

# **ELECTROMAGNETIC DETECTION OF FATIGUE CRACKS UNDER PROTRUDING HEAD FERROMAGNETIC FASTENERS**

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## **Abstract**

The detection of fatigue cracks under installed fasteners has been a major goal of the aging aircraft NDE community. The Sliding Probe, Magneto-Optic Imager, Rotating Self-Nulling Probe, Low Frequency Eddy Current Array, and Eddyscan systems are among the instruments developed for this inspection. It has been verified that the detection of fatigue cracks under flush head aluminum and titanium fasteners can be accomplished with a high resolution by the above techniques. The detection of fatigue cracks under ferromagnetic and protruding head fasteners, however, has been found to be much more difficult. For the present work, the inspection for fatigue cracks under SAE 4340 Steel Hi-Lok fasteners is explored. Modifications to the Rotating Self-Nulling Eddy Current Probe System are presented which enable the detection of fatigue cracks hidden under the protruding head of the ferromagnetic fastener. Inspection results for samples with varying length EDM notches are shown, as well as a comparison between the signature from an EDM notch and an actual fatigue crack. Finite Element Modeling is used to investigate the effect of the ferromagnetic fastener on the induced eddy current distribution in order to help explain the detection characteristics of the system.

This paper will also introduce a modification to the Rotating Probe System designed specifically for the detection of deeply buried flaws in multilayer conductors. The design change incorporates a giant magnetoresistive (GMR) sensor as the pickup device to improve the low frequency performance of the probe. The flaw detection capabilities of the GMR based Self-Nulling Probe are presented along with the status of the GMR based Rotating Probe System for detection of deeply buried flaws under installed fasteners.

## **Introduction**

Over the past several years the NDE capabilities for detecting small cracks under installed fasteners has been extensively studied<sup>a-e</sup>. As a result of this research, several systems have been found to show good detectability for first layer fatigue cracks under countersunk nonmagnetic fasteners<sup>a,c</sup>. The results for ferromagnetic protruding head fasteners or fatigue cracks deeply buried beneath the inspection surface are less well documented and remain troublesome. In this work, the use of the Rotating Self-Nulling Probe System is studied to meet these inspection challenges.

The problem geometry for inspection under ferromagnetic protruding head fasteners is first discussed. Finite element modeling results are then presented to show the electromagnetic

field energy coupling into the critical region. Experimental data taken for EDM notches and actual fatigue cracks located under the installed fasteners follow the modeling results.

A brief discussion of deep flaw detection under installed fasteners is contained in the next section. The problem geometry, resulting inspection system requirements, and experimental data for deep flaw detection using a GMR based very low frequency eddy current probe are presented. The incorporation of this modified probe into the Rotating Probe System is planned to enhance the detection capabilities of the system as related to deeply buried fatigue cracks under installed fasteners.

## Detection of Fatigue Cracks under Ferromagnetic Protruding Head Fasteners

### *Inspection Geometry*

Figure 1 displays a simplified geometry of a wing section on the A-10 aircraft<sup>f</sup>. The lower surface of the wing is attached to the inner frame using Hi-Lok fasteners. These high strength fasteners have a slightly protruding head and are fabricated from SAE 4340 steel. The loading on the wing during flight is such as to produce a high stress on the lower wing surface, just under the fastener head. The most likely location for fatigue crack formation and growth is at this location, as pictured in figure 1. Detecting these flaws at an early stage will greatly simplify the repair procedure for the vehicle.

The sample geometry discussed above significantly complicates the inspection. Many NDE procedures rely on a relatively smooth surface across which to scan the eddy current probe. This is eliminated by presence of the protruding head fastener. In addition, the presence of a ferromagnetic layer covering the location of the fatigue crack significantly shields the flaw from diffusing eddy currents originating at the surface of the structure<sup>g</sup>. The Rotating Probe Method, in particular, is vulnerable to each of these factors<sup>b,h</sup>. The effects caused by presence of the raised head can be eliminated, however, if the probe is scanned outside of the outer diameter of the rivet head as depicted in figure 2. A drawback of this approach is the displacement of the sensor from the fatigue crack location. This would appear to further reduce the field energy coupling into the damaged area shielded under the ferromagnetic fastener. As no other options appeared evident, this approach was investigated with finite element and experimental studies.

