4. Conclusions

Based on the experimental results described in the previous sections, the following concluding remarks are obtained:

1. The damage induced magnetization occurs for the SUS304 steel especially in the vicinity of the fatigue cracks. The natural field can be considered as the results of the anisotropy and martensite transformation due to plastic damages. It is possible to detect fatigue cracks in SUS304 stainless steel by measuring the natural magnetic field.
2. The area of the field-strain curve increase with the increasing fatigue cycle number. The amplitude of the natural magnetic field signal is also getting larger especially at the last period of the testing. These parameters are applicable in the online monitoring of the damage state of a key structure component.

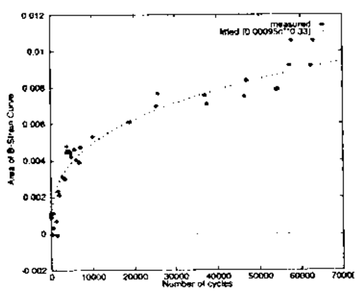

Fig.11 Relation between the area and cycle number

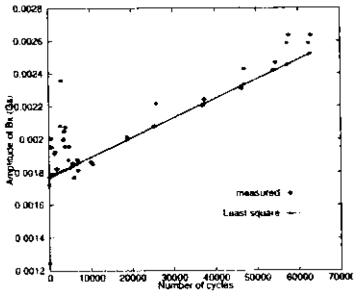

Fig.12 Relation between the amplitude and cycle number

Acknowledgments

The FG sensors used in the testing are provided by the Shimatsu Corporation. The helps from Mr. Fujiyama of Shimatsu Corporation are sincerely acknowledged. The authors would also like to thank Dr.Y.Nagae, Mr.S.Kato of JNC for there helps during the experiments.

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Applied Electromagnetics III

Reconstructions of Inner and Outer Defects in Ferromagnetic Materials from Experimental Remanent Magnetic Measurements by using Neural Networks

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Abstract. The present paper presents the application of remanent field analysis for detecting defects in ferromagnetic materials. The remanent signal from outer and inner defects in magnetized ferromagnetic samples is computed using a FEM-BEM nonlinear code. Also, an experiment is set-up to measure the remanent field around defects. The parameterized defect shape is reconstructed using Neural Networks. Numerical results for the inversion are presented.

1. Introduction

The problem of detection of inner (ID) and outer (OD) defects in ferromagnetic materials is an important task in non-destructive testing area with large application in nuclear power plants. Magnetic based tests such as magnetic flux leakage or flux methods are suitable tools for inspection of cracks in ferromagnetic materials. However, in many cases due to the lack of knowledge of material properties or material history, the application of magnetic methods has difficulties in revealing suitable information about defects.

In the present paper the authors concentrate on the simulation of signals of inner (ID) and outer defects (OD) in ferromagnetic materials after these were magnetized and first demagnetized with a magnetic yoke. A 3D nonlinear code is modified to take into account the demagnetization curve which is parameterized by a analytical model. A database is constructed using simulated signals with the 3D code. The crack shape is reconstructed from measured data by using an adaptive neural network with optimized hidden nodes. Reconstruction is performed for both free noise and noise input signal.

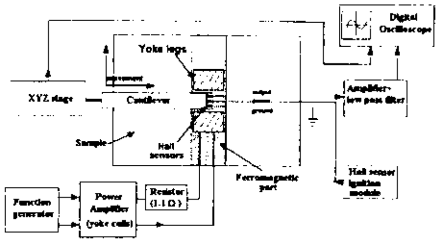

Figure 1. Experiment set-up.

