3-D EDDY CURRENT NONDESTRUCTIVE TESTING MODELING FOR SURFACE FLAWS

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INTRODUCTION

In eddy current non-destructive testing, numerical models have been used for a long time to optimize the method. Those models solve Maxwell's equations and compute the coil impedance. Many 2-D programs have been realized:

- for axisymmetrical geometries, with axisymmetrical or very small flaws, to model tube sheets of a steam generator or wires [1,2].
- for an E-shape sensor which generates a one dimensional field to scan a plane surface [3].

Unfortunately, a lot of actual problems can't be solved with such approximations. Two important examples for industrial NDT in steel plants can be mentioned:

- transverse cracks on steel slabs shown in Fig. 1;
- long cracks on wires.

To study such cases, a 3-D model is necessary because, even if a 2-D computation gives interesting results for a test piece without defect, the symmetry is broken by the presence of a flaw.

Full 3-D programs have been realized [4,5], but are not used for ferromagnetic materials and are very expensive in CPU time (they are implemented on vectorial computers, Cray I or Cyber 205). The aim of our study is to realize a 3-D program for small skin depth problems which can be performed on a mini-computer (HP 9000, VAX 780) with a "reasonable" CPU time. For ferromagnetic materials, the frequencies used in NDT are generally at least 10 kHz: so, the skin depth δ is very small and negligible compared to the other dimensions of the problem. For example,

for ordinary steel, $\sigma = 10^7\ \Omega^{-1} \cdot m^{-1}$ $\mu r = 100$
for f = 10 kHz, and $\delta = 0.2$ mm.

This paper presents a specific formulation using a surface impedance condition for small skin depth.

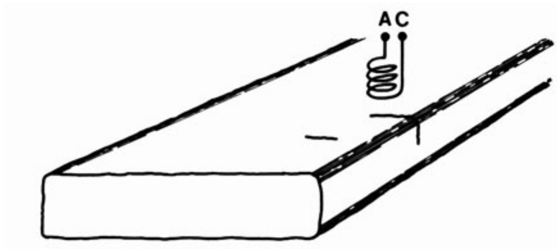

Figure 1. Transverse cracks on steel slab.

THE SURFACE IMPEDANCE BOUNDARY CONDITION

To reduce the computation time, only the exterior magnetic field will be computed. In air, curl $\vec{H}$ is zero so that $\vec{H} = -\,\vec{grad}\,\phi$, where ϕ is a scalar potential. We must then find a boundary condition at the surface of the conducting material which contains all the information about the metal.

The surface impedance is well known in acoustic and electromagnetic wave propagation. It has been used for eddy currents modeling [6] with a finite element resolution. In this work, the surface impedance leads to a boundary condition for a boundary integral equation (BIE) resolution. Some hypotheses are necessary but are not restrictive for many eddy current NDT problems. They are:

- δ is small compared to the other geometrical data.
- Each variable ($\vec{E}$, $\vec{H}$, $\vec{B}$, $\vec{J}$, I,...) is sinusoidal.
- The radius of curvature of the interface is much larger than δ.
- In the local coordinate system $(s1, s2, \vec{zn})$, with the previous hypothesis and in the conducting material, $\vec{H}$ (resp. $\vec{E}$, $\vec{J}$, $\vec{B}$) decreases with depth according to equation (1):

$$\vec{H}\,(s1, s2, zn) = \vec{Ho}\,(s1, s2)\,\exp\left(-\frac{1+j}{\delta}\,zn\right) \tag{1}$$

The physical meaning of the surface impedance condition is to replace, as in [6], the eddy currents in the metal by a surface current density $\vec{Js}$, given by

$$\vec{Js} = \frac{\sigma\,\delta}{1+j}\,\vec{Eot} \tag{2}$$

in which $\vec{Eot}$ is the tangential electric field on the surface and

$$Zs = \frac{1 + j}{\sigma\delta} \tag{3}$$

is the surface impedance.

The air-metal interface relationship between the tangential fields in the air $\vec{Et}$ and $\vec{Ht}$ becomes:

$$\vec{Et} = Zs\ \vec{Ht} \wedge \vec{n} \tag{4}$$

Relation (4) is introduced in Maxwell's equations. The final result is expressed in air in terms of the total scalar magnetic potential ϕ:

$$\vec{H} = -\vec{grad}\ \phi. \tag{5}$$

The impedance boundary condition is then obtained:

$$\frac{\partial \phi}{\partial n} = \frac{1 + J}{\delta \mu r}\ \phi \tag{6}$$

With this boundary condition at the surface of the metal, Maxwell's equations can be solved outside the conducting parts only.