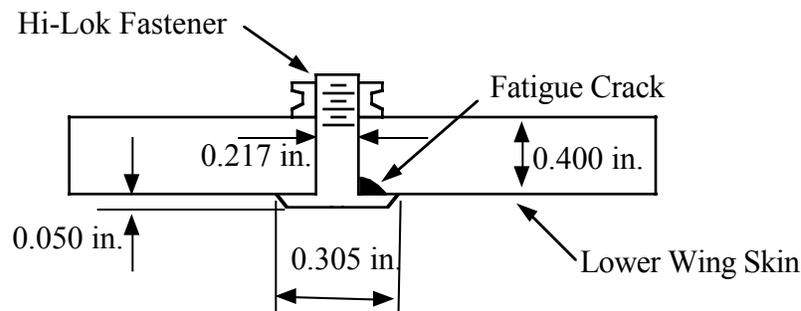


Figure 1. Simplified geometry for fatigue crack inspection under protruding head ferromagnetic fastener.

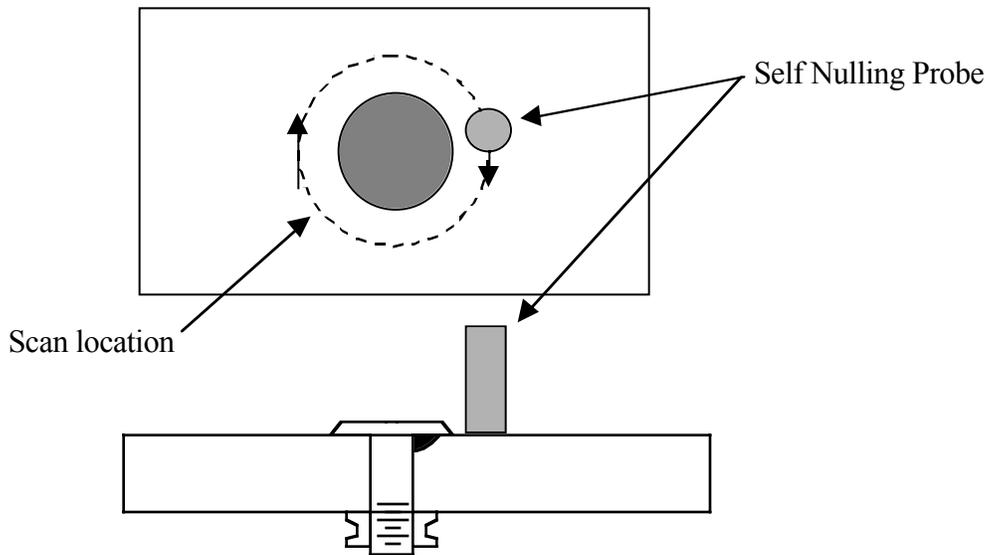


Figure 2. Self-Nulling Probe location and scan line for inspection under ferromagnetic protruding head fasteners.

### ***Finite Element Model***

In order to study the energy coupling into the region of interest a finite element model of the geometry shown in figure 2 was constructed. A full three-dimensional FEM was required due to the lack of symmetry of the problem. Figure 3 displays the individual objects of the model. The probe is positioned slightly above the aluminum plate and outside the outer diameter of the fastener. The large aluminum plate has been broken into separate objects in order to aid in the mesh generation process. The problem was solved using a 50 kHz drive signal and Dirichlet boundary conditions on all outside edges.

