Excerpt from the Proceedings of the COMSOL Conference 2010 Boston

COMSOL Multiphysics Modeling for Design Optimization of Eddy Current Crack Detectors

Evan Weststrate, Mark Steinback, Noa M. Rensing* and Timothy Tiernan
Radiation Monitoring Devices, Inc
*Corresponding author: 44 Hunt Street, Watertown MA 02472, NRensing@RMDInc.com

Abstract: Passing alternating current through a wire placed just above a conducting material induces eddy currents at the surface of the conductor. Any surface cracks in the conductor modify the eddy current distribution, creating a magnetic field signature unique to the crack. The magnitude of the signal depends on the amplitude of the current in the wire, the proximity and relative alignment of the sensor to the crack, and the position of the crack relative to the “no-crack” eddy current distribution. Optimization of the wire/sensor probe must also take into account the heat generated in the wire. The geometry of the probe must allow both the wire and the sensor to be as close to the surface and the crack as possible. We developed COMSOL models to optimize the design of eddy current probes for crack detection under a variety of test object geometries.

Keywords: Eddy current testing, crack detection, induced current.

1. Introduction

Eddy current testing is used to detect cracks in conductive materials. Typically, a coil of wire is placed above the surface to be tested, with the axis of the coil normal to the plane of the material, and an alternating current is passed through the coil. The current in the coil creates magnetic fields, which induce eddy currents in the conducting material. These eddy currents in turn create their own magnetic field. The total magnetic field can be detected by placing a coil above the surface, typically concentric with the drive coil, and the magnetic field contribution of the eddy currents determined by comparison with a reference sample. The influence of the eddy currents may also be inferred by detecting changes in the impedance of the drive coil itself. This single coil configuration simplifies the measurement system but does not allow for the drive coil to be optimized separately from the pickup coil.

If there is a crack or similar imperfection in the conducting material, it may disrupt the path of the eddy current flow. This then modifies the distribution of magnetic field from the usual pattern and can therefore be detected as a change in the signal in the pickup coil. In particular, the amount of flux that couples into the pickup coil depends on whether the coils are near the crack or further from it, so the signal in the pickup coil changes as the coils are scanned over the surface. This method is routinely used to find cracks in critical structural components (**Figure 1**).

In the absence of a crack, the cylindrical symmetry of the system means that the in-plane magnetic field at the center of the coil is identically zero, as is the tangential field everywhere. When the eddy currents are forced

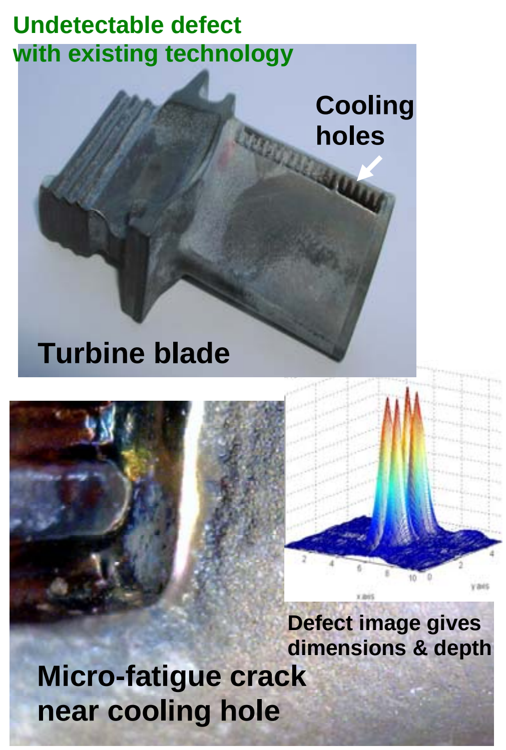

Figure 1: Eddy current method for detecting cracks in jet engine turbine blades.

to flow around a crack or similar imperfection, the symmetry is broken, and there may be additional in-plane components of the field, including tangential field or appreciable field at the center of the drive coil.

RMD has developed magnetic field sensors based on the anisotropic magnetoresistive effect (AMR). These miniature sensors are fabricated photolithographically and are potentially both significantly smaller and dramatically less expensive than wire wound sensing coils. Unlike coils, the sensors are sensitive to magnetic field magnitude rather than to the flux enclosed by a loop, so they do not lose sensitivity as they get smaller.

