Objective function is the torque constant, defined as

$$K_T = \frac{T(output\ torque)}{I(input\ current)}[N \cdot m / A]. \quad (2)$$

Magnet residual flux density, magnet outer radius, number of pole, airgap length, stator outer radius, stator bore radius, coil turns and axial length are assumed to be constant values in accordance with the prototype motor. The teeth length, the teeth angle width and teeth thickness are chosen as the design variables. Torque linearity, weight, volume and convenience of manufacture are considered as evaluation criteria.

The result of optimal design between conventional RCS and RCS-PSM is shown in table II.

TABLE II. RESULT OF OPTIMIZATION

	Prototype motor	Result by conventional RCS	Result by RCS-PSM
teeth length [mm]	2.10	1.86	1.86
teeth angle width [degree]	50	56	56
teeth thickness [mm]	30	28	28
torque constant [N·m/A]	0.029	0.034	0.034
Calculation time [sec]		61647	**45366**

As shown in table II, Results of design variable by conventional RCS and RCS-PSM are same. But the calculation time of RCS-PSM is shorter than that of conventional RCS. RCS-PSM has the time advantage by 26%.

4. Conclusion

In this paper, RCS niching method combined with a pattern search method is proposed to identify multiple niches more efficiently. By applying to the numerical problems and the optimal design of galvanometer, it is shown that the proposed algorithm is more powerful than conventional RCS.

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Applied Electromagnetics III

2D and 3D Simulations of MFL Signals for Non-linear Magnetic Materials

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Abstract. The paper is concerned with the assessment of MFL inspection techniques application for flaws detection in ferromagnetic materials. A 2D Green function approach and a 3D FEM-BEM coupled approach were devised. In both methods the non-linearity of materials is treated by means of polarization method. Results of simulations obtained with 2D and 3D approaches are compared against measurement results in several distinct cases.

1. Introduction

Non-destructive evaluation (NDE) testing plays a well-established role in many industrial domains of paramount importance – one of them being nuclear power plant maintenance. If the parts under inspection consist of materials exhibiting non-linear magnetic characteristics then applying techniques such as Magnetic Flux Leakage (MFL) may prove to be an extremely suitable choice. MFL can provide a quick and relatively inexpensive assessment of the integrity of ferromagnetic materials. The leakage flux contains information dependent upon the material characteristic and upon presence or absence of a flow in the inspected area. In order to extract valuable information from measurement – namely information about crack's existence and geometry – which is to solve the inverse problem, one needs a reliable and fast solver of the field problem, which is the direct problem. We present in this paper two different approaches – one based on a Green function application (a 2D code) and one based on a coupling of FEM and BEM (a 3D approach). On both the approaches the non-linearity of the problem is treated by means of the polarization method [1]. After describing the rationale behind these approaches we are presenting results of the comparisons between measurements and simulations.

2. Polarization method

In the following we are describing a method for non-linearity treatment [1]. Both the 2D and 3D approaches make use of this method. The *Polarization Method* starts by replacing the constitutive relation in magnetic field quantities (1) with a linear one (2):

$$\mathbf{H} = \hat{\mathbf{F}}(\mathbf{B}) \quad (1) \qquad \mathbf{B} = \mu\mathbf{H} + \mathbf{I} \quad (2)$$

in which the non-linearity is hidden [1] in the polarization **I**:

$$\mathbf{I} = \mathbf{B} - \mu \cdot \hat{\mathbf{F}}(\mathbf{B}) = \hat{G}(\mathbf{B}) \tag{3}$$

The iterative convergent algorithm for polarization computation [1] goes as follows:

a) An arbitrary value $\mathbf{I}^{(0)}$ is given;
b) Magnetic field $(\mathbf{B}^{(n)}, \mathbf{H}^{(n)})$ is computed, which verifies:

$$\nabla \times \mathbf{H}^{(n)} = \mathbf{J}, \quad \nabla \mathbf{B}^{(n)} = 0, \quad \mathbf{B}^{(n)} = \mu\,\mathbf{H}^{(n)} + \mathbf{I}^{(n-1)};$$

c) $\mathbf{I}^{(n)}$ is corrected according to (3): $\mathbf{I}^{(n)} = \hat{G}\left(\mathbf{B}^{(n)}\right)$.

Steps b) and c) are repeated until an imposed error limit $\left\| \mathbf{I}^{(n)} - \mathbf{I}^{(n-1)} \right\|_{L^2(\Omega)}$ is attained [1]. Upon applying the method, the field problem becomes linear and solutions for this type of problem are presented in the followings.