The model results are best viewed along a cut plane just below the surface of the plate. Plotting the eddy current density in this plane shows the extent of the sample area that is interacting with the probe. These results are plotted in figure 4. A close inspection of the data reveals that the eddy current density is not symmetric about the center of the probe, but is concentrated toward the fastener. The asymmetry in the eddy current density can be more clearly seen by viewing the fields along a line just under the sample surface that travels from the center of the rivet, under the probe, to the edge of the problem space. These data are shown in figure 5. The ferromagnetic fastener draws the magnetic field away from the probe. This, in turn, results in the increased eddy current density near the fastener. For comparison, figure 5 also displays the results of the model solved with the steel fastener replaced with an aluminum rivet of the same dimensions.

The results discussed above indicate that the detection of fatigue cracks under ferromagnetic protruding head fasteners can be performed with the Rotating Probe System using the configuration shown in figure 2. The difficulties raised by the presence of the protruding fastener have been minimized by scanning the probe over the base metal at a location outside the outer diameter of the rivet. The concerns regarding the shielding of the flaw by the ferromagnetic

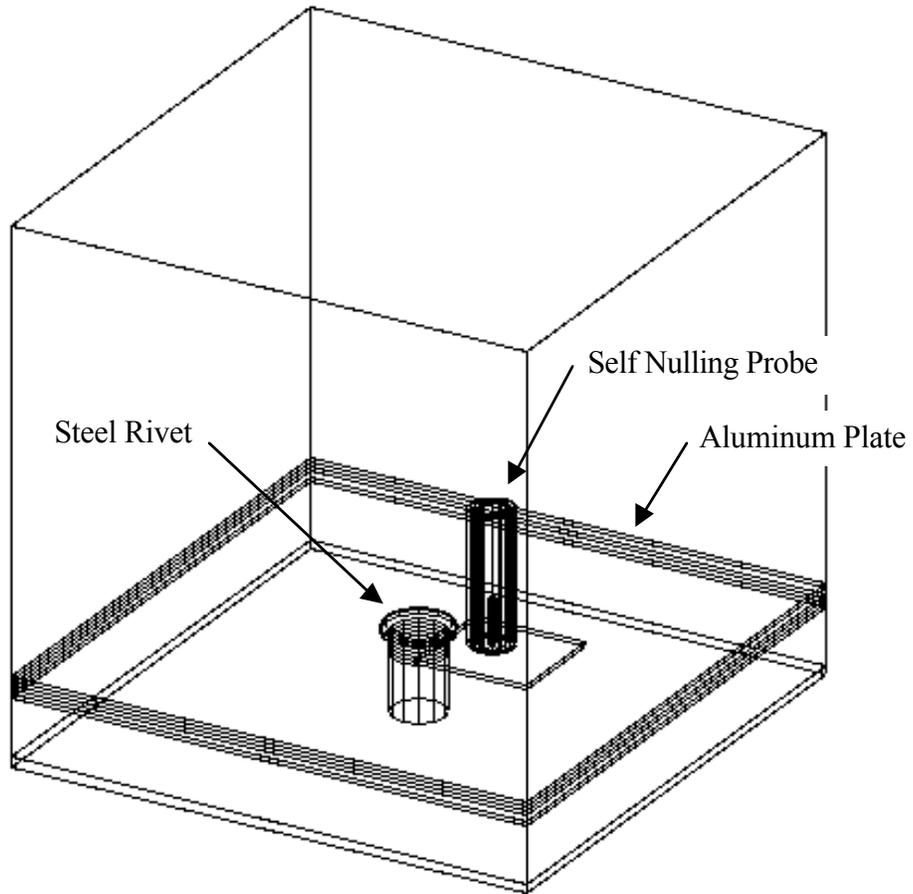


Figure 3. Finite element model for Self-Nulling Probe operating near a ferromagnetic fastener.

