SURFACE FLAW DETECTION WITH FERROMAGNETIC RESONANCE PROBES

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ABSTRACT

Eddy current methods of flaw detection have been in use for many years. Frequencies used in this type of flaw detector normally range from tens of kilohertz to a few megahertz. We report on recent progress using a resonant probe which operates in the gigahertz frequency range, and compare its performance with classical eddy current methods.

INTRODUCTION

Physical Configuration: The probe consists of a single crystal yttrium iron garnet (YIG) ellipsoid, less than a millimeter in diameter (Fig. 1). An external magnet lines up the magnetic (and angular) momenta of the electrons in the YIG, which then behaves as a precessing magnetic dipole. The crystal is in a wire loop at the end of a semi-rigid coax line, and an RF signal excites the resonant precession. Although uniform precession of all the electrons together is generally the dominant mode, other higher-order modes are possible. These modes are conveniently displayed experimentally on a network analyzer (with Smith Chart display), where each mode appears as a loop on the frequency-scan trace (Fig. 2).

Fig. 1. Probe geometry for flaw detection, showing spherical resonator and coupling loop.

Fig. 2. Display of resonator modes on the Smith Chart. Reflected amplitude is given by the distance of the trace from the center, relative phase by the polar angle. In this display, frequency is swept from about 850 to 950 MHz; the trace advances in phase as frequency increases.

Each mode has a characteristic distribution of magnetization within the YIG, and a characteristic external magnetic field. This oscillating field interacts with the test sample, inducing currents in it, which in turn change the strength (Q factor) and center frequency of each of the modes. Thus, the analyzer output from a cw input changes as a function of the distance to and conductivity of the test sample. This "wall effect" is well-known in YIG technology. Experimentally, we measure the impedance of the loop as a function of position on the test surface. We maintain the lift-off between 25 and 50 microns. Because the spatial distribution of the magnetic fields of the higher modes varies even more quickly than the dimension of the YIG, resolution is not strictly limited to the size of the probe. Since different modes can be accessed by changing the frequency of operation, a single probe can have many different "window functions", even though its physical configuration is unchanged. This allows us to discriminate the effect of lift-off from the presence of a flaw, and should ultimately make possible detailed quantitative flaw characterization.
Experimental Set-up: An end-on view of a probe used for flat samples is shown in Fig. 3. The YIG is mounted on a piece of microwave circuit board with a loop etched in it. Wire leads connect the ends of the loop to a semi-rigid coax line. A small SmCo magnet in a nearby brass holder maintains the necessary DC bias field. This is one of the latest generation probes, which has a standardized mechanical mounting for the coax cable, and SMA connector.

A block diagram for the network analyzer we use is shown in Fig. 4. Since flaw detection requires high-gain differential measurement, as well as compactness and portability, we use a miniaturized analyzer based on a phase discriminator, rather than a commercial network analyzer. The entire device weighs a few pounds, and is small enough to be carried with one hand. For most experiments, positional information as well as probe response is of interest; a mechanized translator with a Linear Voltage Differential Transformer (LVDT) provides this information.

**Theory**

Behavior of the Modes: Before attempting to invert the signal from the FMR probe, it is necessary to consider more closely the behavior of the modes. The magnetic bias field is not, in general, exactly parallel to the surface. This is not an experimental requirement, but allowing tilt of the field gives one more parameter for the user to optimize. Since all dimensions of interest are much larger than an electromagnetic wavelength in air (about 30 cm), we use the magnetostatic approximation throughout our calculations. Thus, we write the external field of the probe as a superposition of the fields of the individual modes

$$H = \sum M \phi_M$$  \hspace{1cm} (1)
Electromagnetic Field Interaction With Flawed Conducting Surfaces: The past several years have seen a renewed interest in theoretical research on eddy current probes. We will use much of this work as a foundation for our own theory; our ultimate goal is to invert the crack signature to obtain quantitative flaw parameters. The general approach we will follow is applicable to all eddy current measurements, although some features are specialized for the FMR probe. We will outline the method for prediction of the probe output from a given flaw geometry first, and then suggest means of inversion.

Beissner, et al. have shown that solutions for hydrodynamic flow of an incompressible, non-viscous fluid can be applied to electric currents in conductors. Analytic solutions exist for many special cases, and extensive numerical algorithms have been developed for the solution of this equation. The solutions we present here assume a uniform applied field, which is equivalent to a uniform far-field flow. Although this approximation is not in all cases realistic, it makes possible analytic solutions in both two- and three-dimensional geometries. It is clear from Fig. 6 that a probe with a uniform induction near the flaw will not have the null often found in standard probes. The FMR probe operating with the bias field nearly parallel to the surface is, in fact, such a probe.

