Maximizing the Fatigue Crack Response in Surface Eddy Current Inspections of Aircraft Structures

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Abstract: Detection of fatigue cracking in metallic aerospace structures relies on capable and efficient eddy current inspection procedures. For best results, inspections with surface scanning eddy current techniques are following rigorous procedures that indicate the instrument settings, probe type and configuration. Parametric numerical simulations are representing great tools for optimizing these types of inspections, can considerably decrease the resources dedicated to procedure development and enhance the interpretation of the scans. In this study, the crack length with respect to the coil diameter, the crack orientation along the scanning direction, as well as the crack depth are investigated in order to observe the optimal eddy current inspection arrangement. Through limited empirical investigations, agreement between experimental findings and COMSOL simulations is sought.

Keywords: eddy current inspection, non-destructive testing, defect detection

1. Introduction

The eddy current technique is one of the mainstream applications of non-destructive testing (NDT) for the inspection of metallic components and structures [1]. According to Faraday's law of induction eddy currents are generated in an electrically conductive part by applying a time-varying magnetic field,. Normally, the generating source is a coil, and is regarded as a primary component of magnetic field, while the induced eddy currents in the part represent the secondary, and their field opposes the primary one, as indicated by Lenz' rule. The presence of discontinuities, such as fatigue cracks, corrosion, geometrical or material changes are disrupting the uniformity of the eddy current flow and the secondary magnetic field, producing in this way signal indications that are interpreted accordingly.

Due to the fact that eddy current physics is described by a diffusion equation (rather than a wave-one, as is the case of the ultrasonic inspections, for example) the technique requires specialized expertise for application and data interpretation. The diffusion equation defining the eddy currents flow is derived from Maxwell's equations and written in terms of the magnetic vector potential, **A**:

$$\nabla^2 \boldsymbol{A} - \mu \cdot \sigma \frac{\partial \boldsymbol{A}}{\partial t} = -\mu \boldsymbol{J}$$

where μ is the magnetic permeability, σ is the electrical conductivity, and **J** is the source current.

NDT inspectors need to localize and size cracks based on the eddy current signal features. For example, peak locations are used to estimate the crack tip, while the signal amplitude and the phase are related to the crack volume and depth, respectively.

The problem analyzed herein represents a case frequently encountered in surface scanning eddy current NDT for fatigue cracks. Since in the majority of inspections performed on airframes, the fatigue cracks are starting from the fastener holes, due to local stress concentrations or non-homogeneities in the structure, as a result of riveting or hole drilling processes. In this work, only the crack (in the absence of the rivet hole) interaction with an absolute eddy current coil is analyzed and discussed, as based on experimental and computational results. The wide acceptance of finite element modeling, bolstered by increased computation capabilities, creates opportunities to understand certain inspection situations and parameters that help with probe design, inspection optimization, and data interpretation.

2. Experimental Results

The eddy current technique is expected to respond to discontinuities that are hindering the flow of the currents induced in the conductive test piece. It is obvious that the highest response is expected when a crack-like discontinuity is oriented along the radial direction of a circular coil. Other orientations of the crack are providing indications of smaller amplitude, but highly influenced by the crack length and depth, introducing additional challenges in interpreting the inspection outcomes. Moreover, the crack length with respect to the excitation coil diameter is seen as a factor that affects the sizing of the defect. This study is addressing exactly these concerns.

2.1 Experimental setup

The experimental study investigated the interaction between an eddy current coil and electrical discharge machined notches in a 1 mm thick, 2024-T3 aluminum alloy of an electrical conductivity of 1.9575 x 10^7 S/m. The coil contained 96 turns of copper wire (AWG #36), had an outer radius of 3.2 mm, an inner radius of 2.2 mm, and a height of 1.9 mm. The coil used in the experimental measurements had a resistance of 3.64 Ω and an inductance of 33 μH when in air. The coil was voltage-driven with a sinusoidal waveform of 5 V amplitude and 25 kHz frequency, while the output voltage signal was read across a 1 Ω resistor in series with the coil. The coil distance from the plate, *i.e* the lift-off value, was maintained at 0.9 mm throughout all experiments. The notches introduced in the Al specimens had the same width, of 0.2 mm, but different lengths, of 2, 4, and 6 mm, while they were penetrating through the entire thickness of the plates. In the laboratory tests, the coil was moved along the scanning line, as shown in Figure 1, with a step of 0.2 mm.