RESOLUTION BY A BIE METHOD

The total exterior magnetic field $\vec{H}$ is computed in two steps:

$$\vec{H} = \vec{Ho} + \vec{Hi} \tag{7}$$

where $\vec{Hi}$ is the induced magnetic field and $\vec{Ho}$ the magnetic field generated by the eddy current probe alone in the air, without any conducting material. $\vec{Ho}$ is calculated analytically (using Biot-Savart's law for example). Curl $\vec{Hi}$ is zero in the air and $\vec{Hi} = -\vec{grad}\ \phi i$, where ϕi is the induced magnetic potential and $\Delta \phi i = 0$.

ϕi is the unknown function and Laplace's equation, with the surface impedance boundary condition, is solved in 3-D by a classical BIE method (we have implemented the surface impedance boundary condition in the BIE package 'PHI3D' [8] developed in the electrical engineering department of Ecole Centrale de Lyon).

Why do we choose the induced potential as the unknown function? The variation of the magnetic field due to the flaw is very weak. Computing an induced potential instead of a total value gives the best accuracy because the flaw modifies only the induced field.

RESULTS OF THE FIELD COMPUTATION

An example of the results of the field computation obtained to validate the method is presented. The best piece is a steel cylinder (conductivity $10^7\ \Omega^{-1}.m^{-1}$, permeability 100) whose geometry is shown on Fig. 2. The probe is a single turn coil, fed with 10 kHz alternating current, centered on the axis of the cylinder. Two symmetries are used for the 3-D computation. Figure 3 shows the mesh of a quarter of the test piece. This mesh has 115 nodes and 32 second order quadrilateral elements. On each node, the unknown function is the scalar potential ϕi, so that there are as many unknowns as nodes. The result of the comparison between the 3-D computation and an axisymmetric program is shown on Fig. 4, Hn being the normal magnetic field on a radius of the top surface of the cylinder.

The good agreement between the two computations shows that the surface impedance boundary condition, with a BIE resolution, is well adapted to model small skin depth problems and can be used to acknowledge a lot of NDT phenomena.

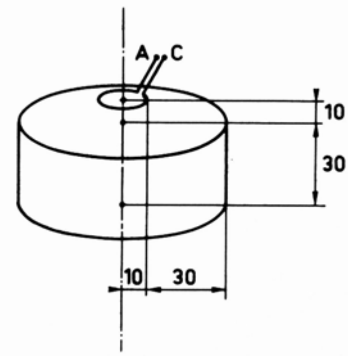

Figure 2. Geometry of the test piece.

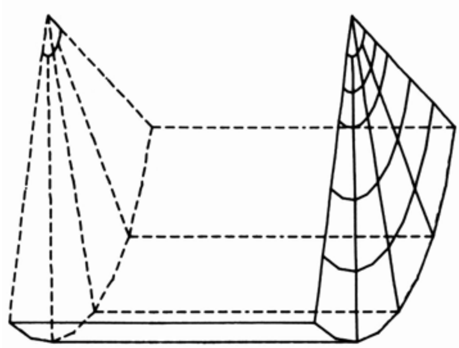

Figure 3. 3-D mesh of a quarter of cylinder.

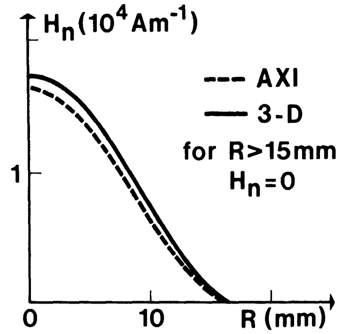

Figure 4. Comparison of 3-D and axisymmetrical results.

ADVANCES IN IMPEDANCE COMPUTATION AND FLAW MODELING

Impedance Computation

Different methods are generally used to compute the probe impedance: energy calculation, theorem of reciprocity, flux calculation. The first method is used by [3 and 5] but it appears to be interesting only when the exterior induced field is zero [3]. With our method, only the energy dissipated in the metal is easy to compute, but it does not lead to impedance values. The theorem of reciprocity will be programmed because it is well adapted to our computation (the impedance is calculated from the values of the fields on the surface of the crack and those values are easy to obtain from our computation). In order to simulate separate functions probes, a flux calculation is essential because the two other methods do not take into account the geometry and the position of the receiver. So the flux calculation is the most interesting way to compute the sensor impedance, but unfortunately, the most expensive in CPU time.

