Nonlinear Integral Formulation and Neural Networks based Solution for Reconstruction of Deep Defects with Pulse Eddy Currents

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***Abstract*—A method for reconstruction of defects buried deep under material surface of conductive nonlinear materials is proposed. Defects are approximated as zero-thickness, simulation of pulse eddy currents is done using an integral-FEM method, with a polarization method with over-relaxation to speed-up the nonlinear iterations and a Neural Networks method is used for reconstruction of defects shape from the simulated signals.**

***Index Terms*—Eddy currents, Nondestructive testing, Nonlinear magnetic, Neural Networks.**

I. Introduction

In the routine inspection of steam generator (SG) tubing of pressurized water reactors (PWR) of nuclear power plants, the Eddy Currents Testing (ECT) using sinusoidal mode was used extensively for the detection and shape characterization of defects. The fastness and reliability of the method is counterbalanced, due to skin effect, by its limitation to thin and nonmagnetic structures. For deeper structures, including magnetic materials, pulse eddy currents testing (PECT) emerged recently as an robust and effective solution. The rectangular pulse profile accounts for a multi-frequency analysis, higher harmonics penetrating deeper inside the material. Moreover, by reducing the pulse duration, the total amount in the power can be increased accordingly without exposing the probe and the material to extensive heat [1-3]. Although more sensitive to lift-off errors [4] than classical ECT method, PECT was proposed for various industrial applications [1-3], including detection of defects in multiple layered structures around fasteners in aeronautics, crack detection in structural steels [2], nondestructive inspection in ferromagnetic tubes [3]. In the current paper we present the method to detect the presence and reconstruct the shape of zero-thickness cracks using simulated pulse eddy currents in nonlinear magnetic materials, based on a model-free, using Neural Networks inversion procedure. For the simulation of pulse eddy currents we are using an integral-FEM, nonlinear formulation.

II. Nonlinear Integral Formulation for the Direct Problem

The proposed method is based on application of **T**- electric potential to the integral equation of eddy currents, like in [5]. Starting from Maxwell equations in quasi-stationary form and the constitutive relationships:

$$\mathbf{E} = \rho \cdot \mathbf{J}, \tag{1}$$

$$\mathbf{H} = F(\mathbf{B}), \tag{2}$$

where $\boldsymbol{J}$ is the current density, $\boldsymbol{E}$ is the electrical field, ρ is the resistivity in the conductive domain Ω_c, $\boldsymbol{H}$ is the intensity of the magnetic field and $\boldsymbol{B}$ is the magnetic flux density in the whole domain $\Omega = \Omega_c \cup \Omega_0$. In the laboratory frame, the electrical field is:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla V, \tag{3}$$

where V is the electric scalar potential and $\boldsymbol{A}$ is magnetic vector potential. The magnetic vector potential can be calculated using Biot-Savart formula:

$$\mathbf{A} = \frac{\mu_0}{4\pi}\int_{\Omega}\frac{\mathbf{J}}{r}\mathrm{d}v + \frac{\mu_0}{4\pi}\int_{\Omega}\frac{\nabla\times\mathbf{M}}{r}\mathrm{d}v + \mathbf{A}_0 \tag{4}$$

where $\boldsymbol{A}_0$ is the magnetic vector potential due to the impressed current sources:

$$\mathbf{A}_0 = \frac{\mu_0}{4\pi}\int_{\Omega_0}\frac{\mathbf{J}_0}{r}\mathrm{d}V, \tag{5}$$

and Ω_0 is the air. Only conductive and nonlinear media are meshed. The current density is expressed in terms of shape functions associated to the edges in the inner co-tree [5]:

$$\mathbf{J} = \sum_{k=1}^{n}\mathbf{N}_k \nabla \times \mathbf{T}_k, \tag{6}$$

whilst the magnetization **M** is approximated as a piecewise uniform field:

$$\mathbf{M} = \sum_{k=1}^{n}\mathbf{N}_k \mathbf{P}_k. \tag{7}$$

Applying Galerkin approach, the following equation system is obtained:

$$[R][I] + [F][M] + [L]\frac{\mathrm{d}[I]}{\mathrm{d}t} = [U]. \tag{8}$$

where the terms of matrices [$\boldsymbol{R}$], [**F**] and [$\boldsymbol{L}$] are calculated as:

$$L_{ij} = \frac{\mu_0}{4\pi} \int_{\Omega_c} \int_{\Omega_c} \frac{\nabla \times \mathbf{T}_i \cdot \nabla \times \mathbf{T}_j}{r} \mathrm{d}\, v_c \, \mathrm{d}\, v_c \ , \qquad (9)$$

and:

$$M_{ij} = \int_{\Omega} \frac{\nabla \times \mathbf{T}_i \cdot P_j \times \mathbf{r}}{r^3} \mathrm{d}\, v_c \, \mathrm{d}\, v_c \ , \qquad (10)$$

