EDDY CURRENT EVALUATION OF FLAWS IN COATED CONDUCTORS

A. Ptchelintsev and B. de Halleux
Catholic University of Louvain
B-1348, Louvain-la-Neuve, Belgium

D. Degreve
Laborelec
B-1630, Linkebeek, Belgium

INTRODUCTION

Thermal protective coatings find an increasing demand in industry. They are currently used in power generating combustion turbine engines, allowing to rise up significantly the operating temperatures. We report results of an exploratory study, developing a technique, allowing to evaluate the magnitude of a flaws in coated conductor surface from a change in the electrical impedance of an eddy current coil. A theoretical solution is based on the finite difference method (FDM) for the two dimensional vector magnetic potential and electric potential around a coated conductive half space with a long surface breaking crack. The diffusion equation was solved by decomposing the coil field by plane waves and taking into account only the main frequency in the coil spatial frequency spectrum. In order to verify obtained results, experimental modeling was carried out. A set of austenitic stainless steel samples electroplated with 60 and 100 μm tin coatings, containing EDM notches of varying depth from 0 up to 600 μm, was manufactured. The specimens were studied experimentally in the frequency range 100-500 kHz using rectangular shape air core surface coils. Comparison between the experiment and theoretical predictions is given.

SPATIAL FREQUENCY ANALYSIS TO PREDICT THE COIL IMPEDANCE

For a surface coil placed over an unflawed planar conductor the following formula for the normalized electrical impedance can be used [1, 2]:

\[
\frac{Z}{Z_{\text{air}}} = \frac{j\omega \mu_0 \int_0^\infty \psi(\alpha) B_1 e^{-2\alpha l_1} \, d\alpha}{j\omega \mu_0 \int_0^\infty \psi(\alpha) \, d\alpha},
\]

where \( \mu_0 \) is the permeability of vacuum, \( B_1 \) is the coefficient depending on boundary conditions, \( l_1 \) is the coil liftoff, and \( \psi(\alpha) \) is the coil function. For a rectangular surface coil with a large length-to-width ratio (which can be approximated by a two-conductor line model), \( \psi(\alpha) \) is represented [2]
where $y_1$ and $y_2$ are the turns spatial limits in the transversal direction. A similar formula can be obtained for the circular surface coil. Formula (1) works very well for rectangular coils with a length-to-width ratio greater than 5. The coil function for a rectangular coil $y_1=1$ mm, $y_2=2.5$ mm, is given in Figure 1a. In practice to evaluate formula (1), integrals are computed by sums:

$$Z = \frac{Z_{air}}{\alpha_{cutoff} \sum_0^\infty \psi(\alpha) B_1 e^{-2\alpha l}},$$

(3)

where $\alpha_{cutoff}$ is the cutoff spatial frequency, which can be taken equal to the main lobe limit. Sums in formula (3) can be computed with 5 percent errors in comparison with integral formula (1) using as few as 10 terms within the main lobe (Figure 1b), and even a single term associated with the main spatial frequency $\alpha_{max}$, gives a relatively good approximation.

If the crack is perpendicular to the coil long side and its length is greater than the coil width, one has to solve a problem of the coil above an infinite length surface breaking crack. Rectangular coils with a large length-to-width ratio (about 6-10 in practice) being approximated with excellent accuracy by the two-conductor line theoretical model [3], allow easier solution in comparison with common pancake coils. The solution is obtained carrying out the Fourier transform, and analyzing the interaction of a plane wave of the spatial frequency $\alpha$ with a conductor. Let us regard a rectangular coil placed above a flawed conductive specimen (Figure 2), the flaw representing a long surface breaking crack. In general, two trajectories of induced currents are possible, both shown in Figure 2 by dotted lines. If the crack depth is relatively small, the $z$-component of eddy currents can be taken to be zero ($I_z=0$). In this case the problem can be described by the two dimensional vector potential

![Fig. 1](image)

Fig. 1. a) Spatial frequency spectrum of two-conductor line $y_1=1$ mm, $y_2=2.5$ mm; b) corresponding normalized impedance diagram calculated with 500, 30, 20, 10 terms in the...
coil spatial spectrum and using single term $\alpha_{\text{max}}$, (half space $\sigma=0.9$ MS/m coated with a 0-150 $\mu$m thick layers $\sigma=1.5$ MS/m, $\mu_r=100$).

