N^2}{J_s \cdot S} \cdot 2\pi f \cdot \int_S 2\pi r \left(A_{real}\right) dS \end{cases}$$

With S, N the area and number of turns forming coils probe, A_{imag} A_{real} the imaginary and real part of magnetic vector potential respectively and f the excited frequency.

4 Simulation of the probe displacement

The displacement of the probe displacement along the load specimen is made using the geometrical band technique [5]. This technique consists on two steps:

- Create a geometrical band, which is subdivided in elementary regions of height Δz.
- Locate in the geometrical band the finite element corresponding on the probe and air for assignment their physical properties at each step displacement.

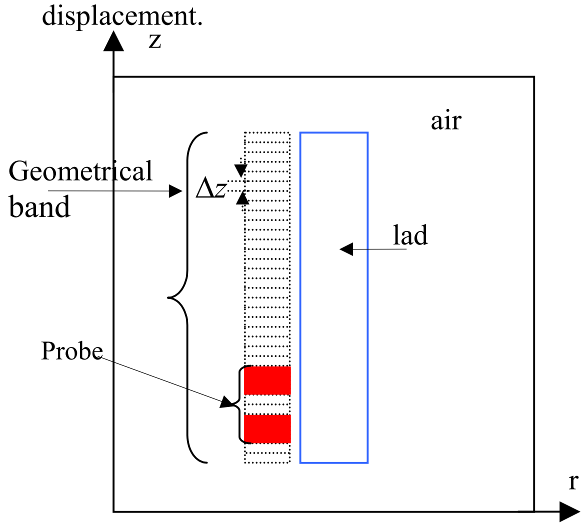

Fig. 1. Geometrical band of probe displacement

After one displacement, the probe nodes and it-surrounded air are localised for assignment of their properties. This method is simply implemented for conducting or non-conducting media with imposed fixed step displacement.

5 Applications

The inspection of heat exchanger tubes is usually carried out by using the eddy currents testing through the analysis of the impedance variation of the axial probe on differential mode. An alternative sinusoidal current with opposite direction excites the two coils placed on the load tube. The following Fig.2 represents the studied device.

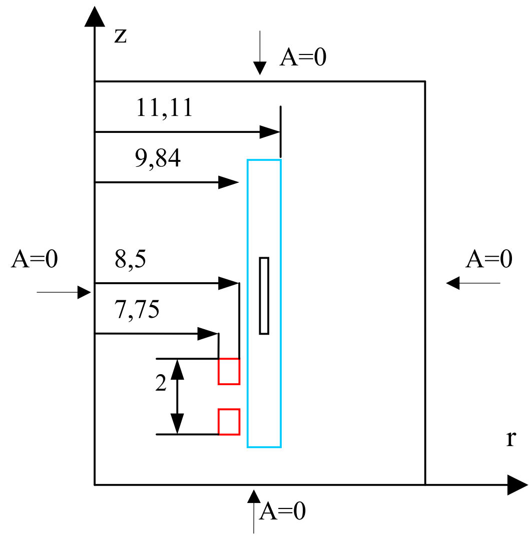

Fig.2. Dimensions of the device in [mm]

The coils are composed of 70 turns excited by sinusoidal current $5*10^{-3}\ [A]$. The conductivity and relative permeability of tested load tube is $\sigma = 10^6\ [S/\cdot m]$ and $\mu_r = 1$ respectively. The distance between the coils is $0{,}5mm$. Different types defect considered such as rectangular external, internal and middle, internal stepwise, elliptical and slopes. The rectangular external defect have $4mm$ length and 40% of the load thick and the circular defect have $2mm$ diameter. The other defects have $1mm$ length and 10% of the load thick.

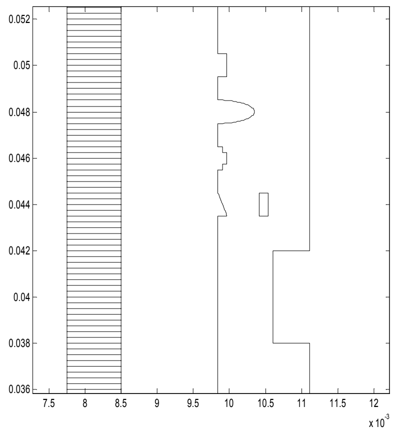

Fig. 3. Description of the defects geometry

The geometrical band is containing air and the probe region. For each displacement the nodes and finite element probe are locate for assignment their properties.

For the validation and showing the effectiveness of the implemented finite element model, the impedance change for the rectangular external and internal defects calculated and showed in Fig.4 and Fig.5 are compared with experiment results related in [6].

