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Detection and Characterization of Defects by the Electric Current Perturbation Method

Abstract
The electric current perturbation (ECPI) method of nondestructive evaluation is a powerful technique for detection and characterization of very small defects in nonferromagnetic material. It consists of establishing a current flow in the material to be inspected and then measuring current perturbations caused by nonconducting defects such as fatigue cracks. The current perturbation is sensed by a non-contacting magnetometer probe which detects the associated magnetic field perturbation. Recent findings from ECP investigations are reviewed in this paper. First, analytical modeling and experimental results show that single and multiple, closely spaced slots can be characterized from their unique ECP signatures; second, ECP inspection results from tiebolt holes in TF-33 gas turbine-engine disks demonstrate the capability to characterize very small (0.305 mm long by 0.137 mm deep), tightly-closed, service-induced fatigue cracks; and third, preliminary results of an ECP experiment on a two layer fastener configuration show that radial slots in fastener holes can be detected in the second layer with the fastener installed.

Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering
DETECTION AND CHARACTERIZATION OF DEFECTS
BY THE ELECTRIC CURRENT PERTURBATION METHOD

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ABSTRACT
The electric current perturbation (ECP) method of nondestructive evaluation is a powerful technique for detection and characterization of very small defects in nonferromagnetic material. It consists of establishing a current flow in the material to be inspected and then measuring current perturbations caused by nonconducting defects such as fatigue cracks. The current perturbation is sensed by a non-contacting magnetometer probe which detects the associated magnetic field perturbation. Recent findings from ECP investigations are reviewed in this paper. First, analytical modeling and experimental results show that single and multiple, closely spaced slots can be characterized from their unique ECP signatures; second, ECP inspection results from tiebolt holes in TF-33 gas turbine engine disks demonstrate the capability to characterize very small (0.305 mm long by 0.137 mm deep), tightly-closed, service-induced fatigue cracks; and third, preliminary results of an ECP experiment on a two layer fastener configuration show that radial slots in fastener holes can be detected in the second layer with the fastener installed.

INTRODUCTION
The nondestructive detection and characterization of (1) tightly-closed, low-cycle fatigue cracks in gas turbine engine components and (2) fatigue cracks emanating from fastener holes in structural elements of aircraft are two of the most pressing problems confronting the Air Force. Nondestructive evaluation (NDE) methods for advanced superalloy and titanium alloy gas turbine engine components are, in fact, pacing the development of retirement-for-cause based on fracture mechanics analyses of crack severity. The size range of interest is 0.254 mm or less surface length, with an aspect ratio of approximately 2 to 1. NDE methods for the detection of interior-layer cracks on critical wing-fastener configurations such as the C-5A wing-splice joint are needed to satisfy both safety-of-flight and repair inspection criteria (2.54 mm and 0.76 mm radial crack length, respectively). It is well documented that fatigue cracks originating at fastener holes are the primary cause of airframe failures (1).

The purpose of this paper is to present results of recent analytical and experimental investigations with the electric current perturbation (ECP) method of nondestructive evaluation which relate to each of these two critical problems. Three areas of research, development and engineering applications are reviewed: (1) analytical and experimental results on surface slots approximating fatigue cracks of both single and multiple closely-spaced configurations; (2) demonstration inspection results on actual service-induced LCF cracks in TF-33 3rd stage, gas turbine engine disks originating in the tiebolt holes of the disks; and (3) preliminary results on interior layer fastener hole cracks approximated by EDM slots in the faying surface of the second layer.