Fig. 2. A rectangular surface coil above a flawed conductive medium.

$A \{A_x(z), A_y(z) \}$ and the scalar electric potential $\phi(z)$. Performing the Fourier transform over the $z$-coordinate, and determining interactions of plane waves of the coil spatial spectrum with an infinitely long flaw, the coil response can be evaluated. Approximately, the coil electrical impedance variation $\Delta Z$ can be evaluated taking into account the main spatial frequency $\alpha_{\text{max}}$ only.

FORMULATION AND BOUNDARY CONDITIONS

Eddy current modeling in 3D is a very involved task both from the point of view of the memory (RAM) requirements and computational time. On the other hand the 2D models can be easily handled by a personal computer with a solution time of a few minutes. It seems to be practical developing a simple 2D eddy current model allowing the evaluation of the coil response in order to reduce the computational cost and make an easy inversion of eddy current data. Carrying out the Fourier transform of the potentials and boundary conditions over the $z$-coordinate $\bar{F} = \int Fe^{-j\omega z}dz$ gives the basic equations in the form:

in the air

$$\frac{\partial^2 A_x}{\partial x^2} + \frac{\partial^2 A_y}{\partial y^2} - \alpha^2 A = 0 \quad (4)$$

in the conductor

$$\frac{\partial^2 A_x}{\partial x^2} + \frac{\partial^2 A_y}{\partial y^2} - (\alpha^2 + j\omega\mu)A - j\omega\mu\nabla\phi = 0 \quad (5)$$

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \quad (6)$$

where $A$ and $\phi$ are defined as follows $B = \nabla \times A$, with $B$ being the vector magnetic induction, and $E = -j\omega(A + \nabla\phi)$, with $E$ being the vector electric field.

On boundaries one can chose to work with continuous or discontinuous functions. Working with continuous potentials $A$ and $\phi$ (i.e. $A_{x1}=A_{x2}, A_{y1}=A_{y2}$ and $\phi_1=\phi_2$ on boundaries) is more convenient in practice, for in this case $E_{x1}=E_{x2}$ is always satisfied, due to the vector electric field definition $E = -j\omega(A + \nabla\phi)$. The condition of conservation of the $B_n$ is also automatically satisfied, and condition of conservation of $H$, for non magnetic materials is
\[
\frac{\partial A_{x1}}{\partial y} = \frac{\partial A_{x2}}{\partial y} - \mu_0 I_x, \text{ and } \frac{\partial A_{y1}}{\partial x} = \frac{\partial A_{y2}}{\partial x}
\] (7)

for horizontal and vertical boundaries respectively, where \(I_x\) is the x-component of the excitation current. Condition of continuity of the vector current density \(J_{n1} = J_{n2}\) is:

\[
\sigma_{1}(A_{n1} + \nabla \varphi_{n1}) = \sigma_{2}(A_{n2} + \nabla \varphi_{n2}).
\] (8)

We must also specify global boundary conditions on potentials \(A\) and \(\varphi\). We require \(J_{y}=0\) and \(\partial J_{x} / \partial x = 0\) on vertical boundaries, and \(J_{x}=J_{y}=0\) on horizontal boundaries. In terms of the \(A\)-\(\varphi\) formulation that means: \(A_{y}=0\), \(\partial A_{x} / \partial x = 0\) and \(\nabla \varphi=0\) on vertical boundaries, and \(A_{x}=A_{y}=0\) and \(\nabla \varphi=0\) on horizontal boundaries. The induced voltage and the electrical impedance of the coil, are respectively

\[
U = -j \omega n^2 \int A \, dl, \tag{9}
\]
\[
Z = -\frac{j \omega n^2}{I} \int A \, dl, \tag{10}
\]

where \(n\) is the number of turns, and \(I\) is the excitation current.

