

The Depth Limits of Eddy Current Testing for Defects: A Computational Investigation and Smooth-Shaped Defect Synthesis from Finite Element Optimization

T. Mathialakan and V. U. Karthik
Michigan State University

Paramsothy Jayakumar and Ravi Thyagarajan
US Army Tank Automotive

S. Ratnaseevan H. Hoole
Michigan State University

ABSTRACT

This paper presents a computational investigation of the validity of eddy current testing (ECT) for defects embedded in steel using parametrically designed defects. Of particular focus is the depths at which defects can be detected through ECT. Building on this we characterize interior defects by parametrically describing them and then examining the response fields through measurement. Thereby we seek to establish the depth and direction of detectable cracks. As a second step, we match measurements from eddy current excitations to computed fields through finite element optimization. This develops further our previously presented methods of defect characterization. Here rough contours of synthesized shapes are avoided by a novel scheme of averaging neighbor heights rather than using complex Bézier curves, constraints and such like. This avoids the jagged shapes corresponding to mathematically correct but unrealistic synthesized shapes in design and nondestructive evaluation.

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INTRODUCTION

Eddy current testing (ECT) is a widely accepted, cheap and portable method for the detection of cracks and other defects in conductive materials. While ECT is a favorite with engineers for surface defect identification through nondestructive evaluation (NDE), for more deeply embedded defects the literature is not clear. It has been established that low frequency testing can distinguish "all the different levels" of corrosion when a sample is exposed to a very corrosive environment for 3 months [1] while other researchers have established that eddy current testing can identify corrosion to depths down to 15 mm [2, 3]. Submarines and aircraft employ eddy current probes for testing thin (up to 1 inch) conducting systems [4], and ultrasound [5] for thicker submarine hulls [6]. For deeper penetration, pulsed eddy currents [7] or remote field eddy currents are used [8, 9]. ECT Technology is therefore perfect for the purpose at hand.

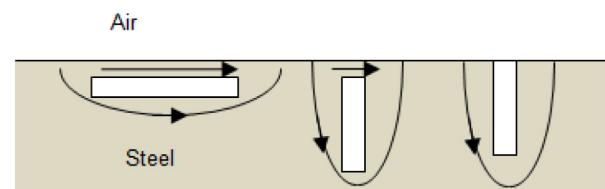


Fig.1. Penetration of Eddy Currents in the Presence of Defects

However, the reality is that, thinking qualitatively about the three situations in Fig.1, the depth for detection depends on defect orientation. In the first, when a defect is parallel to the surface, the defect will be detectable through the interruption of the eddies. In the second situation, it is perpendicular to the surface but not reaching the surface; we would expect the skin-effect to allow the currents to flow along the surface. So it will be hard to detect the defect in the second case. Whereas in the third situation if the defect is perpendicular to the surface without a gap for the eddy current to flow along the surface, the defect would interrupt the flow of eddy currents which would find it difficult to go deep

because of the skin effect. Therefore this will be easily detectable. On the other hand if the defect is thin and long, a 3D model will show no current interruption.

This interruption would make the presence of defects easily detectable. Different types of defect models with the ECT coil are shown in Fig.2. Defects a, b, c, d & e in Fig.2 show the difference in angle, depth and length. Moreover, if the axis of the external exciting ECT coil is parallel to the surface, our considerations need to be entirely different. This study therefore through a series of finite element analyses of parameterized geometries of a single defect, seeks to identify the limits of eddy current testing in NDE. This study is confined to steel plates for army ground vehicle armor. A qualitative relationship between the depth of a detectable defect, the frequency of excitation and the geometric parameters is sought to help engineers choose whether or not to use ECT.

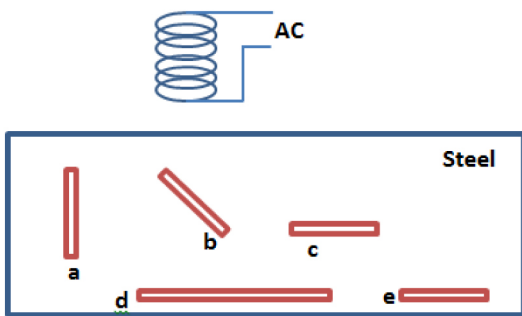


Fig.2. Defect Model: The model has defects in different angle (a, b, c), depth (c, e), and length (d, e).

DETECTION OF DEFECT: FIELD CHANGES

A defect in a material can be varied in shape and location. The defect detection method should concentrate on the characteristics of the defect. These effects are analyzed in this paper for varying size, shape and location of defect in materials. An iterative approach is presented that repeatedly employs the finite element technique for modeling the forward problem to calculate the effect caused by the defects in a steel plate.

