Numerical Method for Nonlinear Simulation of Magnetic Saturated Pulsed Eddy Current Testing Signals and Its Application to Evaluation of Wall Thinning in Carbon Steel Piping

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Quantitative non-destructive evaluation of wall thinning in carbon steel piping is a difficult and urgent issue for safety of nuclear power plants. A magnetic saturated PECT (pulsed eddy current testing) method has been proposed by authors for this purpose, where an electromagnetic magnet is utilized to generate strong static magnetic field to saturate the piping material, i.e., to increase the skin depth, and the PECT is applied then in the magnetic saturated environment. To evaluate the feasibility of the magnetic saturated PECT method for wall thinning detection in carbon steel piping, numerical method for simulation of nonlinear PECT signals is proposed and validated in this study. Firstly, the simulated magnetic polarization approach is adopted for the calculation of the static magnetic field distribution generated by the electromagnetic magnet, and the local permeability distribution is predicted then according to the local magneic flux density and the *B-H* curve. Finally a nonlinear PECT forward simulation tool is developed based on the reduced *A* method and step by step numerical integration strategy, and is applied to validate the magnetic saturated PECT method for evaluation of wall thinning defects in carbon steel.

***Index Terms*—Magnetic saturated PECT, Nonlinear, Numerical method, Carbon steel, Nondestructive evaluation.**

I. INTRODUCTION

IN nuclear power plants (NPP), degradation in the coolant piping is a key that threatens the safety of NPP, and a periodic non-destructive testing (NDT) is mandated in order to guarantee the structural integrity. However, NDT technique for local wall thinning, a type of pipe defect caused by flow accelerated corrosion (FAC) and/or liquid droplet impingement (LDI) is still not fully established especially for pipes of carbon steel material [1]. Recently, PECT (pulsed eddy current testing) method is considered to be a powerful candidate for the NDT of pipe wall thinning [2-5]. However, due to the quite large permeability (lower penetration depth of eddy current), it is still difficult to apply the PECT directly to the piping of the carbon steel [6]. Fortunately, magnetic saturation could be a solution to reduce the permeability of the carbon steel material.

To understand the mechanism of saturated PECT and to investigate its validity, a numerical simulation method is important. The objectives of this study are to develop a numerical method for simulation of the nonlinear magnetic saturated PECT, and to validate its feasibility for the quantitative NDT of the wall thinning defect in a carbon steel piping.

II. PRINCIPLE OF MAGNETIC SATURATED PECT METHOD

Magnetic saturation strategy can reduce the permeability of carbon steel, therefore, it is a useful way to increase the skin depth of eddy current in carbon steel. Figure 1 shows the schematic of the proposed magnetic saturated PECT approach. An electromagnetic magnet (a magnetic yoke wounded by coils with large direct current) is applied to generate strong static magnetic field to make the carbon steel into magnetic saturation state. Pulsed ECT is then applied in the magnetic saturation environment to detect the far side wall thinning defect.

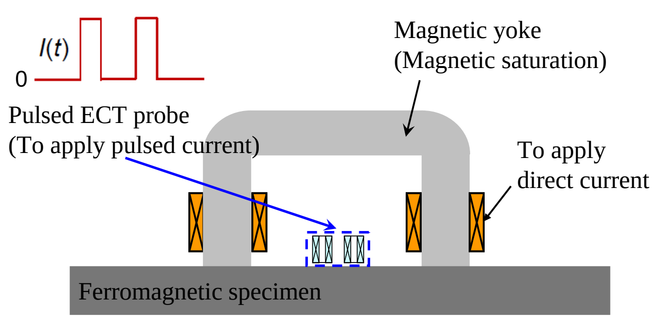

Fig. 1. Schematic of magnetic saturated PECT.

III. NUMERICAL SIMULATION METHOD

At first, the simulated magnetic polarization approach is adopted to calculate the static magnetic field distribution generated by the electromagnetic magnet based on a hybrid FEM-BEM code.

The governing equations of the polarization approach are

$$-\frac{1}{\mu_0}\Delta \boldsymbol{A} = \nabla \times \boldsymbol{M} \quad in \quad \Omega_{FEM} \tag{1}$$

$$-\frac{1}{\mu_0}\Delta \boldsymbol{A} = \boldsymbol{J}_0 \quad in \quad \Omega_{BEM} \tag{2}$$

where Ω_{FEM} means the ferromagnetic domain of carbon steel specimen and magnetic yoke, and Ω_{BEM} means the air domain with the exciting source coil of magnet, $\boldsymbol{J}_0$ is the current source in the exciting coil and $\boldsymbol{M}$ is the magnetization inside the ferromagnetic bodies and $\boldsymbol{A}$ is the vector magnetic potential and μ_0 is the permeability of the air.