Fig. 6. Patterns of surface eddy currents induced by different probe geometries. (a) Vertical probe (standard eddy current) induces currents with a null at the center. (b) Horizontal probe (FMR or modified standard eddy current) induces a uniform current in the vicinity of the probe.

We consider two limits: where the electromagnetic skin depth in the test sample is much smaller and much larger than the flaw dimensions (Fig. 7). The skin depth is given by the formula

\[ \delta = \frac{2}{\omega \mu_0} \]  

For Al and steel alloys, \( \delta \) is of order 1 micron at gigahertz frequencies, and 1 mm at kilohertz frequencies. For flaws with dimensions of order 1 mm, we see that low-frequency eddy current methods are often described by the small flaw approximation, and FMR-eddy current behavior is described by the large-flaw approximation. For microcracks, the small \( a/\delta \) form applies to FMR.

Fig. 7. (a) Three-dimensional view of currents induced when \( a \ll \delta \). The flow around the flaw depends almost exclusively on the flaw area, rather than on opening. (b) Same view of currents induced when \( a \gg \delta \). The currents cling to the sides of the flaw, and there is strong dependence on the flaw opening.

Small \( a/\delta \) Approximation: Beissner, et al. have shown that when the flaw depth is much smaller than the skin depth, the electric field obeys the equation

\[ \nabla^2 E = 0 . \]  

Although this work was done in connection with flux leakage methods, the result is applicable to eddy current as well. In Fig. 8, we illustrate such solutions for a three-dimensional void (analogous to a nonconducting inclusion or a widely opened crack) and a half-penny shaped crack. A feature of small-flaw detection which becomes immediately apparent is that the magnitude of the current disturbance is dependent primarily on the area rather than on the volume of the flaw. For flaw detection and sizing, this implies that crack opening measurements will be extremely difficult to make.
Large $a/\delta$: For the case where skin depth is much smaller than the flaw dimensions, we can neglect the current normal to the surface. We thus have

$$ (\text{two-dim laplacian}) \ E = 0 \ . \quad (5) $$

This is mathematically identical to the problem of a two-dimensional incompressible, non-viscous flow on a curved surface. Dover et al. have devised a clever means of unfolding the surface to reduce the problem to a hydrodynamic flow in two dimensions with a boundary. It should be emphasized that this is an entirely analytic solution.

Electromagnetic Fields: To relate the behavior of the currents induced in the sample to the observed impedance of the probe, we consider the fields near the conductor. Throughout this discussion, primed fields are to be taken in the presence of the flaw, while unprimed fields are to be taken for the case of an unflawed conductor. From the reciprocity relation it can be shown that the change of probe impedance produced by a flaw is

$$ \Delta Z = \frac{1}{I^2} \int_{S_F} (E \times H^\prime - E^\prime \times H) \ dS \ . \quad (6) $$

Note that the surface of integration is over any volume containing the flaw; therefore, only changes between the primed and unprimed fields need to be taken into account when evaluating the integral; changes in geometry appear only in the fields.

For the high $a/\delta$ case we use the plane of the unflawed conductor as the surface of integration. We then have three regions to integrate over: to the right and left of the flaw, and over the flaw opening. The normal vector to the surface of integration is in the $z$-direction. $H$ is assumed to lie in the $y-z$ plane. This permits us to write the cross product in the $\Delta Z$ formula as

$$ (E \times H) \cdot \hat{n} = E_x H_y \ , \quad (7) $$

from which we are able to write for a two-dimensional crack

$$ \Delta Z = \frac{|H|^2}{I^2} \int_{0}^{\infty} (E_x^\prime - E_x) \ dX \quad (8) $$

where $\chi$ is normal to the flaw line. Further development leads to the formula

$$ \Delta Z = \frac{|H|^2}{I^2} \left\{ \frac{i \omega_0 \alpha u}{\sigma} + \frac{i \omega_0 \alpha u}{2} - (1+i) \frac{\Delta u}{\delta} \right\} \quad (9) $$

which directly relates the change in impedance due to the flaw to the crack opening displacement. Here, $\Delta u$ is the crack opening displacement, $a$ is the depth of the flaw, $\mu$ is the frequency of operation, $\delta$ is the skin depth, $I$ is the current in the loop, and 0.28 is a geometrical factor.

This simple inversion formula discards much information, since the physical model used does not allow for three-dimensional cracks or nonuniform induction by the probe; it also does not attempt to describe the detailed behavior of the probe as it is scanned over the flaw. Far-reaching conclusions can, however, be drawn from this model, as will be seen.

For the low $a/\delta$ case, a similar formula is obtained,

$$ \Delta Z = \frac{|H|^2}{I^2} \left\{ \frac{i \pi a}{\delta} + \frac{a u}{2} - (1+i) \frac{\Delta u}{\delta} \right\} \quad (10) $$

Note that in both formulae, the dependence on crack opening grows linearly with frequency. This implies that to see crack opening, it is necessary to use a high-frequency probe.