We calculate the magnetic field density for the known defects from the forward problem using the finite element method [2] and examine the extent to which the exterior field is altered by the defect to see if the presence of the defect can be discerned through the changes in the measurable external field.

PROBLEM STATEMENT

Magnetic fields in a ferromagnetic material can be generated by placing an AC (Alternative Current) coil on top of the material. For AC magnetization, the vector magnetic potential $\mathbf{A}$, and the exciting current density $\mathbf{J}$ at angular frequency ω , are related by

$$-\nabla \times \frac{1}{\mu} \nabla \times \mathbf{A} = \mathbf{J} - j\omega\sigma\mathbf{A}$$

(1)

where μ is the spatial permeability distribution and σ is the conductivity. The magnetic flux density $\mathbf{B}$ is related to the magnetic vector potential as,

$$\nabla \times \mathbf{A} = \mathbf{B} \quad (2)$$

In two dimensional problems, the current density $\mathbf{J}$ and the magnetic vector potential $\mathbf{A}$ will be in the $\hat{z}$ direction (i.e. the transverse direction in which no changes occur). Therefore the magnetic field density $\mathbf{B}$ will be in the $\hat{x}$ and $\hat{y}$ directions. From (1) and (2) we can write,

$$\frac{\partial}{\partial x} \left(\frac{\partial \mathbf{A}}{\mu \partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\partial \mathbf{A}}{\mu \partial y} \right) + \mathbf{J} = 0 \quad (3)$$

Finite element analysis [10] provides the solution to (1) by applying certain boundary conditions. This leads to the finite element matrix equation

$$[\mathbf{P}]\{\mathbf{A}\} = \{\mathbf{R}\} \quad (4)$$

where $[\mathbf{P}]$ is the finite element stiffness matrix and $\{\mathbf{R}\}$ is a column vector.

Any defect in the material should affect the magnetic field density $\mathbf{B}$ between the AC coil and the material. The magnetic field $\mathbf{B}$ is calculated at a line called the measuring line which is divided into m points. The effect in $\mathbf{B}$ caused by the defect for the m measuring points can be calculated using the expression

$$R_{(\theta,d,l)}^B = \max_{i=0..m} \left(\left| \frac{B_{nodefect}^i - B_{defect}^i}{B_{nodefect}^i} \right| \right) \quad (5)$$

$R_{(\theta,d,l)}^B$ is the maximum value of flux ratio between flux changes and flux without the defect, where a defect with length l is at depth d from the material surface and rotated by angle θ clock-wise from the “horizontal” line parallel to the steel surface.

METHODOLOGY

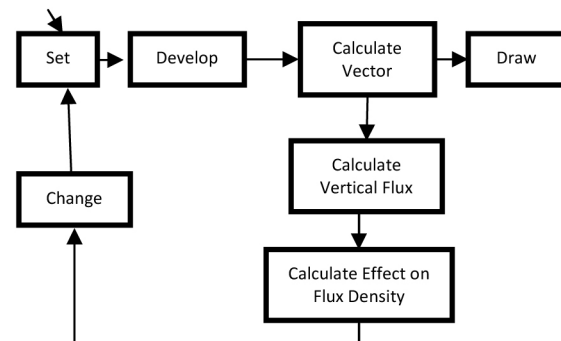


Fig.3. Design Cycle for the computation process

The computational process in the defect identification system is shown in Fig.3. It calculates the effect on the flux density for different kinds of defect that vary in their characteristics: depth (d), angle (θ) and length (l). The characteristics of a defect are the changing parameters in each calculation of the above computational process. In the latter part of our work, we extend this model for design optimization. Mesh generation is a very important part of finite element analysis based design optimization. We need to use a parameter based mesh generator, because in each iteration the mesh has to be generated automatically when design parameters change. Therefore we use a special script-based parametric mesh generator [11] using as backend the single problem mesh generator Triangle [12] to get the corresponding finite element solution for the magnetic vector potential $\mathbf{A}$. Then from $\mathbf{A}$, we compute the magnetic field density $\mathbf{B}$. From $\mathbf{B}$ we calculate the effect on the flux density $R_{(\theta,d,l)}^B$. In each iteration, the electric field map is also generated and analyzed visually.

APPLICATION

The numerical example in Fig.4 is used to validate the proposed algorithm. The coil (with $\mu_r = 1.0$, current density $J = \pm 1 \text{ A/m}^2$, and $\omega = 10 \text{ rad/s}$) excites the magnetic field in the steel plate (with $\mu_r = 100.0$ and current density $J = 0.0$). The conductor is surrounded by air (with $\mu_r = 1.0$ and current density $J = 0.0$). The magnetic field density in the $\hat{y}$ direction B_y is calculated at 10 points as shown in Fig.4. labeled as the measuring line.