3. The linear field problem

3.1 The Green function approach

We replace all ferromagnetic media by a medium having the vacuum permeability μ_0. The ferromagnetic regions are divided in n_f subdomains ω_i, where the polarization $\mathbf{I}$ has constant values. In each sub-domain the flux density is given by:

$$\mathbf{B}_i = \mathbf{B}_{0_i} + \tilde{\mathbf{B}}_i \tag{4}$$

where $\mathbf{B}_{0_i}$ is given by the current density:

$$\mathbf{B}_{0_i} = -\frac{\mu_0}{2\pi} \sum_{k=1}^{n_J} J_k \oint_{\partial\gamma_k} \ln R\, d\mathbf{l} = \sum_{k=1}^{n_J} \mathbf{u}_{ik} J_k \tag{5}$$

and $\tilde{\mathbf{B}}_i$ is the average value of the flux density given by the polarization [2]:

$$\tilde{\mathbf{B}}_i = -\frac{1}{\sigma(\omega_i)} \int_{\omega_i} \mathbf{B}\, dS = \frac{-1}{2\pi\sigma(\omega_i)} \sum_{k=1}^{n_f} \oint_{\partial\omega_k} \oint_{\partial\omega_i} \ln R(\mathbf{I}_k d\mathbf{l}_k) d\mathbf{l}_i = -\frac{1}{\sigma(\omega_i)} \sum_{k=1}^{n_f} \overline{\overline{\alpha}}_{jk} \mathbf{I}_k \tag{6}$$

In order to speed up the computation and to protect against numerical errors the difference field – between the flawed situation and the un-flawed situation is directly computed. Use of over relaxation drastically speeds up solution. The method is largely documented in [2].

3.2 The FEM-BEM approach

A 3D *FEM-BEM* coupling, based on A-formulation in the limit of static magnetic field was developed. From Maxwell equations in this case, taking into account the nonlinear constitutive relationship (1) and using the Coulomb gauge $\nabla \cdot \mathbf{A} = 0$, the governing equation (7) is obtained, where $\Omega = \Omega_0 \cup \Omega_F$ is the whole space, Ω_0 being the air domain and Ω_F the ferromagnetic media. The sources of magnetic field are the impressed current sources $\mathbf{J}_0$ in the air region Ω_0 and the magnetization $\mathbf{M}$ inside the ferromagnetic bodies Ω_F.

$$-\frac{1}{\mu_0} \Delta \mathbf{A} = \mathbf{J}_0 + \nabla \times \mathbf{M} \quad in\ \Omega \tag{7}$$

The FEM and BEM formulations are coupled on the boundary of the material. This, from computational point of view, enables a decrease of the size of the problem since only the interior of the material has to be divided for FEM. The continuity of the tangential component of the magnetic field is shown to be equivalent, in a weak sense, with the continuity of the $\partial \mathbf{A}/\partial n - \mu_0 \mathbf{M} \times \mathbf{n}$ which, assures the correct coupling of the two formulations. The method is extensively described in [3].

4. Results: simulations versus measurements

An experiment was set up in which an U-shaped yoke was placed above a ferromagnetic plate. The system was energized by means of coils as shown in Fig.1 (coil height: 35 mm, inner radius 12.5 mm, outer radius 37.5mm). The yoke's material is pure iron (cross section: 15x15 mm) whilst the plate is F82H ferrite. A line scan was performed on the lines showed in Fig. 1, picking the values of the magnetic flux density by means of a Hall sensor. Two kinds of experiments – and correspondingly simulations were conducted. First the field was measured for a configuration in which only the yoke appeared. Comparisons of results are shown in Fig. 2. Then a block of small dimensions was placed beneath the yoke (F82H ferrite, 31 mm x 14 mm x 25 mm). Figures 3, 4 and 5 present the results for lines 1 and 2..The yoke-block air-gap was 0.6 mm, the sensor lift-off 2.5 mm.. The 2D mesh consisted of 1988 triangles with 2181 nodes, whilst the finest 3D mesh consisted of 11232 hexahedra with 13720 nodes. The 3D code is highly sensitive to mesh coarseness (see Fig. 6).

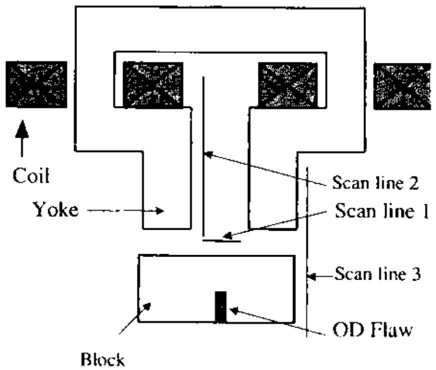

Fig. 1 Experimental set-up

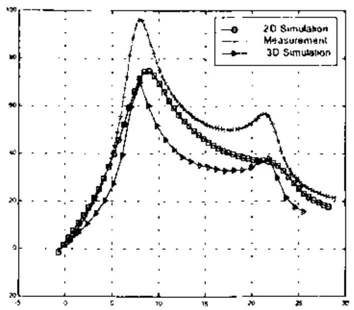

Fig. 2. Comparison for line 1 - yoke with no plate (B [G] versus x [mm])

