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B-H curve reconstruction from MFL signals based on Genetic Algorithms

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Abstract. B-H curve reconstruction starting from magnetic flux leakage (MFL) signals measured outside the tested specimen is attempted. Non-linear constitutive relation is modeled by means of three parameters, suitable for describing low fields magnetization curve. A FEM-BEM approach is used to solve the forward problem whilst the inverse problem is tackled with a genetic algorithm application. Results of the reconstruction are presented.

1. Introduction

The problem of B-H curve reconstruction arises as a crucial task for the Non-Destructive Testing specialists. Aged material, stressed material or inclusions to name but a few causes may alter to some extent previously known magnetic characteristics. The necessity of inferring the magnetic constitutive relation relying only on measurements of the magnetic quantities outside the tested sample called lately for efforts in devising a suitable inverse procedure for the task. In the paper the authors concentrate on the reconstruction of the low field approximation of the B-H nonlinear characteristic. The difficult task of mapping the inverse relation existing between measured values of magnetic field and the magnetic characteristic that originated the signal is addressed by means of a genetic algorithm application. Each generation and in turn each individual in a generation in the genetic algorithm means solving a magnetic field problem, performed by means of a FEM-BEM magnetostatic code. Results of the reconstruction prove that the approach has well enough potentiality for extension to the much more difficult task of hysteresis curve reconstruction.

2. Magnetic field problem

From Maxwell equations in the limit of magnetostatic field, taking into account the nonlinear constitutive relationship (1) and using the Coulomb gauge $\nabla\cdot\mathbf{A}=0$, the governing equation (2) is obtained:

$$\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M}), \qquad (1) \qquad\qquad -\frac{1}{\mu_0}\Delta A = J_0 + \nabla\times M \quad in\,\Omega, \qquad (2)$$

where $\Omega = \Omega_0 \cap \Omega_F$ is the whole space, Ω_0 being the air and Ω_F the ferromagnetic media. The sources of magnetic field are the impressed current sources $\mathbf{J}_0$ in the air Ω_0 and the magnetization $\mathbf{M}$ inside the ferromagnetic bodies Ω_F. A linear medium of vacuum permeability replaces the ferromagnetic nonlinear media and the magnetization is iteratively corrected through a fixed-point procedure based on polarization method [1-2]. 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 [3]:

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

The iterative process is fully described in [2]. An important improvement in terms of computation speed (the nonlinear procedure has linear convergence) was obtained by introducing an overrelaxation procedure.

2.1 *B-H constitutive relation parameterization*

A simplified parametrical model for a hysteretic material is introduced, to model hysteresis in the case of low field in the degraded material zone. The parametrical model is easy described using relation (4):

$$c\frac{d\mathbf{B}}{dt} = -\mathbf{B} + \mu_0\left((1+a)+bH^2\right)\mathbf{H} \qquad (4) \qquad\qquad \mathbf{B}= \mu_0\left((1+a)+bH^2\right)\mathbf{H} \qquad (5)$$

where: $a = \mu_i - 1$ is the initial magnetic susceptibility, $b = (\mu_m - \mu_i)\,/\,H_0$, with μ_m the maximum relative permeability and H_0 the saturation value. The value of the field should not overpass this value or else the

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model doesn't describe proper the field variation. c is the parameter describing dynamic hysteresis. This effect will be small enough to be neglected, therefore we will further simplify this model, setting c = 0 and thus obtaining the an-hysteretic B-H material characteristic used further on in the simulations, shown in (5). The non-linearity may vary from small values (μ_m *close to* μ_i) to big values (μ_m much larger than μ_i).

