INTRODUCTION AND SUMMARY

Presently, the rotary wing-head and hub subassemblies of the Army's Black Hawk helicopter require almost complete disassembly to inspect failure critical threads of the main spindle. Even with direct access to the threads, detection of fatigue cracks in the thread roots is very difficult using visual and penetrant methods. Therefore, the purpose of this project was twofold: (1) to demonstrate an improved nondestructive inspection method for the spindle threads applicable to routine teardown maintenance, and (2) to determine the feasibility of performing safety-of-flight inspections on the spindle with only minimal disassembly.

Recent projects funded by the Air Force have shown that the electric current perturbation (ECP) method is capable of detecting very small surface fatigue cracks in gas turbine engine disks and second layer defects in relatively thick structural wing sections. Based on these results, the ECP method was evaluated for its capability to inspect the spindle thread roots not only by scanning the outside diameter (crest of the threads), but also by scanning the hollow spindle bore under the threads and inspecting through the wall thickness for flight-critical cracks. With an ECP probe located on the crest of the threads, high sensitivity to very small defects in the thread roots was achieved and thumbnail shaped EDM slots as small as 0.53 mm long by 0.23 mm deep by 0.064 mm wide were detected. Inspection from the bore requires only that the rotary wing be removed so that a probe can be inserted into the spindle bore. Since this inspection is performed through the spindle wall, sensitivity is reduced and only larger defects are detectable. From the bore,
detection of a thumbnail shaped EDM slot measuring 7.75 mm long by 2.21 mm deep by 0.102 mm wide was successfully demonstrated.

EXPERIMENTAL

The ECP method consists of establishing an electric current flow in the material to be inspected and then detecting components of the magnetic field associated with current perturbations caused by nonconducting defects such as cracks. Usually, the current flow is established by a noncontacting induction coil and the magnetic field components are detected by a separate sensor.

Two Black Hawk helicopter rotary wing-head spindles were supplied by the Army for use in this project. Figure 1 is a photograph of one of the spindles; the threaded end to the right is the area inspected with the ECP method. The thread specification is 2.500-12 UNJ-3A, and threads are numbered beginning at the splines.

![Figure 1. Black Hawk Rotary Wing-Head Spindle](image)

An ECP probe which uses miniaturized induction coils to establish current flow and a separate sensor to detect field perturbations associated with defects was configured to ride on the crest
of the threads as shown in Figure 2. This probe provides current flow perpendicular to the threads at a frequency of 100 KHz yielding optimum detection of small fatigue cracks which grow along the thread root.

Figure 2. ECP Probe on Crest of Spindle Threads

A second ECP probe was designed for use in the spindle bore to provide defect detection through the spindle wall thickness as shown in Figure 3. This probe is comprised of an elongated induction coil to produce current flow in the spindle wall perpendicular to the direction of the threads. As in the case of the thread crest probe, a separate sensor is used for detection of field perturbations associated with defects. The bore probe was operated at a frequency of 5 KHz which provided a skin depth approximately equal to the spindle wall thickness of 9.32 mm. During inspection from the bore, the spindle nut was left in place to simulate a spindle installed on a helicopter.

Slots were machined in both spindles to simulate fatigue cracks as shown schematically in Figure 4. The slots used in experiments with the ECP probe on the crest of the threads are given in Table 1 and those used in experiments with the ECP probe in the spindle bore are given in Table 2.
Figure 3. ECP Probe in Spindle Bore

Figure 4. Typical Simulated Crack Location in Spindle Thread Root
Table 1. Simulated Cracks for Detection From Crest of Threads

<table>
<thead>
<tr>
<th>Defect</th>
<th>Length (mm)</th>
<th>Depth (mm)</th>
<th>Width (mm)</th>
<th>Shape</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.69</td>
<td>0.36</td>
<td>0.20</td>
<td>Rectangular</td>
<td>Air Abrasive</td>
</tr>
<tr>
<td>B</td>
<td>1.73</td>
<td>0.25</td>
<td>0.18</td>
<td>Rectangular</td>
<td>Air Abrasive</td>
</tr>
<tr>
<td>C</td>
<td>0.64</td>
<td>0.43</td>
<td>0.18</td>
<td>Rectangular</td>
<td>Air Abrasive</td>
</tr>
<tr>
<td>D</td>
<td>1.32</td>
<td>0.36</td>
<td>0.074</td>
<td>Thumbnail</td>
<td>EDM</td>
</tr>
<tr>
<td>E</td>
<td>0.99</td>
<td>0.25</td>
<td>0.066</td>
<td>Thumbnail</td>
<td>EDM</td>
</tr>
<tr>
<td>F</td>
<td>0.53</td>
<td>0.23</td>
<td>0.064</td>
<td>Thumbnail</td>
<td>EDM</td>
</tr>
</tbody>
</table>

