INTRODUCTION

This paper contains a brief status report on analytical modeling of the probe-flaw interactions for surface breaking cracks and some data on comparisons of theory and experiment for EDM notches and true fatigue cracks. The goal of the work reported here and in companion papers by Rummel and Rathke (1984), Auld, et al. (1984), and Martinez and Bahr (1984) is to improve the quantitative character of eddy current testing. In this joint effort, the role of probe-flaw interaction modeling is to provide engineering tools not previously available for: (1) setting design guidelines to optimize sensitivity and spatial resolution, (2) permitting analytic extrapolation of measured flaw response data, (3) defining a test basis for monitoring probe calibration, and (4) establishing a rational inversion procedure based on multifrequency measurements and the shape signature of a scanned flaw signal as a function of position.

The general dependence of flaw and liftoff response on probe geometry, workpiece conductivity and probe operating frequency is described in Eq. (1) and Fig. 1 of the paper by Auld, et al. (1984), emphasizing the importance of phase separation in discriminating between liftoff and flaw signals. A brief summary of the frequency dependence of liftoff and flaw signals was given by Bahr and Cooley (1983), with references to general literature on the subject. The earlier theories dealt exclusively with situations where the flaw is interrogated by an essentially uniform field. This is not a very realistic assumption for high sensitivity eddy current testing, where the flaw and probe must be roughly comparable in their dimensions. Figure 1(a) illustrates such a case, where it is obvious
that the field applied to the flaw is substantially nonuniform.
When the flaw is much smaller than the probe [Fig. 1(b)] approxi­
mately uniform excitation is obtained only if the flaw is directly
under the turns of the coil. As will be seen below, the flaw sig­
nal in either case varies significantly with the relative position
of the flaw, giving a "signature" characteristic of the probe-flaw
geometry. It is important to note that scanning the flaw along
$X_0$ in Fig. 1 gives maximum sensitivity because the interruption
by the flaw of the circular eddy current loops in the workpiece is
maximum.

HIGH FREQUENCY ($a/\delta > 1$) FLAW RESPONSE IN A NONUNIFORM FIELD

The literature of surface breaking crack signal analyses,
reviewed by Bahr and Cooley (1983) and Kincaid and McCary (1983),
treats the problem in either the low frequency regime ($a/\delta < 1$)
or the high frequency regime ($a/\delta > 1$). However, incomplete
evidence now suggests that optimum performance occurs at or
slightly above $a/\delta$ equal to one, where no satisfactory theory
yet exists. Furthermore, the practically important case of a non­
uniform interrogating field has not yet been treated for all flaw
generics and frequency ranges. Table 1 reviews the present
status of flaw signal modeling, showing that only in the rather
artificial case of a rectangular flaw is a completely parametrized
solution available for the nonuniform field case and then only for
$a/\delta > 1$. Muenemann, et al. (1983) developed the basic theory
for the case, worked out the details for both uniform and linear
interrogating field distributions (Fig. 2), and described a pro­
cedure for applying the results to the inversion problem. In the
present paper this approach has been extended to general field dis­
tributions obtained either by calculation or measurement of practi­
cal probes (Auld, et al., 1984). As in the 1983 paper it is as­
sumed that only the parallel component of the interrogating mag­
netic field interacts significantly with the flaw. In the present
Table 1. $\Delta Z$ Modeling Status

<table>
<thead>
<tr>
<th>Flaw</th>
<th>Uniform</th>
<th>Linear</th>
<th>Nonuniform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half Circle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a/\delta &lt; 1$</td>
<td>(a)</td>
<td>(a)</td>
<td>(d)</td>
</tr>
<tr>
<td>$a/\delta &gt; 1$</td>
<td>(a)</td>
<td>(b)</td>
<td>(b)</td>
</tr>
<tr>
<td>Part Circle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a/\delta &lt; 1$</td>
<td>(d)</td>
<td>(d)</td>
<td>(d)</td>
</tr>
<tr>
<td>$a/\delta &gt; 1$</td>
<td>(b)</td>
<td>(d)</td>
<td>(d)</td>
</tr>
<tr>
<td>Half Ellipse</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a/\delta &lt; 1$</td>
<td>(a)</td>
<td>(a)</td>
<td>(d)</td>
</tr>
<tr>
<td>$a/\delta &gt; 1$</td>
<td>(c)</td>
<td>(c)</td>
<td>(c)</td>
</tr>
<tr>
<td>Rectangle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a/\delta &lt; 1$</td>
<td>(d)</td>
<td>(d)</td>
<td>(d)</td>
</tr>
<tr>
<td>$a/\delta &gt; 1$</td>
<td>(a)</td>
<td>(a)</td>
<td>(a)</td>
</tr>
</tbody>
</table>

(a) Available  
(b) Possible  
(c) Probable  
(d) Doubtful

formulation, however, the magnetic field (rather than the magnetic potential) is expanded in terms of characteristic functions of the crack interior,

$$H_x = \sum_{n=1}^{\infty} \frac{B_n \cosh \left[ n\pi(z-a) / 2c \right]}{\cosh (n\pi a / 2c)} \sin \frac{n\pi x}{2c}, \quad (1)$$

where the $x$-direction is along $2c$ in Fig. 2 and the origin is at one edge of the crack rather than in the center. It should be emphasized that this analysis assumes a highly conducting workpiece, so that the accuracy is expected to decrease with decreasing conductivity. The resulting $\Delta Z$ again has the form shown in Fig. 2, but differs from the previous results in two important respects. In the present paper the workpiece conductivity $\sigma$ is not included in the definitions of the $\Sigma$'s and appears explicitly as an inverse overall multiplicative factor in the formula of Fig. 2. Furthermore,
the $\Sigma$'s are no longer real and vary with frequency in a complicated manner determined by the probe-flaw geometry and the workpiece skin depth. Software has been developed by S. Jeffries to implement this calculation with either theoretical probe fields (air-core) or measured probe fields (ferrite-core). Figures 3, 4, and 5 show examples calculated for rectangular shaped models of two of the fatigue cracks grown at Martin-Marietta (Rummel and Rathke, 1984). The scan direction is along $X_0$ in Fig. 1, and the results show that the shapes of the scanned signal curves are strongly dependent on the geometry and the operating frequency.

