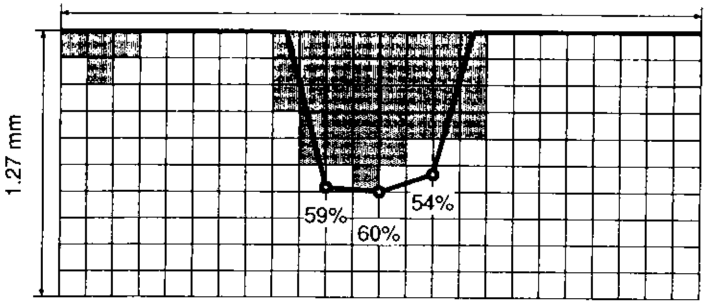

Figure 3: True and reconstructed profiles of the natural crack

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Applied Electromagnetics III

Fast Procedure for Crack Reconstruction in Nonlinear Materials using FEM-BEM with Polarization Method and Neural Networks

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Abstract. A FEM-BEM A-based formulation for static nonlinear magnetic field was implemented using Polarization method and various computation accelerating techniques. Magnetic Flux Leakage simulated signals are used for cracks reconstruction, using a Neural Network approach. Both direct simulation of nonlinear magnetic field phenomena and Neural Networks-based inversion techniques are performed. Numerical results for the inversion are presented.

1. Introduction

The detection of defects in structural steels, including magnetic materials, thick structures and welded parts raised recently the necessity to develop new and reliable Nondestructive Testing techniques. The use of Neural Networks as inversion technique requests large amount of simulation data for training the network. Particularly in the case of nonlinear magnetic field phenomena, a fast and reliable forward solver method is required. We have developed a 3D *FEM-BEM* coupling code using A-formulation method [1-2] for nonlinear static field, based on polarization method [3], featuring several acceleration techniques when used to build a database.

2. Numerical formulation for forward problem

From Maxwell equations in the limit of magnetostatic field, taking into account the nonlinear constitutive relationship:

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}), \tag{1}$$

and using the Coulomb gauge $\nabla \cdot \mathbf{A}=0$, the governing equations are obtained:

$$-\frac{1}{\mu_0}\Delta\mathbf{A} = \nabla\times\mathbf{M} \quad in\,\Omega_F, \tag{2}$$

$$-\frac{1}{\mu_0}\Delta\mathbf{A} = \mathbf{J}_0 \quad in\,\Omega_0 \tag{3}$$

where $\Omega = \Omega_0 \cup \Omega_F$ is the whole space, Ω_0 being the air and Ω_F the ferromagnetic media. The sources of magnetic field are the imposed current sources $\mathbf{J}_0$ in Ω_0 and the magnetization **M** inside the ferromagnetic bodies Ω_F. The ferromagnetic nonlinear media are replaced by a linear one having vacuum permeability and a magnetization iteratively corrected through a fixed point procedure based on polarization method [3]. The unknowns are the nodal values of magnetic vector potential **A**. On the interface between *FEM*-domain (magnetic material) and *BEM*-domain (air) the tangential component of **H** is enforced only in a weak sense [2]:

$$\frac{1}{\mu_0}\frac{\partial\mathbf{A}}{\partial\mathbf{n}} - \mathbf{M}\times\mathbf{n}\,|_{FEM} = \frac{1}{\mu_0}\frac{\partial\mathbf{A}}{\partial\mathbf{n}}\,|_{BEM}\,. \tag{4}$$

For the ferromagnetic domains Ω_F, a *FEM* formulation is developed. Using Galerkin approach, equation (2) is discretised by projecting each term of the equation on the shape functions and integrating over the whole problem domain Ω. Thus the equation system obtained is:

$$[P]\{\mathbf{A}\} = \{f\} + \{f_M\}. \tag{5}$$

with $\{f\} = [D]\{\partial A/\partial n\} + [D]\mu_0\{\mathbf{M}\times\mathbf{n}\}$ where *[D]* is the distribution matrix.