The skin depth equation indicates the depth in the material, δ, at which the magnetic field intensity decreases by 37% of its value at the surface of the plate, as a function of the material properties and probing frequency, f.

$$\delta = 1/\sqrt{\pi \cdot \mu \cdot \sigma \cdot f}$$

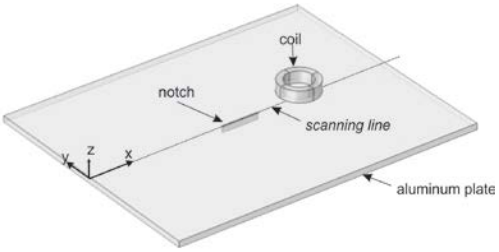

Figure 1. Schematic representation of one of the testing arrangements.

For the aluminum plate and the frequency used in this study, the skin depth was found to be 0.72 mm. It is generally accepted that the eddy current technique can probe to a depth of about three times the standard skin depth.

2.2 Experimental results

As the coil is moved along the scanning line and interacts with the test object, its inductance changes when the eddy current flow is diverted by an air-filled, non-conductive crack. Figure 2 shows plots of the voltage read across a resistance in series with the coil, for notches of 2, 4, and 6 mm length. The coil position is changed, while the notch-containing Al plate is kept stationary. It is observed, that in all cases, the signal presents a double-peak feature, and its amplitude increases with increasing the notch length.

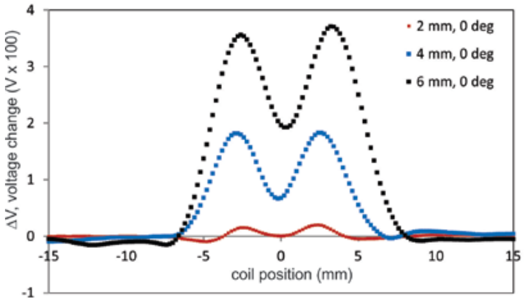

Figure 2. Voltage change across a 1 Ω resistance in series with the coil for different notch lengths.

In the second set of experiments the orientation of the 6 mm long notch was changed with respect to the coil movement, and the line scanning results are shown in Figure 3. When the notch makes a 45° with the scanning line, it still presents a double-peak feature, but of a smaller amplitude. This observation suggests the eddy current notch result may be misinterpreted as a defect of smaller length. When the notch was oriented perpendicularly to the scanning line of the coil, the response shows only a single peak, a feature that could be used in signal interpretations.

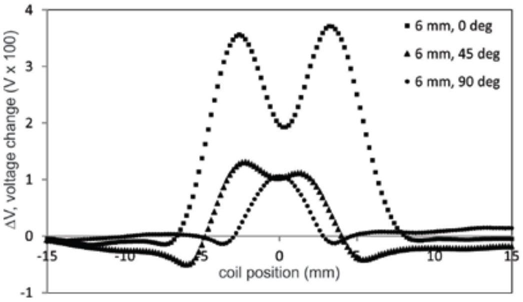

Figure 3. Voltage change across a 1 Ω resistance in series with the coil for different orientations of the 6 mm notch.

3. Numerical Model

The numerical model replicated the coil geometry and parameters, as well as the inspected notch-containing Al plates described in section 2.1. While the empirical results were used for qualitative validation of the simulations, additional defect parameters, such as the notch length and depth were investigated via modeling.