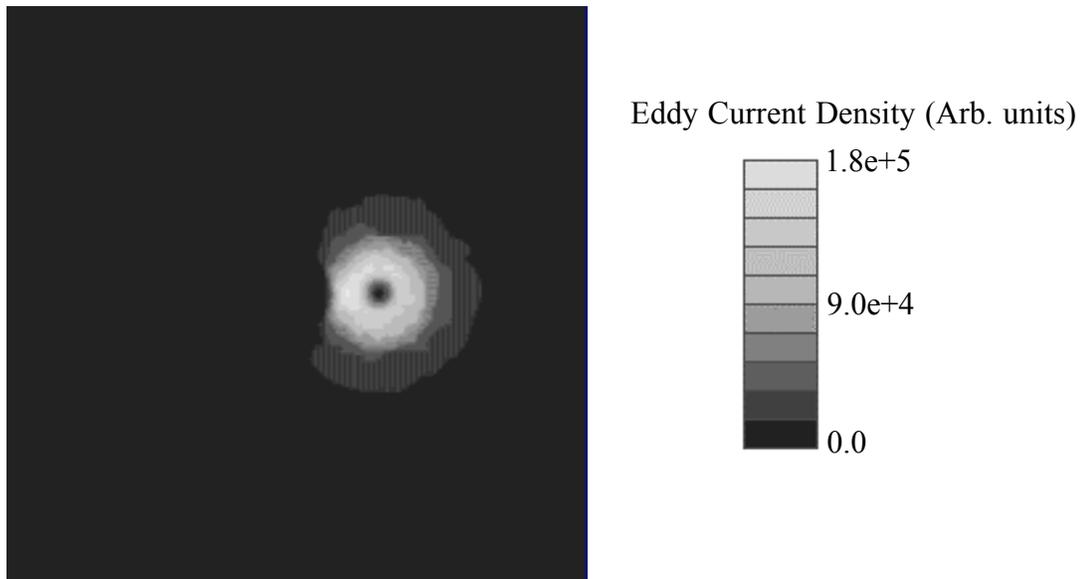


Figure 4. Finite element modeling results for eddy current density. Ferromagnetic fastener causes an asymmetry as magnetic field is drawn toward the high permeability material.

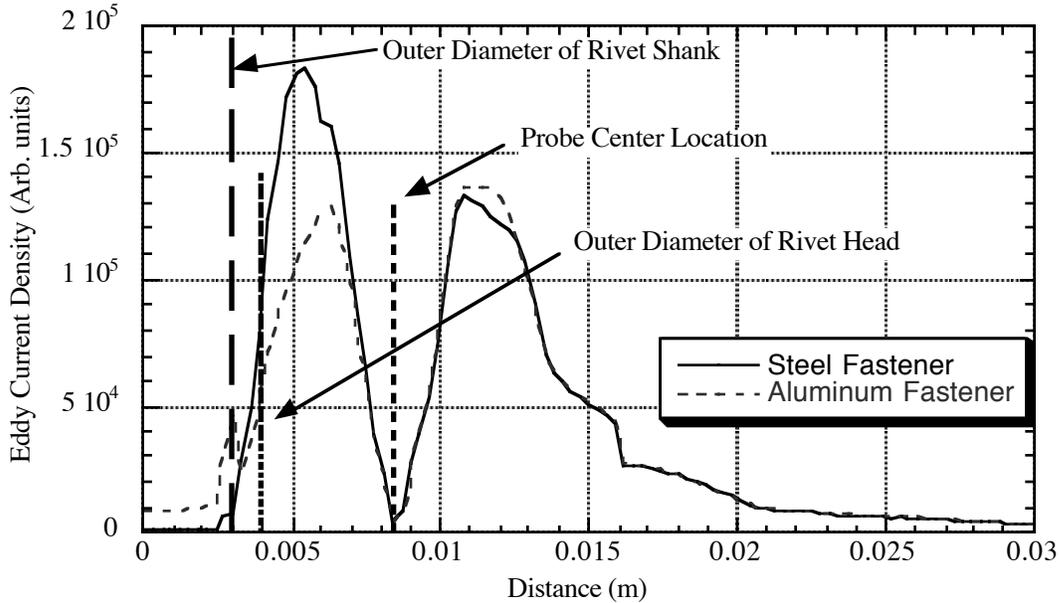


Figure 5. Line graphs of eddy current density on the sample surface from the rivet center to outer edge of the sample. An increased density near the rivet head is observed with the ferromagnetic fastener. Directly under the fastener head, the eddy current density for the two cases is nearly equivalent.

fastener head have also been eliminated. In fact, the finite element model predicts that the ferromagnetic fastener will increase the eddy current density at the critical location where fatigue cracks are likely to occur.