For the air domain Ω_0, the boundary element method (*BEM*) is used. Multiplying the equation (3) corresponding to the air domain (without magnetization source term), with the elementary solution u* = 1/ 4πr of the *Laplace* equation and integrating it over the whole free space we obtain, after several operations [1], the discrete system equations of *BEM*:

$$[H]\{\mathbf{A}\} + [G]\{\partial A/\partial n\} = \{F_0\}\,. \tag{6}$$

The matrix equations (5) and (6), after scalling, are coupled using the relation (4):

$$[P+K]\{\mathbf{A}\} = [D][G]^{-1}\{F_0\} + [\overline{\overline{S}}]\{\mathbf{M}\} \tag{7}$$

where $[K] = 1/2([K'] + [K']^t)$, $[K'] = [D][G]^{-1}[H]$ and $[\overline{\overline{S}}]$ is coefficient matrix of magnetizations, computed only once, at the beginning.

The nonlinear equation is solved through a fixed-point procedure described in [3]. The main drawback of the polarization method is its slow, because of linear, convergence speed. This may be further improved by overrelaxation procedure [3].

2.1 Fast procedure for computation of a database of signals

An important dimmension reduction is performed due to identity between the three diagonal subblocks of matrix *[P+K]*. Only first block (coresponding to A_x component) is inverted and subsequently used for solution of full matrix system, decomposed in three parts. The right-hand side term modelling the current and magnetic sources is also divided, during this operation, on components. After solution of the three separate subsystems we assamble again the solution vector, to be used in the magnetization corection.

Due to the formulation, the system matrix does not change during nonlinear iterations. Because crack zone is modeled as a region with zero-magnetization, for all the problems, matrix coefficients computation and matrix inversion shall be performed only once. These data are stored in two databases and used for solution of all cases. Therefore, CPU time for overall database building reduces drastically when repetitive computations are required.

Before constructing the databases for practical use, several tests were conducted to diagnose efficiency of new method to construct a set of results. As we can see in Fig. 1, the average CPU time per case for a problem with dimension 1477 decrease, for a database with 1000 cases, from 55 sec. to 4 sec. For a problem with dimension 4000, for 100 cases, the speed-up is in the range of 50 without post-processing (signal computation) and in the range of 25 with post-processing added to each case (see Fig. 2). These two tests were performed on an Alpha 21264 workstation with 667 MHz, 1 GB RAM, whose OS is Linux.

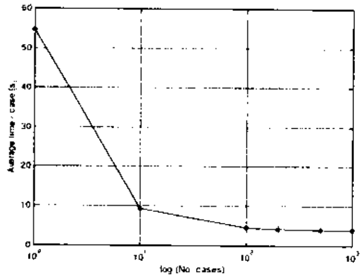

Fig. 1 Average CPU time per case for a problem with dimmension 1477 decreases to 4 sec. (speed-up is 14) for a database with 1000 cases.

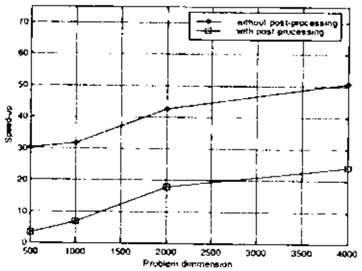

Fig. 2 Speed-up dependence on the problem dimmension, with and without post-processing; database with 100 cases.

3. Inverse problem solution

An inversion procedure to reconstruct the shape of cracks in magnetic materials from Nondestructive Testing (*NDT*) signals by using a Neural Network (*NN*) is applied. The inputs of the *NN* are the MFL signals (difference signals of x-component of magnetic flux density) and the outputs are the crack parameters. The crack is parameterized at a cell level, for each sub-domain in the analysis zone being associated a 0 or 1 value, corresponding to vanishing or non-vanishing material. The *I-O* pairs of the initial database are partitioned into training, validation and verification sets. The validation set is used only to control the training optimality, by monitoring the currently achieved estimation error. A statistical analysis and transformation of input data, by Principal Component Analysis (*PCA*), and *NN* with incremental learning is used. The training starts with only one hidden node and for each training epoch a new node is created and the unknown input-output and hidden-output weights are solved by a least-square minimization using singular value decomposition [4].