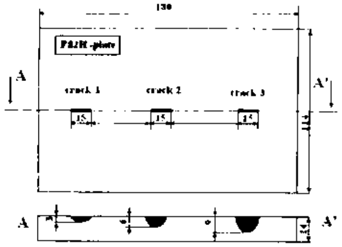

Figure 2. Crack locations and shape on the plate

2. Experiment set-up

An experiment was set-up to measure the remanent signals from outer and inner defects in F82H plates [1]. The schematic of the experiment is shown in Figure 1. A ferromagnetic plate is first magnetized and then demagnetized using a magnetic yoke. During magnetization the defect is centered between yoke legs. After the removal of magnetizing device, the Bx component (which is parallel with the plate surface) of the remanent field is measured using Hall sensor. The F82H plate sample is drawn in Figure 2. The plate dimension is 180x114x14 mm. Three cracks with semi-elliptical shape have been machined in the central part of the plate. Their dimensions are: 15 mm length, 0.5 mm width and 3, 6 and 9 mm width as is shown in Figure 2.

3. Simulation of the remanent field using a 3D nonlinear static code

The simulation tool for the forward problem numerical computations involved in this paper is a 3-D code [2] based on a FEM-BEM formulation for magnetic vector potential **A**. 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 *div* **A**=0, the governing equation becomes:

$$-\Delta \mathbf{A}/\mu_0 = \mathbf{J}_0 + \nabla \times \mathbf{M} \quad \text{in}\,\Omega, \tag{2}$$

where Ω is an unbounded domain. The sources of magnetic field are the impressed current sources $\mathbf{J}_0$ in the air and the magnetization **M** inside the ferromagnetic bodies. The nonlinear media that has the above constitutive relationship are replaced by a linear one having vacuum permeability and a magnetization iteratively corrected through a fixed point procedure based on Hantila's method [3]. On the interface between FEM-domain (magnetic material) and BEM-domain (air) the tangential component of **H** is conserved only in a weak sense:

$$\frac{1}{\mu_0}\frac{\partial \mathbf{A}}{\partial \mathbf{n}} - \mathbf{M} \times \mathbf{n}\,|_{FEM} = \frac{1}{\mu_0}\frac{\partial \mathbf{A}}{\partial \mathbf{n}}\,|_{BEM}\,. \tag{3}$$

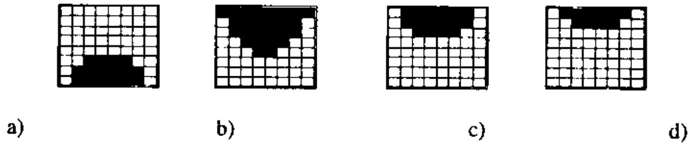

Figure 3. Parameterization of defects during simulation : a) OD 6mm; b) ID 9mm; c) ID 6mm; d) ID 3 mm

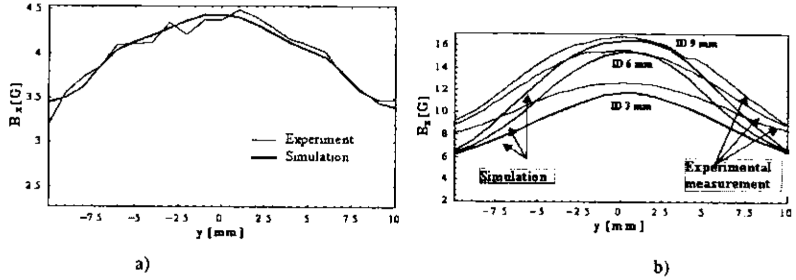

Figure 4. Comparison between experimental measurements and simulated signals for OD and ID

The remanent magnetization calculation is introduced in the code by using a multiple nonlinear approximation for the first demagnetization curves. An analytical approach based on the Potter model [4] is taken into consideration.

A simplified 3D model for the F82H ferromagnetic plate structure was used further to investigate the effectiveness of this method for crack reconstructions from remanent magnetic measurements. The plate and the defects area have been divided in finite elements. The parameterizations of cracks shape is presented in Figure 3. Defect area is drawn in black and magnetic permeability in the corresponding cells was set to void permeability: $4\pi x 10^{-7}$.

In Figure 4 are shown the comparison between simulated signals and measurements for both outer and inner defects. For outer defects, the coarse parameterization of defect does not have strong influence on the simulated crack signal. Good agreement was observed between experimental data and simulated signals. For inner defects the signal is different especially at the beginning and ending of crack. This is due to the mesh of the defect area. However, even in this case it was obtained a relatively good agreement.