DESCRIPTION OF THE ELECTRIC CURRENT PERTURBATION METHOD
The fundamental principles of the electric current perturbation method are illustrated in Fig. 1. Figure 1A shows an idealized specimen with no defect present in which there exists an unperturbed current density \( \mathbf{J}_0 \) and a corresponding magnetic flux density \( \mathbf{B}_0 \) immediately above the surface of the specimen. When a defect such as a crack is introduced, the distribution of current density is altered as indicated in Fig. 1B, and the flux density above the surface of the specimen changes from \( \mathbf{B}_0 \) to \( \mathbf{B}_0 + \Delta \mathbf{B} \). The ECP method consists of detecting \( \Delta \mathbf{B} \) with a differential magnetometer probe (Fig. 2) as a function of probe position and relating the resulting signal characteristics to defect geometry.

\[
\begin{align*}
\mathbf{B}_0 & \quad \mathbf{B}_0 + \Delta \mathbf{B} \\
\mathbf{J}_0 & \quad \mathbf{J}_0 + \Delta \mathbf{J}
\end{align*}
\]

Fig. 1. Principles of the electric current perturbation method

Fig. 2. Schematic of a magnetometer scan
Electric current flow may be introduced by either direct (ohmic) contact with the specimen using a suitable current source or by inducing the current flow in the specimen with an induction coil. A typical laboratory setup for direct injection experiments is shown in the block diagram of Fig. 3. Frequencies in the range of less than 100 Hz to 100 kHz are used depending on the depth of the defect to be detected and the conductivity of the material (skin depth effect).

Two important signal characteristics are immediately obvious: first, the center of the slot can be located by the null and the polarity reversals on either side. Second, the spacing between maxima in the signal amplitude is related to slot length. In addition, it has been empirically demonstrated that the peak amplitude of the signal is directly proportional to the interfacial area of a slot for small slots.

These characteristics in amplitude, polarity and shape, as well as excellent repeatability, reproducible background from the material and a high signal-to-electronic-noise ratio, are all important in the detection and characterization of defects as discussed in the following sections.

**SINGLE VS. MULTIPLE CLOSELY SPACED CRACKS**

Of significance to retirement-for-cause (RFC) inspection requirements is the potential of the ECP method to discriminate individual cracks from multiple, closely spaced cracks. Low-cycle fatigue cracks initiate in regions of high strain concentration such as bolt holes in engine disks. In nickel-base superalloy disks, microcracks on the scale of the grain diameter initiate very early in the life of the disk. Most of the lifetime to form a detectable LCF crack, on the order of 0.76 mm length on the surface, consists of the linkup between microcracks. Thus the discrimination between a single, linked-up crack and a row of isolated microcracks, is important to predicting residual lifetime. In particular, the inability to discriminate between single and multiple cracks in coarse-grained materials would cause retirement of the part long before its fatigue life was exhausted.

An approximate analytical model has been developed (2) which gives ECP signal characteristics as a function of defect shape and size for both single and closely spaced slots. A description of the model follows, along with a comparison of theoretical and experimental results for single and closely spaced slots.

**Analytical Model** - The analytical model for a single slot is based on the following assumptions:

1. An idealized crack geometry adequately represents the perturbation to current flow and end effects may be ignored.

2. The unperturbed current density is uniform and constant in time since the skin depth is large compared to slot dimensions.

A geometrical model consistent with these assumptions is shown in Fig. 5. Here, a slot of depth d and infinitesimal width is shown at right angles to the surface. The effect of slot length is ignored and the current perturbation is approximated by a function of x and y only. The resulting two dimensional current density perturbation may then be used to calculate an approximate change in magnetic flux density by integrating over the slot length 1. Expressions for the components of the change in flux density caused by the slot were obtained using the method of complex potentials to calculate the current density perturbation (3,4).
To predict the response of two closely spaced slots, it was further assumed that the solutions to the flux perturbation equations are mathematically uncoupled and obey the law of superposition. Thus, the perturbation in the x-component of the flux for two closely spaced slots is simply the superposition of solutions for the x-component of the change in flux density for each slot. Characteristics of these solutions are most apparent in plots of peak amplitude as a function of position along and beyond the ends of the slots as discussed below.