Table 2. Simulated Cracks for Detection from Bore

<table>
<thead>
<tr>
<th>Defect</th>
<th>Length (mm)</th>
<th>Depth (mm)</th>
<th>Width (mm)</th>
<th>Shape</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>15.24</td>
<td>2.79</td>
<td>0.56</td>
<td>Thumbnail</td>
<td>Abrasive Wheel</td>
</tr>
<tr>
<td>H</td>
<td>4.95</td>
<td>1.52</td>
<td>0.064</td>
<td>Thumbnail</td>
<td>EDM</td>
</tr>
<tr>
<td>I</td>
<td>7.75</td>
<td>2.21</td>
<td>0.102</td>
<td>Thumbnail</td>
<td>EDM</td>
</tr>
</tbody>
</table>

In all laboratory experiments the spindles were simultaneously rotated and translated axially by means of a motor drive and lead screw. For scans on both the crest of threads and in the bore, the probe remained stationary and the relative motion between the probe and spindle produced a helical path equal to the thread helix. This scanning configuration maintained a fixed spacial relationship between the probe and the threads and minimized the influence of thread geometry on the overall signal response. Rotational speed was 5.26 rpm.

A block diagram of the ECP instrumentation is shown in Figure 5. Analog ECP signals were digitized as a function of probe position using a digital oscilloscope and were transferred to a desk-top computer for signal processing and plotting. To provide enhancement of the flaw signals, a digital high-pass filter was used to reject the lower frequency signal components not associated with defects. The digital filter was used for convenience in this investigation; an analog filter could be used in inspection hardware.
RESULTS

ECP Probe on Crest of Threads

Initial ECP data were obtained on the first spindle which contained three rectangular slots designated A, B, C in Table 1. These slots were machined by an air-abrasive process and were spaced 120° apart around the circumference in the root of one thread. Excellent ECP signals were obtained from all three defects as shown by the experimental results in Figure 6. These data exhibit several important characteristics. First, the signal background is far above electronic noise and is highly repeatable for repeat scans. The ECP sensitivity is limited only by the signal background obtained from the spindle itself and not by electronic noise. Second, signals are obtained not only when the probe passes directly over the slots in the same thread, but also when the probe is located over adjacent threads as indicated by the satellite signals designated A', B', C' in Figure 6. Note that when the probe passes directly over each slot, the signal is first positive-going and then negative-going. However, when the probe is located over the adjacent thread on either side of the slot, the signal reverses polarity and is first negative-going and then positive-going. This relationship of ECP signal polarity with respect to probe position is characteristic of a typical ECP response and indicates that the ECP signals respond as expected even in the presence of the complex geometry imposed by the spindle threads.
To determine the sensitivity of the ECP method to even smaller defects which more closely approximate the thumbnail shape of a fatigue crack, a series of EDM slots designated as D, E, F in Table 1 was machined in a thread root of the second spindle. ECP data from these slots are shown in Figure 7. Note that satellite signals are again evident in adjacent threads for the two larger slots as denoted by the symbols D' and E'.
In order to improve the signal-to-background ratio for slot F, the cutoff frequency of the high-pass filter was adjusted to remove additional low frequency background components from the signal. While the signal-to-background ratio is improved by this process, the signal shape is somewhat distorted (e.g. the polarity reversals are no longer evident) as shown in Figure 8. For detection purposes only and not defect characterization (i.e. size, shape and orientation), this distortion is not significant since it is only the flaw signal level with respect to the signal background which is meaningful. By altering the filtering cutoff frequency, the signal-to-background ratio was increased to 2:1. Therefore, the minimum detectable defect is on the order of 0.53 mm long by 0.23 mm deep with a signal-to-background ratio considered acceptable for reliable detection.

![Figure 8. ECP Signals from EDM Slots with Probe on Crest of Threads and Additional Low Frequency Components Removed](image)

**ECP Probe in Spindle Bore**

Initial data were obtained from defect G (15.24 mm long by 2.79 mm deep) in the fourth thread of the first spindle (see Table 2). The experimental data are shown in Figure 9 beginning one revolution before the first thread is reached (designated thread 0) through the sixth thread. It is quite evident from the satellite signals on either side of the main signal that a substantial response is obtained from this defect not only when the probe passes directly under the defect but for a significant number of revolutions on either side. Although the signal reverses polarity as it did with the small defects on the crest of the threads, this polarity reversal occurs outside the region shown in the plot because the signal is significantly more spread out due to the effect of the spindle wall thickness.
In order to determine the minimum detectable defect size with the bore probe, slot H (4.95 mm long by 1.52 mm deep) was machined in the first thread of the second spindle. However, this defect was not detected above the signal background. Subsequently, slot I measuring 7.75 mm long by 2.21 mm deep was then machined 180° from slot H and the ECP signals from this slot are shown in Figure 10. The signal-to-background ratio obtained from this defect is 2:1. Therefore, defects of this size are detectable with the probe positioned in the spindle bore without removal of the spindle from the helicopter.
Equivalence of Slots and Fatigue Cracks