Eq. (1) is nonlinear as the applied field is large and the nonlinear constitutive relationship is,

$$\boldsymbol{M}(\boldsymbol{B}) = \frac{\boldsymbol{B}}{\mu_0} - \boldsymbol{H}(\boldsymbol{B}) \tag{3}$$

The basic idea of the magnetic polarization method is to transform the equations to linear ones and to solve it iteratively. In practice, with a supposed magnetization distribution and take it as excitation magnetic current source, Eq. (1) becomes linear and vector potential $\boldsymbol{A}$ can be solved with the FEM-BEM hybrid method [7] and then the new distribution of magnetization can be obtained using the constitutive relationship of Eq. (3) which in turn is to be used to calculate the new vector potential $\boldsymbol{A}$. If the supposed $\boldsymbol{M}$ distribution is near enough to the calculated one, the iteration procedure will be terminated and the potential will be taken as the final solution.

Secondly, a nonlinear PECT forward simulation tool for ferromagnetic material is developed. Based on a numerical method developed by authors for nonlinear ECT problem [8], the numerical code is updated to calculate the nonlinear PECT problem. The nonlinear PECT forward simulator is based on the $\boldsymbol{A}_r$ method and edge element finite element method. Time integration method based on Crank-Nicholson is adopted to treat the transient problem. To cope with the nonlinear property, the permeability distribution at each Gauss point is adjusted at each time integration step. With a small time step, the nonlinear property of the PECT can be properly considered.

IV. Numerical Results

Figure 2 shows the static magnetic field distribution of a typical magnetic saturated PECT problem. It can be found that the magnetic field inside the specimen between two yoke legs is rather large and these areas are saturated. Figure 3 shows the permeability distribution at the specimen surface where one can see that the permeability of the area saturated is dramatically reduced, which gives a promising effect to enlarge the skin depth of eddy current.

Figure 4 shows a comparison of the transient PECT signals under saturation and the case before saturation (relative permeability 80) for the wall thinning of 3 mm depth with linear PECT calculation. It can be found that the transient PECT signal is larger when the specimen is saturated which validates the efficiency of saturated PECT method. In the full paper, the results with nonlinear PECT simulation will be described in details.

V. Conclusions

In this work, numerical method for simulation of nonlinear magnetic saturated PECT signals is proposed and validated. The simulated magnetic polarization approach is adopted to calculate the static magnetic field due to the EM magnet, and PECT signals are then calculated by taking into account the nonlinear ***B*-*H*** property and the distributed permeability. Numerical results for the saturated PECT signals of a carbon steel specimen demonstrated the validity of the numerical method and the efficiency of the saturated PECT method.

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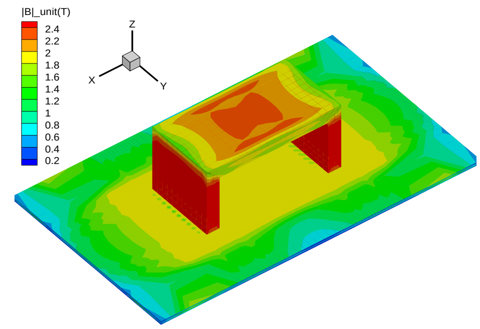


Fig. 2. Static magnetic field distribution.

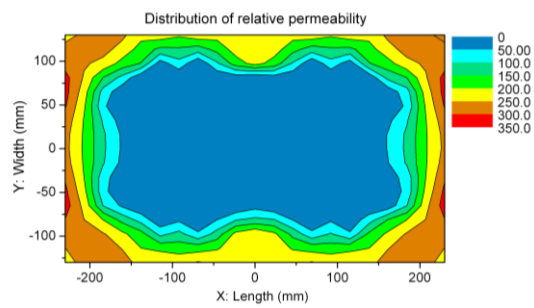
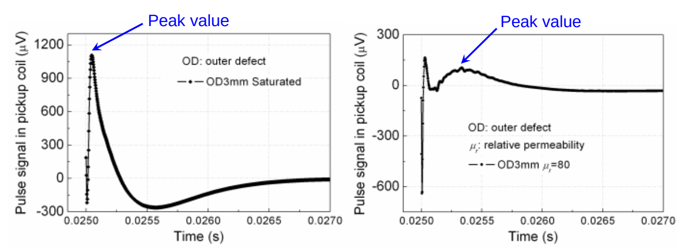


Fig. 3. Permeability distribution of carbon steel specimen.



(a) Saturated (b) μ_r=80

Fig. 4. PECT signals for saturated and not saturated case.

VI. References

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