Comparison Between Theory and Experiment - Two cases were modeled analytically and experimentally:

1. discrimination of two small cracks of the same size placed end-to-end with a relatively close spacing of less than one crack length from a larger single crack of approximately the same overall length as the two cracks (all cracks having the same aspect ratio).

2. discrimination of the same two small cracks from a small single crack of the same size and aspect ratio.

In the first case theoretical predictions were calculated using superposition of solutions for two 0.559 mm long by 0.203 mm deep slots with a spacing of 0.381 mm and a single large slot measuring 1.499 mm long and 0.546 mm deep having the same aspect ratio. Theoretical results for these two cases are shown in Fig. 6. Here the distributions of calculated peak signal amplitudes from scans perpendicular to the slot length are plotted versus position along the slot length. The single large slot produces a very large difference in the peak-to-peak amplitude (almost an order of magnitude) compared to the two small slots, and the peak-to-peak spacing for the large slot is significantly greater than that for the two smaller slots. Also, there is a slight inflection in the plot for the closely spaced slots.

This first case was approximated experimentally with two small slots 0.610 mm long by 0.203 mm deep, spaced 0.381 mm apart and a single 1.575 mm long by 0.533 mm deep slot. The slots could not be made exactly the same size as in the theoretical calculations due to limitations of the air-abrasive machining process. Figure 7 is a plot of the ECP experimental data with both curves normalized so that the peak amplitude of the double slot signal has the same value as in Fig. 6. Note the excellent agreement of experimental results with the theoretical calculations shown in Fig. 6.

In the second case, discrimination is desired between two closely spaced cracks and a single crack of the same size as one of the closely spaced cracks. Figure 8 shows the theoretical prediction of the peak-to-peak amplitude distributions for this case, utilizing the same 0.559 mm by 0.203 mm slots spaced 0.381 mm apart and a single 0.559 mm by 0.203 mm slot. Again, the signal features can be used to differentiate between the two conditions, i.e. the change in peak-to-peak separation and peak-to-peak amplitude, and again, in the case of the two closely spaced slots, a slight inflection of the curve in the signature region between the upward and downward peaks.

Fig. 5. Geometry for the calculation of electric current perturbation signals

Fig. 6 Theoretical ECP peak signal amplitudes vs. position along slot length for a single 1.499 mm by 0.546 mm slot and two 0.559 mm by 0.203 mm slots separated by 0.381 mm

Fig. 7. Experimental ECP peak signal amplitudes vs. position along slot length for a single 1.575 mm by 0.533 mm slot and two 0.610 mm by 0.203 mm slots separated by 0.381 mm
Fig. 8. Theoretical ECP peak signal amplitudes vs. position along slot length for a single 0.559 mm by 0.203 mm slot and two slots of the same size separated by 0.381 mm.

This second case was approximated in an experiment which compared ECP signals from a single 0.635 mm by 0.229 mm slot with those from a set of two 0.610 mm by 0.203 mm slots separated by a spacing of 0.381 mm. Figure 9 is a plot of experimental data for these two conditions with both curves normalized so that the peak amplitude of the signal from the single slot has the same value as in Fig. 8. The signal features in the experimental case are similar to those predicted by the theoretical model (Fig. 8) with the exception of the difference in peak-to-peak amplitudes. Also, the experimental peak-to-peak spacing is similar to that predicted by the model and there is a slight inflection in the signal from the closely spaced slots at the center. Some of the differences in the experimental data such as asymmetry of the positive and negative peak amplitudes can be attributed to the fact that the slots, generated by air-abrasive material removal, are somewhat irregular and are slightly different in size than those used in the model predictions. Also, the slots were slightly deeper on one end than on the other as determined from replicas. These data do show, however, that the approximate model predictions agree remarkably well with experimental data obtained from single and closely spaced slots.

Fig. 10. ECP scanning system for TF-33 turbine disc tiebolt holes.