Although machined slots were used to simulate fatigue cracks in this investigation, the signals obtained are equivalent to those from fatigue cracks of the same sizes since the ECP method produces equivalent signals from cracks and slots. Furthermore, a linear relationship exists between ECP signal amplitude and crack/slot interfacial area independent of the defect opening.

To establish the equivalence of ECP signals from a fatigue crack and a slot, a direct comparison was made between these two types of defects. In prior work, a 1.30 mm surface length fatigue crack was grown in a smooth Ti 6-4 rod type tensile specimen in a laboratory fatigue machine under stress conditions which produced a true half-penny shaped crack with a 2:1 aspect ratio. The ECP response from this closed fatigue crack was compared to the response from an EDM slot measuring 1.27 mm surface length, 0.65 mm deep and 0.10 mm wide machined in an identical Ti 6-4 specimen.

Plots of ECP signal amplitude vs. position along the defect length are shown in Figure 11 for both the crack and slot. Identical experimental setups were used for both defects and the absolute signal amplitudes are plotted (i.e. no normalization was used). As seen in the figure, the amplitudes and shapes of the two curves are essentially identical. The overall agreement between signal behavior from the crack and the slot is excellent. Therefore, a slot provides an excellent simulator for determining the ECP response to a fatigue crack with current flow normal to the interface of the defect.
Another important characteristic of the ECP method is the linear relationship which exists between ECP signal amplitude and crack/slot interfacial area. This is illustrated in Figure 12 where ECP data for the machined slots in the spindles (probe on crest of threads) are plotted as a function of slot interfacial area. The slot data are from both rectangular air-abrasive slots with widths of approximately 0.2 mm and from thumbnail shaped EDM slots with widths of approximately 0.07 mm. For both types of slots an excellent linear relationship is obtained (within experimental error) showing that the interfacial area determines the ECP response and not the shape or width of the slot.

![Figure 12. ECP Signal Amplitude vs. Interfacial Area for EDM and Air-Abrasive Slots in Titanium Spindle](image)

**CONCLUSIONS**

The ECP method was shown to be capable of inspecting the complex geometry of the Black Hawk helicopter rotary wing-head spindle threads for fatigue cracks in the thread roots. The ECP method is applicable in two inspection configurations. For detection of very small fatigue cracks, the spindle would be removed from the helicopter and the probe scanned on the crest of the threads. Under these conditions the method was shown to be capable of detecting simulated fatigue cracks measuring 0.53 mm long by 0.23 mm deep by 0.064 mm wide for a thread depth of 1.22 mm. For safety-of-flight inspection with the spindle still in place on the helicopter, the ECP method was shown to be feasible for detecting fatigue cracks in the thread roots by inserting a probe into the spindle bore and
inspecting through the spindle wall thickness. With this arrange­ment, detection of simulated fatigue cracks as small as 7.75 mm long by 2.21 mm deep by 0.102 mm wide was successfully demonstrated through a 9.32 mm wall thickness. It is anticipated that with addi­tional signal processing methods, detection of even smaller defects could be realized.

Based on the direct comparison of ECP responses from a labora­tory grown fatigue crack and an equivalent size EDM slot and also the linear relationship which exists between ECP signal amplitude and defect interfacial area, it is concluded that EDM slots may be used to simulate fatigue cracks for purposes of evaluating the sen­sitivity of the ECP method on complex parts.

ACKNOWLEDGEMENTS

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REFERENCES

DISCUSSION

R.C. Addison (Rockwell International Science Center): I didn't quite understand your scanning scheme when you were resting on the crest of the threads and you showed the plot with what you call the ghost signals. I was having a little trouble understanding how you were scanning and what the dynamics of that would be as you scanned along.

C.M. Teller (Southwest Research Institute): Yes, that wasn't very clear; I apologize for that. The probe is actually held stationary in the fixture that you saw, and the spindle is translated and rotated so that the helical scan that's produced is at the pitch of the threads. So the threads always present the same position with respect to the sensor. Using differential measurements, one can then cancel the effect of the threads themselves. But it turns out it's not particularly sensitive to exactly where you are with respect to the thread root. You can get significant cancellation even though you might be off the precise position of the thread root by several mils.

R.C. Addison: And where was the current being induced?