3. Inverse problem strategy – Genetic algorithm application

In order to solve the inverse problem we used a genetic algorithm, aimed to cope with the ill posedness of the problem of inferring the magnetic nonlinear characteristic of the flawed material. In practice we solve the optimization problem of finding the extreme of a fitness function, describing how good the actual estimated parameters reproduce the original signal. This function is the only connection between the physical problem and the genetic algorithm. GA's are robust, stochastic search methods, modeled on the principles and concepts of natural selection and evolution. GA's are known for their ability of escaping local minima and for not being a model oriented approaches thus allowing independence from the forward solver. The *pikaia* genetic algorithm used here was developed by Charbonneau [4] and is distributed freeware [5]. The quantity to be evaluated is coded first using a digit by digit coding, only numbers between 0 and 1 are coded in this way and the number of decimal digits gives the length of chromosome (in this case is set to 6). Each individual have one chromosome for each parameter to be evaluated. The fitness function has values between 0 and 1 and is maximized (i.e. to value 1) through evolution. Therefore, we scaled also the signal and we rewrite the fitness function as $ff = 1 - |Si - S|$ where Si is the current signal and S is the actual one.

4. Results and comments

We consider a plate exhibiting an area with altered magnetic properties that we inspect by means of a yoke energized by a couple of coils placed on each of its legs. The signal we measure spans a line just above the affected zone. As for the inverse problem, we set the options for the genetic algorithm as: mutation mode: variable, mutation rate varying between 0.0005 and 0.25, evolution plan: steady-state replace worst; elitism is used. Stopping criteria is number of generations – here fixed to 150. We attempt to estimate the parameters of material characteristic, as described by (5). The three parameters that are to be evaluated (μ_i ,μ_m and H_0) are set to μ_i = 3, μ_m = 5.5 and H_0= 95 A/m (scaled for GA to x(1) = x(2) = =0.5 and x(3) =0.45). The algorithm went on for 150 generations, population being of 20 individuals. Results are shown in Fig. 1. Fig. 2 shows the evolution of the fitness function for the best individual in each generation. The final estimation of (0.500, 0.500,0.450) is (0.500, 0.320,0.342). We observe that the influence on the signal of the second and third parameter is poor (probably because the functioning point is on the lower part of the characteristic).

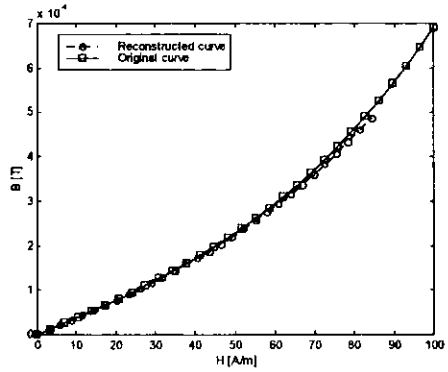

Fig. 1. Original and reconstructed material characteristic

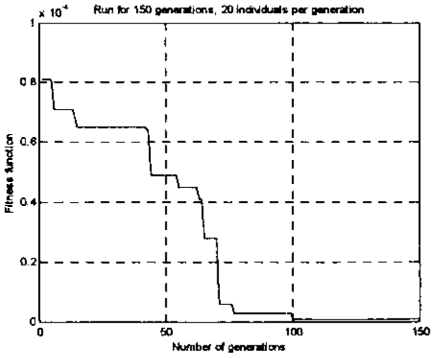

Fig. 2. Fitness function evolution

References

[1] I.F. Hantila, G. Preda and M. Vasiliu," Polarization Method for Static Fields", *IEEE Trans. on Magn.*, Vol. 36, no.4, 2000, pp.672-675.

[2] R.Albanese, F.Hantila, G.Preda and G.Rubinacci, "A Nonlinear Eddy-Current Integral Formulation for Moving Bodies", *IEEE Trans. on Magn.*, Vol. 34, no.2, 1998, pp.2529-2535.

[3] S. Kurtz, J. Fetzer and G. Lehner, "A novel iterative algorithm for the nonlinear BEM-FEM coupling method", *IEEE Trans. on Magn.*, Vol. 33, no. 2, 1997, pp.1772-1775.

[4] P. Charbonneau, "Genetic Algorithms in Astronomy and Astrophysics", *The Astrophysical Journal (Supplements)* , 101, 309 (1995).

[5] http://www.hao.ucar.edu/public/research/si/pikaia/pikaia.htm