The strength of the signal associated with the crack depends on the amplitude and frequency of the drive current, the material properties of the sample, the size of the crack, and the diameter of the drive coil. In the cases where a coil is used for pickup, larger coils have an advantage in enclosing more magnetic flux. However, an AMR sensor is sensitive to the local magnetic field, so larger coils offer no advantage. Furthermore, additional windings to the drive coil may not increase the signal, since they are not used for pickup and the eddy currents associated with them might be far from the crack. Furthermore the additional windings can degrade performance by dissipating heat. Optimizing a system containing an AMR sensor is different from optimizing a traditional coil based system. We developed a COMSOL model to map the magnetic field distribution from various combination of drive coil design, crack sizes, induction frequencies, and materials to optimize the design of AMR sensor based crack detection systems.

2. COMSOL Model

We first developed a COMSOL model of the basic geometry. While the drive coil and the eddy currents in the substrate can be modeled using a 2D axi-symmetric model, introducing a crack breaks the symmetry and requires full 3D modeling. For 3D modeling, we used a DELL Optiplex workstation with dual quad-core processors and up to 72 GB of RAM. The work presented here utilized the AC/DC module in COMSOL 3.5a and 4.0. The geometry is challenging to model for finite element calculations. The skin depth of the eddy currents and the physical size of the crack are very small, on the scale of tens of micrometers, while the coil is meso scale, up to several mm in diameter, and the air space around the system and the substrate must be large enough to allow the fields to decay smoothly to zero.

The multi-turn drive coil was modeled as a square cross section torus with a uniform current distribution. To obtain the best field uniformity, we chose to use a swept mesh for the coil. The substrate was divided into several domains to provide additional control over the mesh size while managing memory and CPU load. To provide adequate mesh resolution at the surface, where the eddy currents flow as well as in the vicinity of the crack, the crack was meshed first with a suitably fine element size. The top surface of the substrate was then meshed, with the element size allowed to grow rapidly from the crack to the edge of the substrate. This surface mesh was then swept through the substrate to allow fine layers near the surface and coarser ones at the bottom.

The results of the initial COMSOL models are shown in **Figure 2**. The top image visualizes the mesh, and the bottom image shows the eddy currents in a plane around the crack. Note that the mesh is fairly coarse relative to the size of the crack and the spacing between the coil and the substrate. In spite of this, however, the model utilized most of the available memory and further refinement of the mesh was not practical.

From the bottom image it is clear that, as expected, the flow of the eddy currents is generally tangential except within a few skin depths of the crack, where the current flows around it. This deviation in the current direction creates in-plane components of the magnetic field.

3. Optimization of a Constrained Geometry Coil

In eddy current crack detection, the induced current in the metal test sample needs to be maximized to cause detectable perturbed currents due to defects. The model described here is a multi-turn coil with an AMR sensor at the tip and orthogonal to the coil axis. The application required a rounded tip construction. Because of the geometry constraints, the coil can not be ideally close to the test sample. This investigation is about the tradeoff of effectiveness vs. heat generated as the number of windings increase. The profile of induced current density [**Figure 3**] contributes to the effectiveness of the eddy current sensor, while too much heat generated in the coil [**Figure 4**] causes coil failure.

In the COMSOL model, the resistive heat generated was fixed at a constant value (Q) for the copper coil volume. The AC coil current was normalized to this constant Q for different winding configurations from one winding to a maximum of twenty windings. For instance, more than half ($1/\sqrt{2}$ at first approximation) of the current can be driven through two windings as is driven through one winding to get the same resistive heating. Therefore, the induced current in the sample is increased with two windings because the total current passing over any given point in the sample is greater. As the number of windings increased, this relationship becomes more complex because of secondary effects such as skin depth and proximity effects, phenomena which the model accounts for. This resulted in more coil resistance as the number and cross sectional area of the windings increased. As windings were added further and further away from the test sample, they were less effective, and a peak could be seen in the data [**Figure 5**]. Three wire sizes were tested: 36AWG, 39AWG, and 42 AWG. As shown in the plot, an optimum number of windings could be found that kept the heat generated at the maximum Q. Interestingly, the peak with each wire size occurred when the windings were stacked up to the same distance from the test sample, approximately 5mm. Smaller gauge wires allowed more windings within the same distance.