### Experimental Results

Experimental studies were performed using the NASA LaRC developed Rotating Self-Nulling Probe System<sup>b</sup>. This device has been found to be very accurate for the detection of fatigue cracks under aluminum fasteners<sup>a</sup>. The detection capabilities of the system for fatigue cracks under ferromagnetic fasteners have been more limited due to a coupling of the magnetic field between the ferromagnetic fastener and the flux focusing lens of the Self-Nulling Probe<sup>g</sup>. As explained above, this effect can be minimized by displacing the sensor radially away from the rivet. In this configuration, as depicted in figure 2, the ferromagnetic fastener acts to increase the eddy current density in the critical area.

For the inspection the Rotating Probe System was adjusted with a scan radius of approximately 6.6 mm. The sensor diameter is roughly 5 mm leaving a clearance between the outer diameter of the rivet head and the sensor of approximately 0.25 mm. The standard 60 kHz first layer excitation frequency of the instrument was used. Although these experimentally optimized parameters differ slightly from those used in the FEM, the trends found in the simulation data are expected to remain. Numerical models more closely matching the experimental conditions are currently being performed.

The initial experimental work was performed on a sample provided by ARINC Incorporated. The sample contained a fatigue crack that was completely hidden underneath the fastener head. The crack length was estimated at between 30 and 40 mils (0.76 - 1.0 mm). The

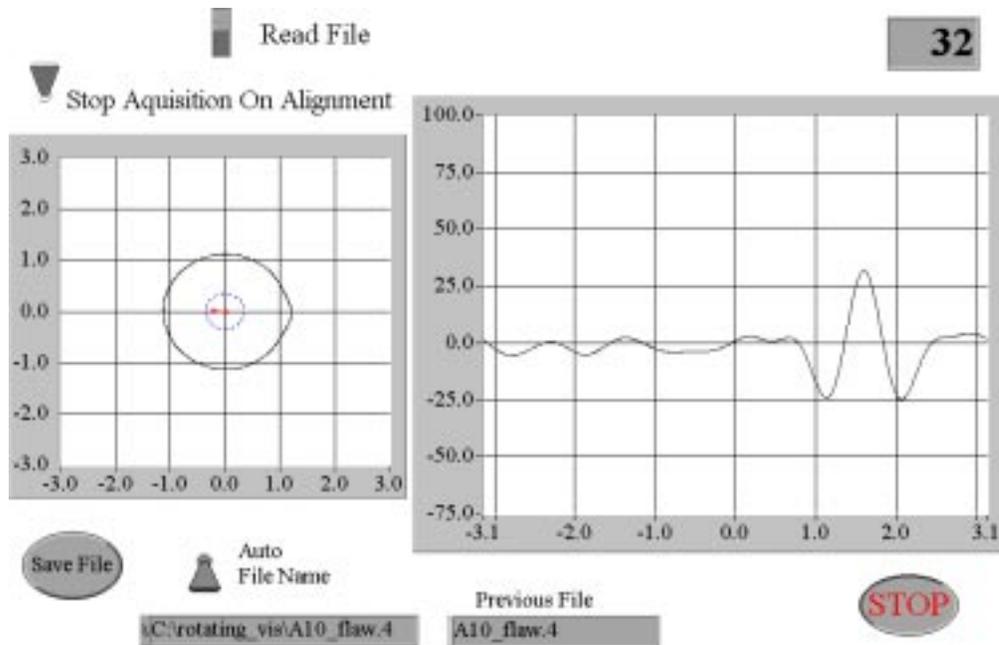


Figure 6. Rotating Probe inspection results for fatigue crack hidden under ferromagnetic protruding head fastener. The graph on the left displays a polar plot of the probe output voltage in volts. The right graph displays the processed output (mV) versus angular position in radians.

test results are depicted in figure 6. The flaw signature is clearly visible in the processed data window, showing up as a large amplitude signal at 1.57 radians. The 32 mV amplitude of the flaw signal is well above the background noise. After testing, the fastener was removed and the flaw location visibly verified.