COMPARISON OF THEORY AND EXPERIMENT

Tests of the theory were performed primarily with EDM notches in aluminum alloy (kindly provided by A. J. Bahr of SRI International), because the theory is most applicable to high conductivity workpieces and because the flaw opening $\Delta u$ appears explicitly as a parameter in the $\Delta Z$ formula. Figure 6 compares the theoretical phase and magnitude of $\Delta Z$, calculated from the analysis above, with measurements performed, using the technique described by Muennemann, et al. (1984), on an EDM notch. The measurements were made by scanning along the $X_0$ direction in Fig. 1 at frequencies
Fig. 3. Scanned amplitude-distance signature for Martin-Marietta flaw 2-3. The mean coil radius is $\overline{r}$.

Fig. 4. Scanned phase-distance signature for Martin-Marietta flaw 2-3.
Fig. 5. Scanned amplitude-distance signature for Martin-Marietta flaw 5-1.

Fig. 6. Comparison of theory and experiment for SRI EDM notch in aluminum alloy (nominal dimensions, $a = 0.020''$, $2c = 0.050''$, $A_u = 0.010''$, $\bar{r} = 0.032''$).
corresponding to the $a/\delta$ values noted, over a range from 61 kHz to 432 kHz. Theoretical values were calculated for both a closed flaw with the same $a,c$ parameters and for the actual $\Delta u$ of the EDM notch. The results show very significant differences between the closed and open flaw responses, even at frequencies in the range of a few hundred kHz. In the experimental data on the right side of the figure, absolute phase (obtained by measurement relative to the signal generator phase and corrected for the bridge transfer function) is plotted. Only relative amplitude values are given. Comparison of theory and experiment for one of the other EDM notches in the SRI sample was also performed as a function of frequency with the flaw positioned at the center of the probe coil, where the interrogating field is most highly nonuniform (Muennemann, et al., 1984). In all of these experiments an air core coil with a mean radius of 0.032" was used (Coil 4 described by Auld, et al., 1984). We also report here some eddy current flaw response data taken by C. Fortunko and J. Moulder at the National Bureau of Standards in Boulder, as part of a collaborative effort with Stanford University (Fig. 7). These measurements were made with a "pancake" coil and bridge assembly similar to that reported by Muennemann, et al. (1983), but operating over a higher frequency range. Since the material (Inconel 718) has a relatively low conductivity, the $a/\delta$ point is at a much higher frequency. As expected from the theory, the phase separation of flaw and liftoff signals is very small. All data were taken with the coil centered by hand over the flaw, and the scatter in the results is probably due in part to positioning errors.

Figure 8 shows the only direct comparison made of theory and experiment for a fatigue crack, in this case the Martin-Marietta flaw designated 2-3, taken at 1 MHz with the same probe as the data of Fig. 6. The scan is along $X_o$ and shows the same general "signature" shape for theory and experiment. However, the theoretical data systematically predicts a reversal of phase near $X_o = 0$, regardless of the value of the crack depth $a$ (Case 4 used the crack depth estimated by Martin-Marietta). This unexplained discrepancy may be due to a difference between the shape of the rectangular model and the actual fatigue crack. Agreement is not nearly as good in this case as it was in Fig. 6, possibly because the signals are smaller (and corrupted by noise) and because these curves are for the Q-channel component of $\Delta Z$ (compared with the $\Delta Z$ curves in Fig. 6). In Fig. 8, as in Fig. 6, only relative amplitudes are plotted.

CONCLUSION

The basic nonuniform field theory of eddy current probe-flaw interactions (Muennemann, et al., 1983) has been extended to include general nonuniform interrogating field distributions obtained
Fig. 7. Measured flaw-liftoff phase separation for EDM notches in Inconel 718. (Fortunko and Moulder, National Bureau of Standards).
either theoretically or experimentally for real probes. For the first time, this theory has been compared directly with measurements on both EDM notches and a fatigue crack, with very good agreement in the first case but only approximate agreement in the second case. Only limited data were available for the fatigue crack comparison and further systematic experiments on fatigue cracks are indicated. Several possible explanations for the observed results can be proposed: (1) the EDM notches closely approximated the rectangular flaw shape of the theory, whereas the fatigue crack presumably did not; (2) the notches were in a high conductivity material, where the theory is most accurate, but the fatigue crack was in titanium 6-4; and (3) the fatigue crack comparison shape was not determined by subsequent destructive testing. All of these points need to be investigated in future work.
ACKNOWLEDGEMENT

This work was sponsored by the Center for Advanced Non-destructive Evaluation, operated by the Ames Laboratory, USDOE, for the Air Force Wright Aeronautical Laboratories/Materials Laboratory and the Defense Advanced Research Projects Agency under Contract No. W-7405-ENG-82 with Iowa State University; and the National Bureau of Standards under grant NB82-NAHA-3015. The magnetic field evaluation program for air-core probes was coded by D. Cooley of SRI International, and S. Jeffries of Stanford University coded the $\Delta z$ evaluation programs. Valuable guidance on bridge design and measurement techniques was provided by C. Fortunko and J. Moulder of the National Bureau of Standards.

REFERENCES