First, B_y for the steel plate with no defect is calculated at the measuring line and named $B_{\text{no defect}}$. Since our study is about whether the defect is detectable or not, we defined a single defect with parameterized geometries $\{x, d, l, w, \theta\}$ (Fig.4.).

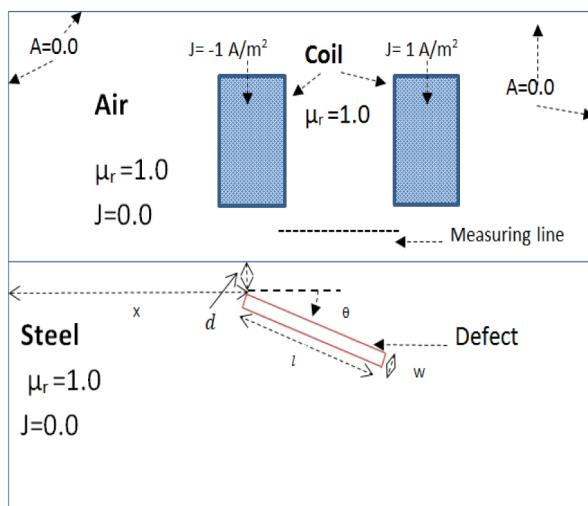
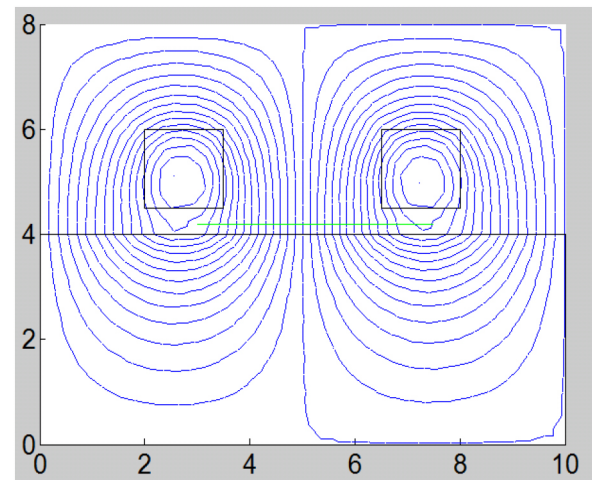
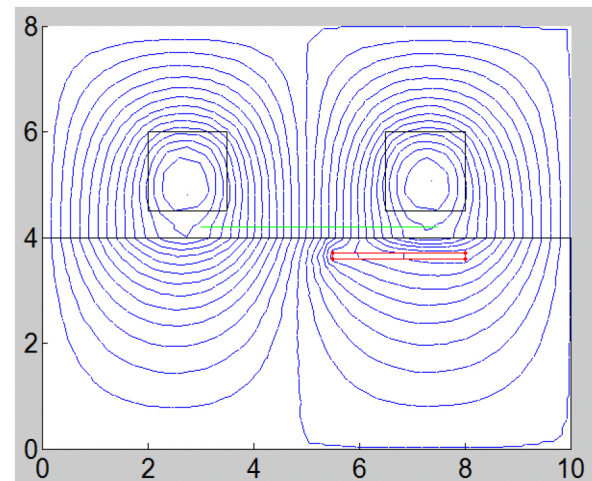


Fig.4. Numerical Model

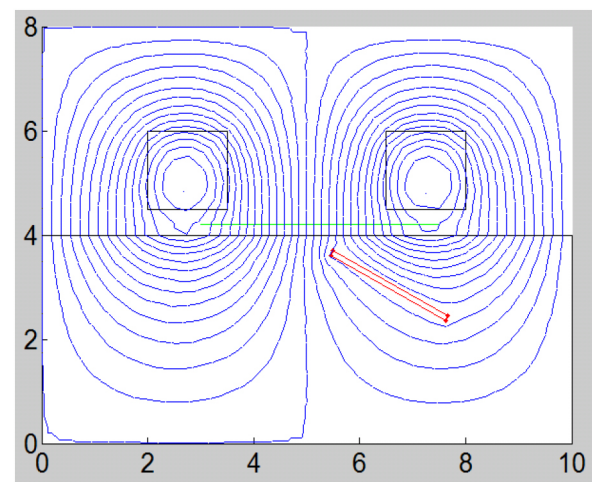
By changing the parameters of the defect, we change the position of the defect as shown in Fig.5. and calculate B_y at the measuring points, which we name B_{defect} . Then the effect on flux density $R_{(\theta,d,l)}^B$ was calculated for each defect and tabulated. By considering the maximum of R , we establish the defect detecting quantity which is measured.



a. No defect



b. $d = 0.3$ and $\theta = 0^\circ$



c. $d = 0.3$ and $\theta = 30^\circ$

Fig.5. Equipotential lines for the defects at various positions