4. Inverse mapping of data using neural network. Results and conclusions.

The proposed reconstruction algorithm is based on a statistical regression (inversion) of the inverse mapping signal to defect parameters.

Two modules are used: the first one transforms the input data using Principal Component Analysis (PCA); the second one is a neural network (NN) with an incremental learning algorithm [5], presented in Figure 5. During training the number of hidden nodes is increased at every epoch. New nodes receive random weights and the rest of weights are solved by least-square minimization using singular value decomposition (SVD).

The data set, coming from simulation is split into three sub-sets, for training, validation and verification (test). The validation error is evaluated every training step and the training is stopped when an optimum is achieved. The database (250 cases) was created using forward simulation, for different types of cracks in the F82H plate sample. We used only randomly generated OD and ID with shapes not identical or close to the shapes scanned in the experiment. The only crack parameter assuming to be known was the width of defect. Measured data was divided in 21 points and added to the reconstruction set (20 cases). Verification set (30 cases) consists in sets of 21 points and is used in controlling the training set. Data jittering have been also employed by enriching the initial database with noise-polluted sets: 15%, 20%, 25% and 30%. In Figure 6 are presented reconstruction of crack shape from measured data. Even if the signal from OD is smaller, OD shape is better reconstructed than ID shape. When the database was increased by adding signal with noise the reconstruction improved for both inner and outer defects.

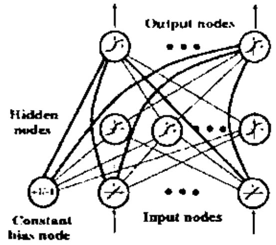

Figure 5. Adaptive neural network arhitecture

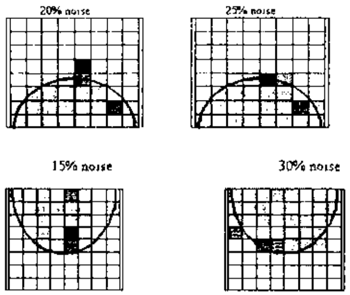

Figure 6. Reconstruction of ID and OD. Continuous line represents the true shape of the defect

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Inverse Analysis of Eddy Current Signals due to Natural Cracks using a Four Sensor Probe

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Abstract The present paper proposes a novel inversion scheme that reconstructs crack profile from eddy current signals. The biggest advantage of the scheme is that it can deal with conductive cracks. After efficiency of the scheme is validated, it is applied to profile reconstruction of natural cracks that occurred actual steam generator tubes. Remarkable agreement between reconstructed and true profile is obtained.

1 Introduction

More than thirty years have already passed since the first nuclear power plant in Japan was constructed and its operation started. Life time of the plants was estimated as thirty years when they were constructed and demand on integrity of nuclear power plant is significantly increasing, while constructing new plants is very difficult especially in view of public acceptance. Enhancement and optimization of maintenance of nuclear power plants are strongly desired, and, therefore, non-destructive testings play much more important role than ever. One of the most important components of pressurized water reactors is steam generator tubes that transfers heat energy of first coolant to second one. A steam generator have more than 3,000 steam generator tubes that must be inspected during in-service inspection period. The authors have proposed a novel inversion scheme that can reconstruct conductive cracks from eddy current signals in a previous study[1]. The scheme will be highly developed in the present study and applied to profile reconstruction of natural cracks that occurred in actual steam generator tubes.

2 Numerical Simulations

2.1 Configuration and Forward Analysis

Figure 1 shows geometrical configuration of the problem and a four sensor probe[2, 3] used in the inspection. An axial crack is present on the inner surface of a SG tube whose thickness is 1.27 mm and outer diameter is 11.12 mm, and the probe scans directly above the crack along the axial direction of the tube. The probe has four pick-up coils and one large exciting coil. The exciting coil is 45 degree slanted from the axial direction of the tube and produces also 45 degree slanted eddy current. Therefore, the probe can detect both axial and circumferential cracks with high sensitivity, which is highly demanded in view of practical inspection of steam generator tubes in PWRs. In order to model natural cracks that allow eddy current to flow across their surfaces[4], the crack model shown in right-hand