3.1 Model definition

The simulations were performed in COMSOL Multiphysics (version 4.4), employing the AC/DC module and a Frequency Domain study. An absolute multi-turn coil was driven by a harmonic voltage and it is moved above a defect (*i.e.* notch) present in a conductive test piece, such as a thin aluminum plate. It is known that the changes in the coil inductance and resistance are indicative of the defect presence [2,3]. The overall dimensions of the plate were 50 mm long, 40 mm wide and 1 mm thick, placed in an air box that was 120 mm long, 100 mm wide and 60 mm high, with 10 mm thick domains where infinite elements were defined. Automated physics-based meshing with *finer* element size provided at least two elements across the plate thickness. The same properties as the surrounding air were assigned to the crack domain [2].

The simulations were performed on a desktop computer having an Intel Xeon E5 processor, 64 GB of RAM, and a speed of 3.2 GHz. For a single coil location, the computation time was approximately 60 seconds.

3.2 Numerical results

The model examines the crack orientation with respect to the coil scanning direction (90^o, 45^o, and 0^o), the crack length with respect to the coil diameter, as well as the crack depth location within the conductive plate thickness. For exemplification purposes, Figure 4 shows the magnetic field (color map), the induced eddy currents (gray cone arrows) and the excitation current through the coil (black arrows) when the eddy current coil is centered at 3 mm away from the middle of the 6 mm notch, along the scanning line (x-axis in Figure 1.) As it can be seen from the eddy current-generated magnetic field map, the interaction is strongest when the coil is approaching the notch on a radial direction and the weakest when the notch is oriented tangentially with respect to the current flow.

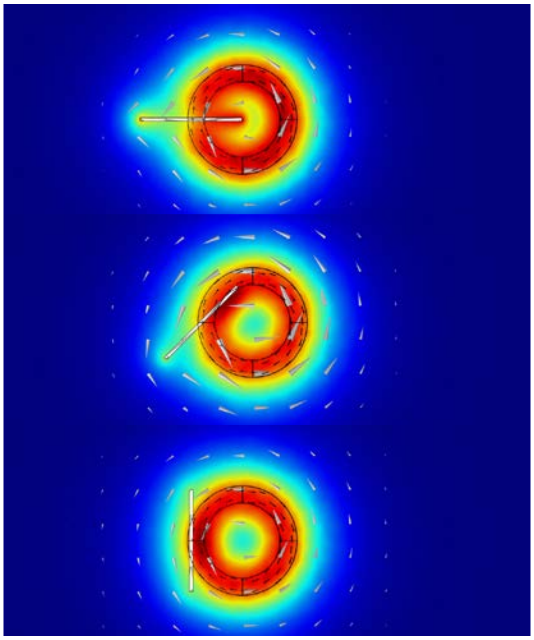

Figure 4. Representation of the magnetic field, applied and induced currents when the coil interacts with the notch at different orientations.

The change of the coil inductance, as the coil is moved over the crack was used for displaying and analyzing the results along the scanning line. A parametric study over the coil position, with an incremental step of 0.5 mm was used for this purpose. Although in the experimental part, the voltage amplitude across a series resistance was monitored, the measured and modelled quantities are related and provide a good basis for qualitative agreement.

The variation of the coil inductance along the scanning line, when the notch length was varied is shown in Figure 5. As expected, both the signal amplitude and peak-to-peak distance increase with the notch length. This result is very similar to the experimental one presented in Figure 2.

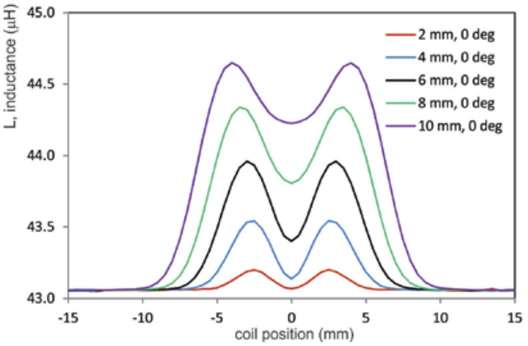

Figure 5. Inductance variation along notches of various lengths.