**EXPERIMENT**

In order to verify the physical model, experiments on 80\(\times\)50\(\times\)4 mm\(^3\) stainless steel plates with the conductivity \(\sigma=1\) MS/m, containing EDM notches, were carried out. One of the samples was uncoated, and two others were electroplated with tin coatings with the conductivity \(\sigma=7\) MS/m of about 60 and 100 \(\mu\)m thickness. The EDM notches of 0.1±0.02 mm width were produced along the largest face of the samples. The notches have had a depth varying near linearly from 0 up to 600 \(\mu\)m (Figure 3). The impedance measurements were taken at 100-500 kHz with a Hewlett Packard HP4549 digital impedance meter. A rectangular surface coil was manufactured whose dimensions and electrical parameters are given in Table I. The coil was connected to the digital impedance meter via a one meter length cable. Eddy current linear scans (the resistance and inductance profiles) carried out moving the coil across the EDM notches, are given in Figure 4. Linear scans and liftoff variation curves were performed using a three-axis scanner driven by a PC. Coils were fastened using non conductive holders with springs to avoid excessive liftoff variations. In the plots (Figure 4) together with

![Fig. 3. Schematic view of a coated stainless steel sample containing an EDM notch.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Coil A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of turns</td>
<td>147</td>
</tr>
<tr>
<td>Coil core size</td>
<td>1x6</td>
</tr>
<tr>
<td>Residual liftoff</td>
<td>0.7</td>
</tr>
<tr>
<td>Inductance in air*</td>
<td>124.4</td>
</tr>
<tr>
<td>Resistance in air*</td>
<td>16.18</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>5.128</td>
</tr>
</tbody>
</table>

* at 200 kHz
Fig. 4. Electrical impedance profiles for the coil moving across a long EDM notch in: a) uncoated sample; b) 60 μm tin coated; c) 100 μm tin coated
signal variations corresponding to notches, one can see also the coil liftoff variation, for coated samples were imperfect and rough (Ra=10-20 μm). Using obtained LR data and equalizing the liftoff level, the normalized impedance diagram were obtained. In Figure 5 experimental series related to the liftoff variation on the three samples (uncoated and coated with 60 and 100 μm tin), and experimental flaw signatures obtained on these samples on 500 μm deep notches, are given. A theoretical data series corresponding to the coating thickness variation computed using integral formula (1) (tin σ=7MS/m, 10 μm thickness variation, liftoff = 0.67 mm) is also shown. On the other hand theoretical predictions obtained using the αmax only in the coil spatial spectrum, related to the coil liftoff, the coating thickness variation and the 500 μm surface breaking notches in coated conductors, are given. Despite significant discrepancies between experimental data and theoretical ‘one term’ predictions, the 500 μm flaw responses are very similar. To show the satisfactory quantitative agreement, the experimental flaw signatures and corresponding predictions are shown in ΔL vs. ΔR diagram (Figure 6). In fact EDM notches were produced with a tungsten wire electrode, so that actual depths can be lower than expected due to the wire tension. Errors due to the approximate character of the model should not exceed 20 percent, comparing results of the full integral and ‘one term’ αmax calculation for non flawed coated conductors.

In conclusion, the discussed model can be used for quantitative NDE of coated components. Further work will concern an increase of the calculation speed, which can be done using an efficient method as conjugate gradients’ in conjunction with finite element methods. On the other hand, using the A-φ-ψ formulation of the problem the memory requirements and the computation time can be reduced.

Fig. 5. Theoretical and experimental normalized impedance diagram.
Fig. 6. Theoretical predictions for 0-500 µm surface breaking flaw in coated stainless steel samples and experimental flaw signatures (200 kHz).

REFERENCES