After the initial inspection results shown in figure 6, a second sample was fabricated. The second sample contained variable length EDM notches cut at a 45° angle to the surface. The results for this sample are summarized in figure 7. The output signal levels from the Rotating Probe System were somewhat lower than expected as compared to the results for the fatigue crack as depicted in figure 6. The cause of the lower signal level is most probably due to the rather shallow angle to the surface at which the EDM notches were cut. The Self-Nulling Probe has a limited response to very shallow flaws<sup>1</sup>, with only low level output for flaws with a depth less than 0.5 mm. For a notch cut at a 45° angle this will reduce the measured flaw length by about 0.5 mm (20 mils), as depicted in figure 8. This correction brings the EDM notch signal levels into line with the results from the fatigue crack. A second EDM notch sample with a more realistic crack profile is being fabricated in order to test this hypothesis.

### Deep Flaw Detection Under Installed Fasteners

Another inspection problem that has received considerable interest is the detection of deeply buried flaws in multilayer conductors. Conventional eddy-current inspection techniques are limited in such applications due to the exponential decay of electromagnetic energy with depth into the conductor. A very low frequency electromagnetic method has been developed to

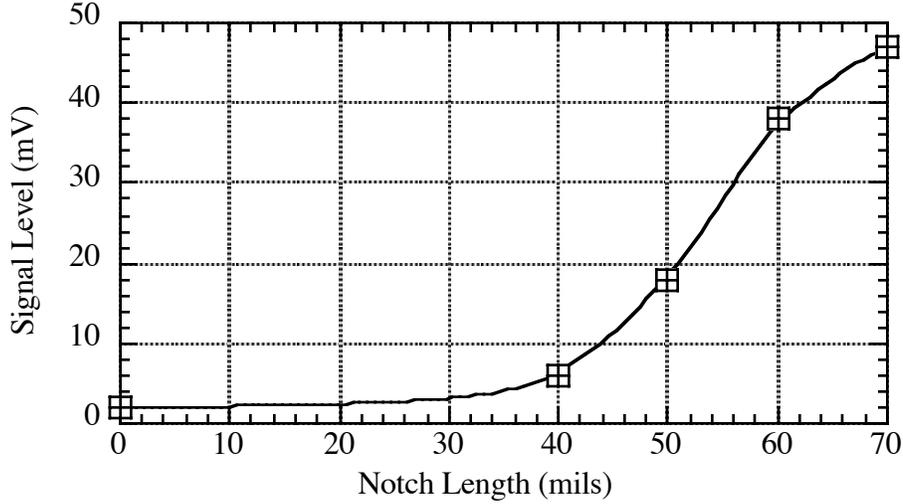


Figure 7. Output signal level of Rotating Self-Nulling Probe System as a function of EDM notch length cut at 45° angle under ferromagnetic protruding head fastener.

perform such inspections. A low frequency induction source coupled with a giant magneto-resistive sensing element allows a significant field intensity to reach the required inspection depths and enables detection of small changes in the low frequency field caused by deeply buried flaws. The use of the GMR device, combined with appropriate shielding and flux focusing has enabled the detection of fatigue cracks buried under more than 0.350" (9 mm) of unflawed aluminum alloy plates<sup>j</sup>. Recently, an active feedback approach has been adapted to the system that greatly enhances the signal to noise ratio<sup>k</sup>. An example of the flaw detection capabilities for this probe is shown in figure 9.

The incorporation of the GMR based Self-Nulling Probe into the Rotating Probe System is currently under way. An initial physical design of the GMR Rotating Probe System has been selected and is being constructed. Only minor modifications of the system electronics appear to be required to enable the recording of the GMR output as a function of angular position during a scan.