Flaw modeling

The hypothesis of large radius of curvature is not true for corners, flaws or cracks. According to [9], the error due to a corner can be neglected. Figure 5 shows the current lines on a perfect conductor with a flaw, computed with 'phi3d'. For a real crack, we are developing a special crack element to take into account the influence of the crack on the surface of the metal, without computing the magnetic field inside the crack.

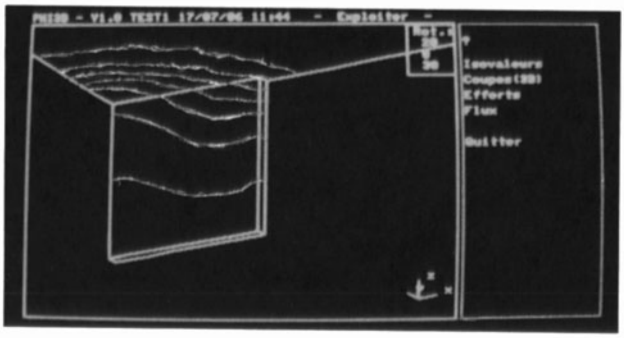

Figure 5. Current lines on a perfect conductor with a flaw.

CONCLUSION

The surface impedance boundary condition has been presented for small skin depth eddy current problems encountered in NDT phenomena. The model was tested and compared to an axisymmetrical program, showing good agreement. Different methods are tested to compute the probe impedance. The flux calculation seems to be the best one to simulate the largest range of sensors, especially separate functions probes. The model will be used on a test object with a crack and compared with experimental data to carry out the model of the crack.

ACKNOWLEDGEMENTS

The authors would like to thank Q. S. Huang and H. Mansir (ECL) for many useful technical discussions and L. Kranbuehl and L. Nicolas (ECL), authors of 'phi3d'.

REFERENCES

1. R. Palanisamy, W. Lord, "Prediction of eddy current probe signal trajectories", IEEE Trans. on Mag., Vol. MAG-16, (September, 1980), 1083-1085.
2. C. V. Dodd, W. E. Deeds, W. G. Spoeri, "Optimizing defect detection in eddy current testing", Material evaluation, (March, 1971), 59-63.
3. N. Burais, A. Foggia, A. Nicolas, J. C. Sabonnadiere, "Electromagnetic field formulation for Eddy Current calculations in non-destructive testing systems", IEEE Trans. on Mag., Vol. MAG-18, (November, 1982), 1058-1061.
4. A. Bossavit, J. C. Verite, "The TRIFOU code: solving the 3-D eddy current problem by using H as state variable", IEEE Trans. on Mag., Vol. MAG-19, (November, 1983), 2465-2470.
5. N. Ida, "Development of a 3-D eddy current model for nondestructive testing phenomena", Review of Progress in Quantitative NDE 3, (Santa Cruz, 1983), 547-554.

6. T. W. Preston, A. B. J. Reece, "Solution for 3 dimensional eddy current problems: the T-O method", IEEE Trans. on Mag., Vol. MAG-18, (March, 1982), 486-491.
7. C. Vassalo, "Electromagnetisme classique dans la matiere", Dunod Universite, (1980), 58-65.
8. L. Kranbuehl, L. Nicolas, A. Nicolas, "A graphic interactive package for boundary integral equations", IEEE Trans. on Mag., Vol. MAG 21, (November, 1985), 2555-2558.
9. S. Ratnajeevan, H. Hoole, C. J. Carpenter, "Surface impedance models for corners and slots", IEEE Trans. on Mag., Vol. MAG-21, (September, 1985), 1841-1843.
10. R. Grimberg, "Modelisation tridimensionnelle en CND par courants de Foucault de defauts de surface", internal report IRSID MCA-SG 965, (Juillet, 1986).
11. R. Grimberg, H. Mansir, J. L. Muller, A. Nicolas, "A surface impedance boundary condition for 3-D nondestructive testing modeling", INTERMAG 1986, IEEE Trans. on Mag., Vol. MAG-22, (Setember, 1986).