C.M. Teller: The current in both cases was being induced in a linear fashion to interact along the axis of the spindle to interact with the interface of the slot. That's done by a configuration of induction coil arrangements to get the approximately linear current flow in that direction. We found that this indeed produces the highest sensitivity with this approach.

E.K. Miller (Lawrence Livermore National Laboratory): Is it the practice to take a signature of a part when it is new and then save that for use later on? It seems like that would improve the processing.

C.M. Teller: That's an excellent suggestion where you have that capability, and we've done that on several parts, using digital subtraction. You can produce amazing results in terms of the size of the defect. Unfortunately, it's not often easy to implement that in practice. I would think some of the work in retirement-for-cause might be amenable to that approach, where absolute tracking of these parts throughout their lifetime is going to be assured. However, these parts we are talking about here are not handled in that fashion, and it is probably impractical to think of tracking them well enough. Precision parts, high-expense parts, may justify it.

T.F. Jones (McDonnell Aircraft Company): Your plot of the interfacial area of the crack versus the signal strength looked very good. I presume if the crack is off angle or crooked, the impor-
tant parameter would be the projected area of the crack perpendicular to the current lines. Is that roughly correct?

C.M. Teller: That's correct. That's what we found. We have looked at slots in various orientations to be able to characterize the orientation of the slot from the signal, and we have had good luck for 45° and 0° slots. If we have a slot with a very small but finite opening, we can still get an appreciable electric current signal with the current flow parallel to the slot. With the T crack, the sensitivity needed to detect the crack in that mode is something that we are working on. It is very difficult with a tightly closed crack, but that again is another piece of the characterization information that potentially can be obtained from this method, and we are investigating that.

M.D. Conley (AMF): Does your data from inside the bore indicate that the flaw is detected not only in its own group but in the neighboring groups as well, and, if so, why would that be the case?

C.M. Teller: Actually, the satellite signals that you see accompanying the primary signal are produced at each rotation of the spindle at that position where the flaw is. So, I'm not implying that the flaw was detected in the other threads but, in fact, we're seeing the flaw from that far away when the probe is not in a position directly under the flaw itself. I hope that's clear.

M.P. Conley: I realize that you were screwing the probe.

C.M. Teller: Right. It is screwed at the helix of the thread--the pitch of the thread.

J.P. Porter (Reinhart Associates): Have you looked at stress corrosion cracks where you might have a corrosion product that swings your conductivity considerably versus the case of an open crack that has zero conductivity?

C.M. Teller: Let me point out one thing. Most of our work has been directed toward fatigue cracks. The potential exists for addressing stress corrosion cracks; however, this technique is not the technique of choice for magnetic materials. If you are talking about stress corrosion cracks in steel, I would think a leakage flux approach would be preferable, or perhaps some adaptation of the ultrasonic surface wave detection of those near-surface cracks. But for stress corrosion cracks and nonmagnetic materials, this would have merit. We don't have any specimens. If you have some, we would be glad to give them a try.

C.V. Dodd (Oak Ridge National Laboratory): I know that you said that the width of the flaw was relatively unimportant, but could you give an approximate width for the actual flaw that you had? You gave one for the EDM notch.
C.M. Teller: The fatigue crack was grown at an R ratio of about .1 in tensile fatigue, and was quite tight. We did measure the opening of the crack under the peak load that was used in fatigue cycling, and when the crack was stressed, the opening of the fatigue crack under those conditions was about two-tenths of a mil. Now, when the load was released, the crack closed up very tight, so at least at the surface there was essentially no difference in the signal with and without load applied on the fatigue crack. The EDM notches that we used were typically 2 to 3 thousandths of an inch wide, and air bracing slots ranged as high as 10 thousandths of an inch wide. So we have two to three orders of magnitude change in defect opening.

C.V. Dodd: You mentioned that many of the results that you got were applicable to eddy currents. Do you feel that the relationship between the types of cracks and the crack widths are applicable?

C.M. Teller: I don't remember exactly putting it the way you mentioned, but I believe that the work that Beissner is doing and also that Bert Auld is doing will come together through some of the suggestions that Bert has made here recently using a reciprocity theorem. We intend to try to come up with a more unified theory for electromagnetic techniques rather than what has been in the past for eddy currents. And now we see things that are being done in eddy current that really aren't eddy current any longer: electric current perturbation—which is a terminology we've adopted. I suppose this would even carry over into the E field kinds of measurements that are being done with the potential drop measurement. I think a unifying theory here would be very beneficial to the whole community in terms of having a way of relating the responses from these various methods. Each has its own advantages and limitations, and as we truly understand these things from the theory, I think we are going to be able to take full advantage of their characterization potentials, and that's what we are really after here.