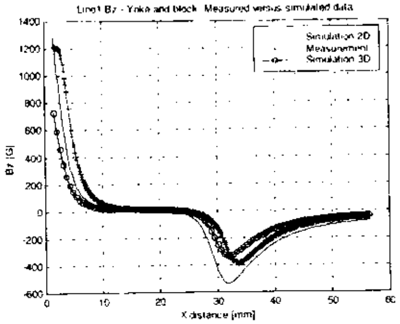

Fig. 3 Comparisons for line 2 (yoke and block configuration)-normal flux component

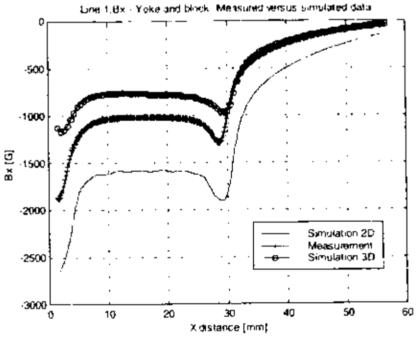

Fig. 4 Comparisons for line 2 (yoke and block configuration)-tangential flux component

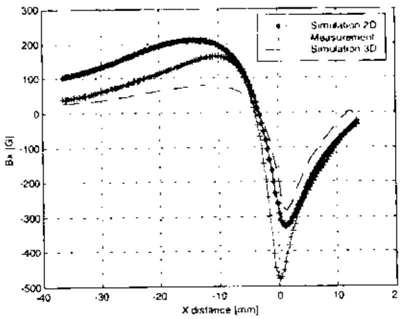

Fig. 5 Comparisons for line 3 (yoke and block configuration)-tangential flux component

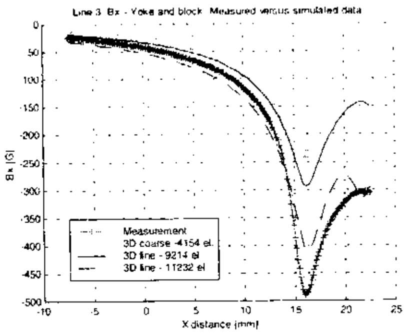

Fig. 6 Comparisons of influence of mesh in 3D simulations

3. Conclusion

A 2D and a 3D approach for solving the direct problem in MFL method were presented. In both cases the non-linearity is treated by means of polarization method. The accuracy of the simulations were tested both on open and closed magnetic circuit configurations.

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Applied Electromagnetics III

Numerical Evaluation of Structural Integrity of Fusion Component subjected to Electromagnetic Force

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Abstract Dynamic elasto-plastic analysis is indispensable in order to establish the structural integrity of fusion reactor because huge sudden electromagnetic force may be unexpectedly applied to different fusion components and may cause their functional and/or fatal damage owing to plasma disruption. First, this paper introduces the governing equation of dynamic elasto-plastic analysis briefly. Second, this analysis code developed is applied to the problem such that the back plate of blanket could be deformed in radial direction by transient electromagnetic force on plasma disruption. Considering that the back plate may have an unexpected crack by iteration of deformation, its structural integrity is estimated by dynamic elasto-plastic fracture mechanics approach.

1. Introduction

Plasma disruption induces large eddy current in fusion reactor components to couple with constant applied magnetic field and generates huge transient electromagnetic force. This force is regarded as a kind of mechanical impact load, therefore it brings about quick deformation in the components. In the case of designing previous large structures, the static elastic analysis or elasto-plastic one, if necessary, often prevails in the engineering filed. However, dynamic deformation is in general larger than static one and therefore the static approach is found inadequate in the design of fusion reactor. In addition, if stress concentrated zone such as structural discontinuity, opening hole or occasionally crack is inevitably included, the generation of large plastic zone and large deformation by transient electromagnetic force is estimated there. This issue may give rise to not only the functional loss of the fusion component but the unrecoverable failure. As a result, the dynamic approach is necessary to clarify the mechanical behavior of the fusion components by transient electromagnetic force and to guarantee the structural integrity during a certain period.

In this paper, the iterative method by FEM is proposed for the dynamic analysis.[1] The scheme of this method satisfies the condition that the stress point moves on the yield surface during plastic deformation. A Von-Mises yield criterion and isotropic hardening are employed in the FEM code. We assume that the temperature rise due to joule heating of electric current affects neither the thermal stress nor the fracture behavior[2].

Next, the application of transient electromagnetic force, for instance, is responsible for some vibration of blanket and back plate in radial direction. Then, a crack is possibly initiated and propagated by the stress cycle. Namely, dynamic consideration is necessary to understand whether the crack is more propagated, say, to a critical length or becomes unstable. In this section, first, using A-ϕ method[3], eddy current analysis was conducted