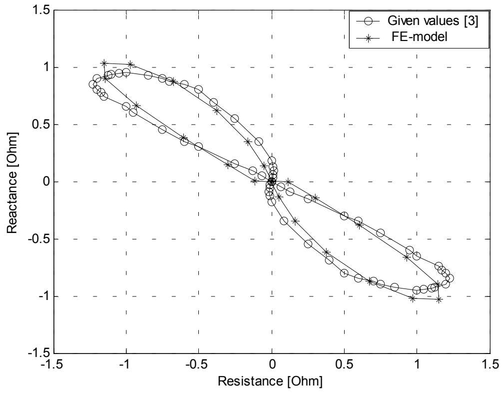

Fig. 4. Numerical results of impedance-plane trajectory for rectangular external defect, at $100Khz$

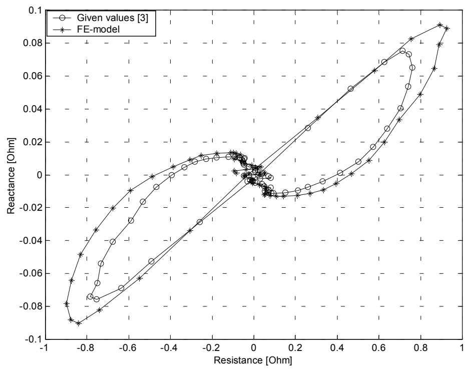

Fig. 5. Numerical results of impedance-plane trajectory for rectangular internal defect, at $100Khz$

To check the validity of the finite element model, we have calculated the change impedance of the probe for other defects at frequency $100Khz$ and $240Khz$. The probe displacement is made using the geometrical band with $0{,}25mm$ step.

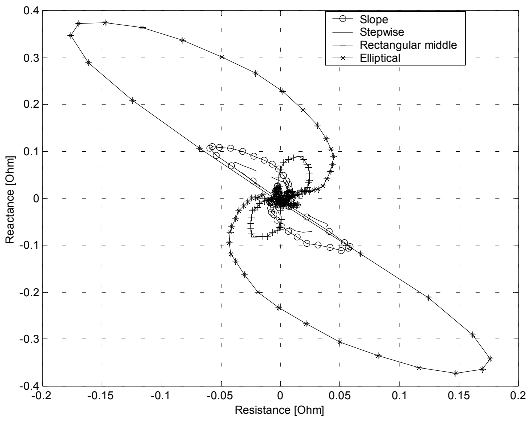

Fig. 6. Computed Lissajous curves at $100Khz$

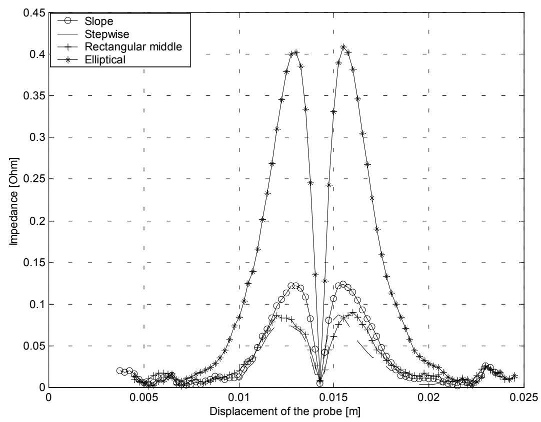

Fig. 7. Change impedance of the probe at $100Khz$

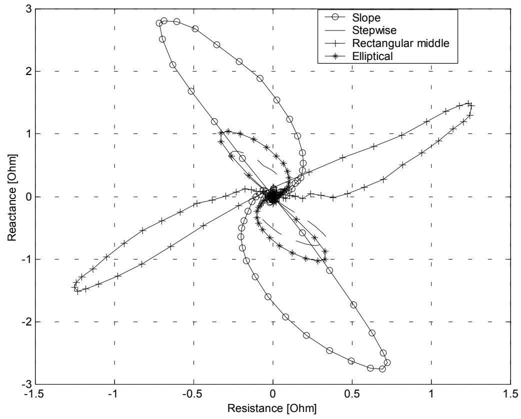

Fig. 8. Computed Lissajous curves at $240 Khz$

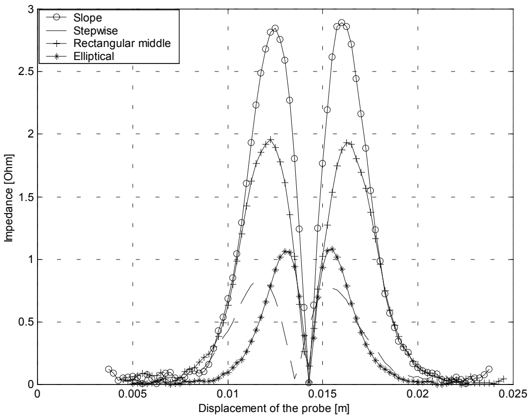

Fig. 9. Change impedance of the probe at $240 Khz$

The obtained impedance changes of the probe for the rectangular external and internal defect are compared with thus given in [6] and show a good agreements. The impedance change value depends of the height of the defect and the phase depends of the thickness of the defect.

5 Conclusion

In this paper, we have presented the eddy current non-destructive testing modelling tools implemented in Matlab software. The numerical approach based on finite element method is used for solving of the electromagnetic equations with magnetic vector potential formulation in 2D axisymmetrical case. For testing the validity of the proposed model, the results for internal and external rectangular shape defect is compared with experimental results given and showed good agreement. For taking into account of the probe displacement, the geometrical band technique based on the physical assignment properties is implemented. The effectiveness of the numerical model is showed through the investigation of effect induced by slope, elliptical, stepwise and rectangular shape defects.

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