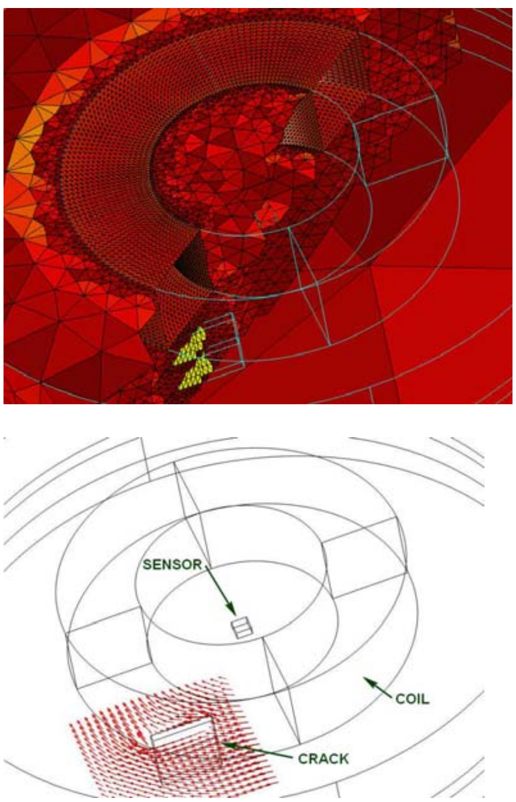

Figure 2: COMSOL model of eddy currents around a crack. (Top) Mesh used for calculations (Bottom) Eddy current in a plane of the substrate around the crack.

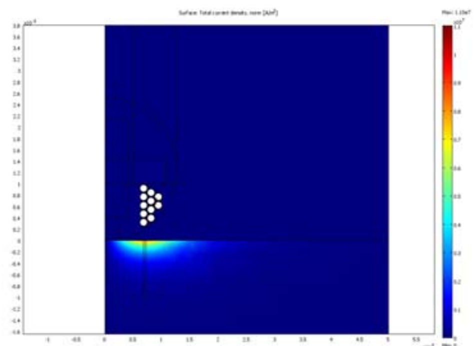

Figure 3: Current density in the test sample

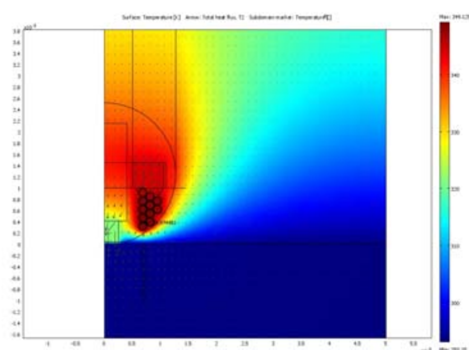

Figure 4: Thermal model

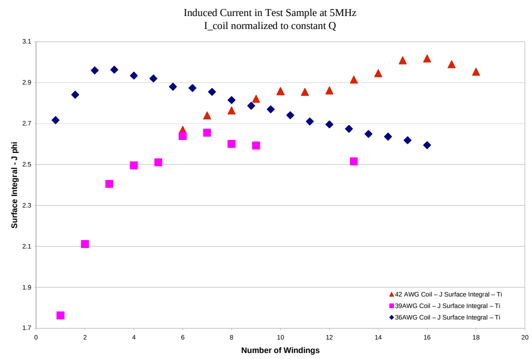

Figure 5: Induced current in test sample as a function of number of windings in the drive coil while keeping the heat generated in the drive coil constant.

Using COMSOL Multiphysics, the thermal model was added to simulate the heat dissipation, thereby providing a tool to help reduce the peak temperature in the coil.

6. Conclusions

The use of FEA electromagnetic analysis in evaluating unique eddy current sensor systems greatly improves the analytical capability and visualization needed to understand and optimize these systems. In addition, including a thermal heating result and coupling it as part of a study of the typical major constraints in a coil/sensor design as shown here has proved to be a valuable tool in the design process.

7. Acknowledgements

The work presented here was supported by NAVAIR contract N68335-08-C-0357.