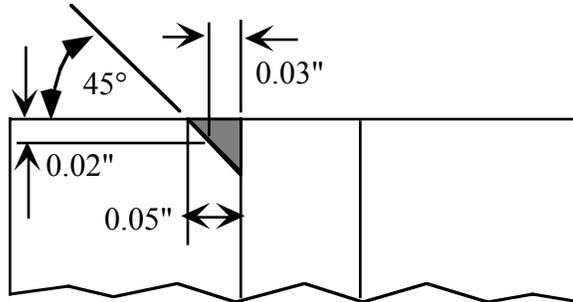


Figure 8. Example of a 0.050" EDM notch cut at a 45° angle. The tip of the notch is very shallow and will contribute little to the probe output voltage.

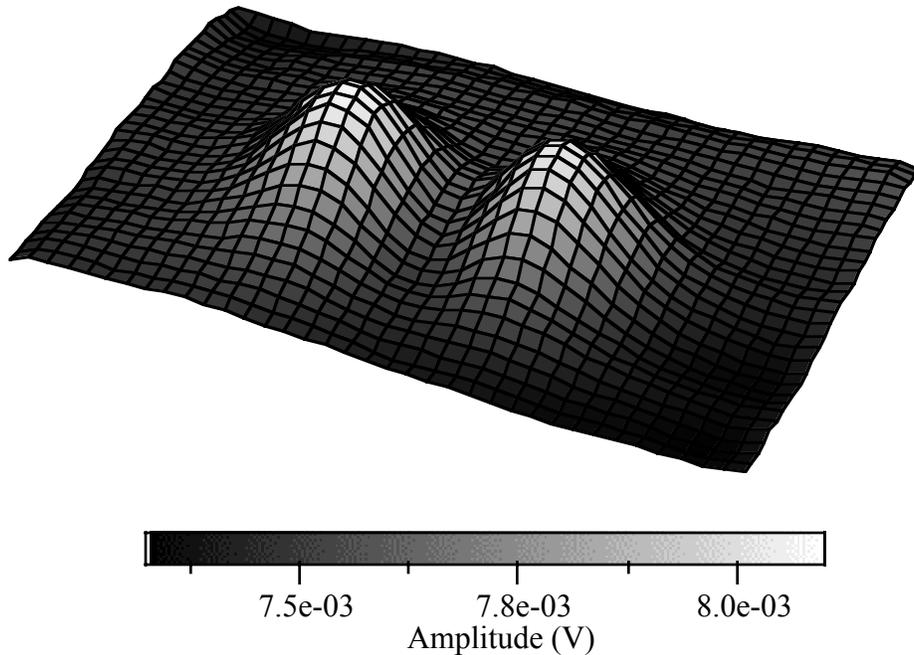


Figure 9. Inspection results for GMR Self-Nulling Probe incorporating active feedback. Experimental results show the detection of a 1.4 cm long EDM notch located in the tenth of thirteen 1 mm thick plates<sup>k</sup>.

## SUMMARY

Modification to the rotating probe system have been presented to expand the capabilities of the system for the detection of fatigue cracks buried under protruding head ferromagnetic fasteners as well as deeply buried fatigue cracks. In the case of the inspection under ferromagnetic protruding head fasteners, no new hardware is required. Only a minor adjustment of the probe radius is necessary to enable the detection of fatigue cracks buried under the fastener head. The experimental results suggest that the depth of the flaw is equally as important as the flaw length in determining the probe output voltage. Additional studies have been planed to further examine the effects of the flaw geometry on the inspection results.

The approach for the detection of deeply buried flaws in multilayer conductors is to replace the sensing element of the Self-Nulling Probe with a giant magnetoresistive sensor. Ongoing research has shown that the deep flaw detection capabilities of the probe are greatly enhanced with this modification. The incorporation of the GMR Self-Nulling Probe into the Rotating Probe System is currently under way and should greatly improve the detection capabilities of the system for deeply buried flaws.

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