The inductance values of the coil along the scanning line for the 6 mm notch at 0^o, 45^o, and 90^o orientations are plotted in Figure 6. The signals are displaying exactly the same features as the empirically obtained ones, seen in Figure 3.

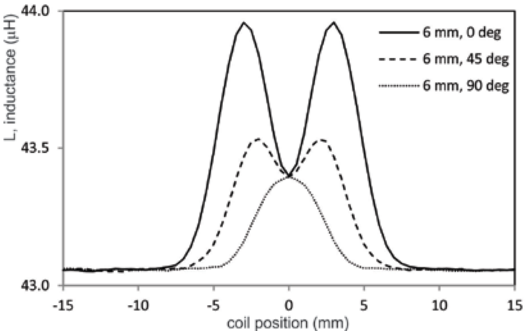

Figure 6. Inductance variation for different orientations of the 6 mm notch.

While in many practical instances it may happen that the fatigue cracks do not penetrate 100% through the structural layer, the outcomes of the 6 mm notch were simulated, but this time the notch had a height of only 50% of the plate thickness. The defect was placed in three locations: opened to the top surface, opened to the bottom surface, and symmetrically embedded in the center of the Al layer. Figure 7 shows the inductance variation obtained through parametric studies after the coil position. According to the obtained value for the skin depth, the eddy currents should have a significant intensity to the back side of the 1 mm thick Al plate. The results shown in Figure 7 indicate that deeper the defect, more difficult it is to obtain a signal of an amplitude that would clearly indicate its presence.

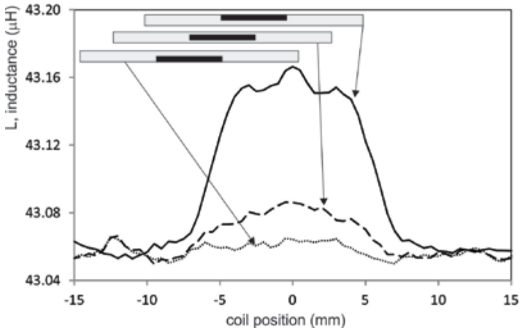

Figure 7. Inductance variation for a 6 mm notch of 50% plate thickness at different depth locations.

Phase analysis of the eddy current responses in the case of changing the defect depth are expected to provide more relevant information.

4. Discussion

The modeling of the eddy current inspection for cracks substantiated the fact that the maximum signal amplitude is detected over the crack tip, when the scanning direction and the crack length are aligned. In Table 1, the notch length is estimated based on the peak-to-peak separation of the double-peak feature of the inspection outcomes, obtained both experimentally and numerically. It is observed that the most accurate length estimation was obtained for the case of the 6 mm notch, the closest to the coil's outer diameter. For notches of smaller lengths, it was found that the eddy current technique overestimated the defect size, while for notches longer than the coil diameter, their size was underestimated.

Other observations of this study are that the amplitude of the signal increases in accordance to the crack length, but only in the cases where they are open to the scanning surface. For cracks not reaching the scanning surface, the signal amplitude alone is not sufficient for sizing and locating the defect.

Table 1: Notch length estimation from the experimental and modeling results

True notch length value (mm)	Peak-to-peak separation	
	Experimental (±0.2 mm)	Numerical (±0.5 mm)
2	4.8	5
4	5.4	5
6	5.8	6
8	-	7
10	-	8

5. Conclusions

The qualitative agreement between the empirical data and numerical simulations discussed here shows that modeling could help in eddy current testing optimization for detection of cracking in thin conductive parts, as is the case for the surface inspection of airframes, but also in many other metallic components used in different industries.

The eddy current inspection situation presented in this paper was meant to provide insight in the analysis of eddy current data when employed for detection, sizing, and locating fatigue cracks in aerospace structures. It had been shown that the maximum signal amplitude was observed when the scanning direction and the crack orientation are parallel. For accurate sizing of the defect length, a probe of diameter comparable to the defect size sought is desirable. The double-peak separation feature seems to overestimate cracks longer than the coil diameter and underestimate cracks that have a shorter length than the coil diameter.

6. References

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