Typical Crack Signals - Figure 11A shows two typical repeat scans of a single scan track to illustrate the excellent repeatability. Every detail of the crack signal and also of the signal background throughout the entire scan is highly repeatable. These data show that the signal and the background characteristics are precisely related to the hole under inspection and are not due to extraneous influences from electronic noise, probe liftoff variations, etc.
To illustrate the ECP technique's potential sensitivity to extremely small defects, Fig. 11B shows a trace made with the probe removed from the tiebolt hole and scanned in air; the sensitivity has been increased by a factor of 50 over that shown in the traces in Fig. 11A. Even the background signals in normal scan traces in Figure 11A are far above the electronic background noise. Thus, sensitivity is limited by material characteristics and not by system noise.

Inspection Results - Since the primary objective was to assess capability of the ECP method for detecting and characterizing small cracks, four tiebolt holes were selected which had signatures with a signal-to-noise ratio of approximately two (based on material background noise). These holes were scanned again at 0.318 mm increments between scans to obtain higher resolution. Portions of the four selected tiebolt holes were removed from the disks and examined on the surface using both an optical microscope and a scanning electron microscope (SEM) to determine surface crack geometry. Selected cracks were then sectioned metallurgically and examined with the SEM to determine subsurface geometry. Since the cracks were very tightly closed in both cases, it was necessary to chemically etch the surface to reveal the cracks.

In each specimen, a large number of cracks spaced relatively close together were found, and in most cases they showed a very complex geometry below the surface. Many were at an angle to the surface, while some branched into multiple cracks beneath the surface. In a few cases, subsurface cracks were found with no surface indications. Many subsurface inclusions were also found.

Figure 12 shows a surface photomicrograph of cracks near the top end of one tiebolt hole and ECP signatures obtained at the designated scan track positions. A photomicrograph of the subsurface geometry of crack A is shown in Fig. 13. Note that the ECP scans for the entire circumference of the bolt hole are shown in Fig. 12 and that the region in the photograph comprises only a small segment of the overall ECP signature. Also, since these scans were taken near the top of the hole, a slight gradient is present in the signal near the center of each trace due to an abrupt change in disk thickness in this region.

As shown in these figures, the crack sizes are very small, yet very pronounced ECP signatures are obtained. Distinct signal features are also evident. For example, as the ECP scans approach crack A from the top, the ECP crack signal is first downward going (negative) and then the signal reverses polarity for successive scan track positions axially along the crack and past the bottom end. A positive polarity is then obtained near the top of crack B. As the scans move over crack B and toward its bottom end, the signal again reverses polarity and also becomes broader in a circumferential direction, probably due to the influence of crack C, the other small cracks shown in the photograph, and additional cracks located further down the hole (not shown).

Because of the complex crack geometries and close spacing of the cracks, interactions exist between the individual ECP signatures. It is therefore difficult at this time to show a precise correlation with crack features since ECP signature characteristics are presently known only for simple crack geometries.
SECOND LAYER FASTENER HOLE CRACK DETECTION

An investigation is presently underway to determine the feasibility of detecting fatigue cracks in the second layer of a two layer structural fastener configuration (fastener installed) using the ECP method. The goal is to detect a slot of approximately 2.54 mm radial length through a full outer layer thickness of 6.35 mm (6). However, this work is not yet complete and only a progress report is given here.

Direct Contact Current Injection Results - Figure 14 is a schematic of a simplified two layer configuration without a hole constructed from aluminum flat plate stock. An electric discharge machine (EDM) rectangular slot measuring 2.794 mm long by 0.889 mm deep was placed in the bottom layer, and several top layer thicknesses were used to study the ECP response as a function of layer thickness. Direct electrical contact was used to establish current flow in the second layer which was separated from the first layer by a 0.076 mm thick nonconducting plastic (Mylar) film. An ECP probe designed specifically for subsurface defect detection was scanned on the surface of the top layer in the direction of current flow.