4. Numerical Results and Conclusions

A plate with dimensions 50 mm × 50 mm × 10 mm is energized using a yoke equipped with 2 coils, each having total current 40 AT. The plate material is nonlinear ferrite F82H

[1], the yoke material has linear characteristic with μ_r = 1000. The air-gap between the polar pieces of the yoke and plate is 1 mm. In Fig. 3 is shown the dependence of the difference signal (ΔB_x) on crack depth for a 0.5 mm width, 9 mm length outer defect. Only 11-points scans, 1 mm equally pitched, with lift-off 0.5 mm were used. The mesh for this problem has 1477 nodes, with 4431 unknowns. The crack is described with 45 cells, each having 1 mm length, 2 mm depth and 0.5 mm width. A database of 300 cases was first computed using the 3D FEM-BEM code previously described. Crack shapes were randomly generated. Only outer defects were simulated. The time for computing the database was only 2175 seconds, on a Alpha DEC workstation with 400 MHz, 1 GB RAM, having Unix operating system. The average CPU time was 7.25 seconds for computation of one case, when using the computing acceleration techniques described before. From the total of 300 cases, 250 were used for training, 40 for validation and 10 for verification (test). The training was stopped after 223 steps, when learning error decreased under 0.5 %. The optimum validation was achieved for the 147th epoch. Results of reconstruction are presented in Fig. 4. For each case, the original (true) crack shape is presented beside in gray-level images. These results show a good sensitivity of the method for detection and sizing even for small cracks.

An optimized method to solve nonlinear static magnetic field problems was developed, using Polarization method and a FEM-BEM approach. The code is optimized to deal with repetitive computations, as occuring in the case of computation of a database for the training set of Neural Network. Important gain in computational efficiency in terms of speed-up is reported. Using a database computed with the optimized method, good accuracy in reconstructing crack profiles from simulated signals is obtained.

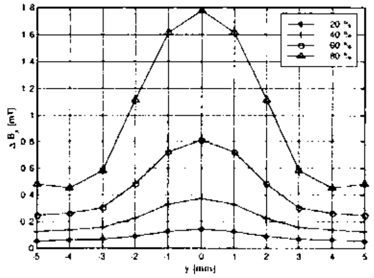

Fig.3 Difference signal (ΔB_r) for 0.5 width, 10 mm length, OD crack; $\Delta B_r = B_{x(crack)} - B_{x(no\_crack)}$.

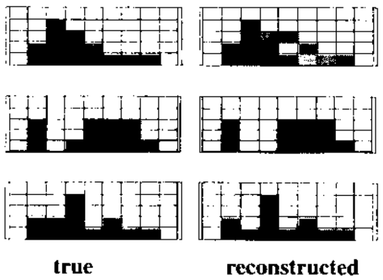

Fig.4 Comparison between reconstructed and original (true) crack shapes

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Applied Electromagnetics III

Development of Rotation Uniform Eddy Current Probe and Field Mock-up Test for Steam Generator Tubes on Nuclear Power Plant

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Abstract. Ensuring the security of the steam generator tubes of the pressurized water reactor (PWR) in the nuclear power plants is a key factor in their safe exploitation. Accordingly, the eddy current testing is used for the reason of high accuracy and high speed because the test must be done in a limited period. We developed a rotating type probe that can detect cracks with distinction between axial and circumferential cracks. The probe is composed with two excitation coils of axial and circumferential windings and a pickup coil. The excitation coil of this probe is able to generate uniform eddy current distribution on a wide area compared with the detection area of the pickup coil. We carried out evaluation of field mock-up testing. From measurement results by the field mock-up testing, the probe is confirmed to be able to measure small cracks on circumstances of the steam generator in the nuclear power plant.

1. Introduction

In the pressurized water nuclear reactors, safety security for tubes of steam generator exchanging primary cooling water and secondary cooling water is an important subject. Eddy current testing (ECT) is applied for this testing [1]. Cracks in actual tubes are mostly outer axial or circumferential cracks and the crack shape is shallow and narrow. Accordingly, the ECT needs high accuracy and high speed, because the test must be done in a limited period. To ensure the reliance of steam generator tubes, it is important to judge shape (length, depth and direction) of cracks detected by the testing. We developed a rotating type ECT probe that can distinguish between axial and circumferential direction cracks and also with high sensitivity.

2. Development of the probe

We developed the novel ECT probe for the purpose of detecting cracks, distinguishing between circumferential and axial direction[2]. The probe consists of two excitation coils for detecting axial and circumferential cracks, and a pickup coil. The excitation coil for axial crack detection is a coil of solenoidal shape. The excitation coil for circumferential crack detection is a coil winded with a fine wire in axial direction on a cylinder divided into two the domains. The pickup coil is a pancake type coil installed on the surface of the two excitation coils. The coil detects disturbances of eddy current distribution due to cracks. The structure and the specification of the probe are shown in Fig.1. We used numerical analysis by