and respectively:

$$R_{ij} = \int_{\Omega_c} \nabla \times \mathbf{T}_i \cdot \rho \nabla \times \mathbf{T}_j \, \mathrm{d}\, v_c \ . \qquad (11)$$

and the right-hand side term U_i is calculated as:

$$U_i = -\frac{\partial}{\partial t} \left(\frac{\mu_0}{4\pi} \int_{\Omega_c} \int_{\Omega_0} \frac{\nabla \times \mathbf{T}_i \cdot \mathbf{J}_0}{r} \mathrm{d}\, v_c \, \mathrm{d}\, v_0 \right) \qquad (12)$$

with Ω_0 being the domain of impressed currents and $\mathbf{J}_0$ being the current density inside Ω_0. U_i results from $\mathbf{A}_0$ component of A, projected on the shape functions and integrated over the whole conductive domain Ω_c.

The nonlinearity is taken into account by the polarization term I [6]:

$$\mathbf{I} = \mathbf{B} - \mu \mathrm{F}(\mathbf{B}) \equiv \mathrm{G}(\mathbf{B}) \qquad (13)$$

The polarization fixed point method consists in the following iterative process:

a) A value for $\mathbf{I}^{(0)}$ is chosen;

b) At each step n, n > 1, B and H are computed from linear equations and therefore:

$$\mathbf{B}^n = L(\mathbf{I}^{n-1}) \, , \qquad (14)$$

where L is a linear function.

c) The new polarization is obtained from equation (13):

$$\mathbf{I}^n = G(\mathbf{B}^n) \qquad (15)$$

The above scheme is a Picard-Banach procedure for computing the fixed-point of the function $\boldsymbol{W} = \boldsymbol{GL}$. We choose a working $\mu = \mu_0$ and we obtain:

$$\left\| \mathbf{W}(\mathbf{I}^n) - \mathbf{W}(\mathbf{I}^{n-1}) \right\| \le \eta \left\| \mathbf{I}^n - \mathbf{I}^{n-1} \right\| \qquad (16)$$

To increase the convergence speed, an over-relaxation technique is proposed in order to get an improved $\mathbf{I}^{(n)}$,

$$\widehat{\mathbf{I}}^{(n)} = \mathbf{I}^{(n-1)} + \omega \left(\mathbf{I}^{(n)} - \mathbf{I}^{(n-1)} \right) \qquad (17)$$

Time step and mesh size are adapted carefully for each problem configuration, to account the fast variable regime of pulse eddy currents and for the equivalent small skin depth corresponding to pulse higher harmonics components [7].

III. Inverse Problem Solution using Neural Networks

Defect shape reconstruction consist in the solution of an inverse problem: from the signals of magnetic flux density (inputs) obtain the parameters for defects geometry (output values). A Neural Network (NN) approach and additional input data statistical analysis and transformation [7] are used. The signal-defect (input-output) parameters sets of data are divided in training and validation sets. A set of fresh signal (input) data is presented to the NN for verification.

IV. Numerical Results and Conclusions

Here we show preliminary results for the reconstruction of outer, zero-thickness defects in a plate made of ferrite steel excited with a pancake shaped coil and a Hall sensor to pick-up the signal. The pancake coil-Hall sensor system is less sensitive to frequency variation and lift-off error than the auto-induction pancake coil used in AC eddy currents testing [1][5][7]. The plate is 16 × 16 cm, with width 10 mm, the exciting coil dimensions are inner radius R_{min} = 2 mm, outer radius R_{max} = 5 mm, axial length l_z = 4 mm, liftoff z = 0.4 mm. The pick-up sensor measures the z-component of magnetic flux density and is placed in the z-axis of the exciting coil, at z = 0.4 mm. The coil signal is a 80 μs, rectangular shaped pulse, with an amplitude of I_{max} = 1000 AT and with a repetition frequency of 25 Hz. Scan path is 20 mm along a 10 mm length defect zone. For each simulation we compute the difference signal between the case with defect and without defect. The resulting difference signal is used for reconstruction. A total of 200 defect configurations were simulated, from which a set of 160 signal-defects geometry couples were presented to NN module for training, 30 were used for validation and 10 were reserved for verification. Fig.1 presents three reconstructed defects profiles compared with the real defect profiles. The reconstruction results agree well with the original defects profiles.

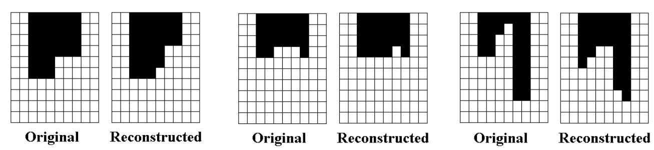

Fig. 1. Reconstruction of outer defects. Original and reconstructed defects are shown side by side. Each cell is 1 × 1 mm in a plate with 10 mm thickness.

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