Experimental results shown in Fig. 15 confirm that the slot can be readily detected through a top layer thickness up to 6.35 mm. Moreover, these ECP signals were obtained without the use of any signal processing. As expected, the signal amplitude decreases with increasing top layer thickness, but it is still significantly above background signal gradient level at a 6.35 mm thickness. Although this experiment is greatly simplified in that no hole or fastener was present in the specimen, it illustrates that in this idealized case the electric current method is capable of detecting a defect of the size range of interest in the faying surface of the second layer of the C-5A wing splice joint.

Induced Current Flow - An induction coil was designed which could be placed on the top layer coaxial with a fastener to induce current flow around the fastener hole. A motor driven scanning system was constructed to scan the ECP probe circumferentially around the fastener hole on the top layer. Figure 16 is a schematic of the experimental configuration. Again, a probe designed for subsurface detection was used.

Fig. 15. ECP signals from 2.794 mm by 0.889 mm slot in second layer configuration using direct contact arrangement

Fig. 16. Induced current configuration for detection of second layer defects
At present experimental data have been obtained only from a 4.318 mm X 4.318 mm triangular slot in the second layer with top layer thicknesses of 1.600 mm and 3.175 mm. The ECP signals are shown in Fig. 17. The excellent signals obtained here provide strong evidence that the desired goal of detecting a 2.54 mm X 2.54 mm triangular slot through a 6.35 mm thick top layer can be achieved.

Fig. 17. ECP signals from 4.318 mm by 4.318 mm triangular slot in second layer configuration using induced current arrangement

CONCLUSIONS

Both theoretical and experimental data show that good potential exists to differentiate between small, closely spaced cracks and single cracks although more experimental data, modeling, probe refinements and signal processing will be required to differentiate between cracks with complex subsurface geometries. The potential also exists to determine crack characterization parameters such as depth although again additional data, modeling and signal processing will be required to characterize complex cracks. The ECP method is capable of detecting very small surface entering fatigue cracks as indicated by the relatively isolated crack measuring 0.305 mm long by 0.137 mm deep that was detected in a TF-33 gas turbine engine disk tiebolt hole. Smaller cracks were also detected; however, their signals were complicated by influences from adjacent cracks. Based on extrapolated data obtained with the surface ECP probe, the minimum detectable crack size (using a signal-to-background ratio of approximately two) for disks investigated is approximately 0.254 mm long by 0.076 mm deep.

Applied in the low frequency mode to the second layer crack detection problem, the ECP method has demonstrated good sensitivity to small EDM slots approximating fatigue cracks in the second layer faying surface. The goal of achieving reliable crack detection for safety-of-flight inspection criteria appears to be attainable.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Tom Doss for assistance with data acquisition and construction of the ECP scanning system; Messrs. Ralph Turner and Ron McInnis for performing metallurgical sectioning and photomicroscopy; and Drs. Gerald Leverant and Clifford Wells for assistance with interpretation of metallurgical results. Partial support was provided by the Air Force Wright Aeronautical Laboratories/Materials Laboratory.

REFERENCES

Jim Martin, Chairman (Rockwell Science Center): I think your friends are lucky to have such a clear speaker to represent them.

Are there any questions?

Unidentified Speaker: The original experiment was in steel?

Richard Smith (Southwest Research Institute): The jet engine experiments?

Unidentified Speaker: Yes.

Richard Smith: That was not steel.

Unidentified speaker: Titanium?

Richard Smith: 910.

Al Bahr (SRI): What were the range of the frequencies of the applied currents?

Richard Smith: They ranged from 100 hertz to 10 kilohertz.

Dick Barry (Lockheed Missiles and Space): Did you indicate that this probe is not sensitive to lift off or some of the other problems you had with the other type of eddy current devices?

Richard Smith: No, I did not indicate that. And it would certainly be affected by lift off.

Jim Martin, Chairman: Let's continue.