The reciprocity relation also leads to a simple three-dimensional inversion solution for a semi-circular surface crack in the low $a/\delta$ limit which bears a remarkable resemblance to the low-$\kappa_a$ scattering formula for acoustic Rayleigh wave scattering.11 The formulae for the reflection coefficient/impedance change are

$$ \Delta Z = \frac{1}{I^2} \int_{S_F} \Delta \phi \cdot \hat{n} \ dS \quad (\text{electromag.}) \quad (11e) $$

$$ \Delta \Gamma = \frac{4 \omega}{4 F} \int_{S_F} \Delta u \cdot \hat{n} \ dS \quad (\text{acoustic}) \quad (11a) $$

Note that $\Gamma$ and $Z$ are related by the formula

$$ \frac{Z}{\Gamma_0} = \frac{1+\Gamma}{1-\Gamma} \ \quad (12) $$

Here, $\Delta \phi$ is the electric potential across the flaw, and $\hat{n}$ is the electric current density. $\Delta u$ is the crack opening displacement, and $\Gamma$ is the acoustic stress. In both formulae, the leading multiplicand accounts for the power input to the probe/transducer. The electric potential across the crack and the crack opening displacement are
The crack opening displacement, \( \Delta u \), is given by:

\[
\Delta u = 2 \pi \left( \frac{1 - \nu}{\mu} \right) \left( a^2 - r^2 \right)^{\frac{1}{2}}
\]

where \( r \) is the radius of the semicircular crack.

An important parameter for stress analysis is the stress intensity factor, \( k_I \), given by:

\[
k_I = 2 \sqrt{\frac{P}{\pi}}.
\]

The inversion formulae for the stress intensity factors are:

\[
\Delta \sigma \sim \frac{f}{k_I} \left( \frac{r}{a} \right)^2,
\]

\[
\Delta \tau \sim \frac{f}{k_I} \left( \frac{r}{a} \right)^2.
\]

Again, the formulae are almost identical, except that acoustic stress replaces the current density, and \( \Delta u \), the crack opening displacement, replaces the potential across the flaw. This result is not surprising when one compares the overall physical configuration of the two probes involved (Fig. 9).

\[
\text{Fig. 9. Comparison of geometries for low } k_a \\
\text{ detection in ultrasonic surface wave detection scheme and for eddy current.}
\]

Although this case will only arise for micro-cracks when using the FMR probe, it provides a useful inversion method for low frequency eddy current testing.

**Signal Interpretation:** A typical flaw signature is shown in Fig. 10. To obtain this trace, the offset controls are used to center the probe response on the CRT. Gain is then increased, and the probe is mechanically scanned over the sample. Lift-off is 25 - 50 microns, and is maintained as constant as possible. The trace moves back and forth along the lift-off curve due to small variations in the vertical position of the probe relative to the surface. The loop occurs as the probe passes over the flaw.

To generate a "map" of the surface, the display is electronically rotated so that the lift-off curve is as nearly as possible parallel to the horizontal direction. Then the response in the vertical direction (perpendicular to lift-off) is plotted against the LVDT output. The operator monitors lift-off via the horizontal channel. A typical response to a fatigue crack in Aluminum alloy is shown in Fig. 11, together with an optical micrograph of the crack. Note that the probe response matches the photograph in overall features, but is insensitive to surface scratches which clutter the optical picture. Although photography required the crack to be stressed open for visibility, the probe easily detects and maps the flaw even when tightly closed. Computer programs are now in the development phase to provide maps with better lift-off discrimination, close correlation to actual flaw depth, and higher resolution.
and uniformity of the magnetic field provided by the external magnet; it is also dependent on the shape of the coupling loop, and its orientation with respect to the crystal structure of the YIG. This large number of variables offers almost unlimited possibilities for the optimization of probes for specific sample geometries.

More information is extracted from the signal by considering the two-dimensional trace, rather than the "separated" flaw signal. At present, this is on an entirely empirical basis; numerical evaluation requires more theoretical development of the probe behavior.

Comparison With Standard Eddy Current Tester: We have compared several aspects of the FMR probe performance with that of a commercial tester. By calibrating the actual impedances of the two probes, we compare sensitivity to tightly closed fatigue cracks and to saw cuts in 6065 aluminum alloy (Figs. 12(a) and (b)). As expected from Eq. (1), the FMR probe is much more sensitive to opening of a flaw. Whereas the responses of the two probes are almost the same for a fatigue crack, the FMR signals for the saw cut (which is electrically very similar to a widely opened fatigue crack) is more than 20 times as large!

As outlined above, theory predicts that the dependence of the signal on flaw opening varies linearly with frequency (see Eq. (9)). Thus, the FMR probe is much more sensitive to crack opening by virtue of its high frequency of operation. This is especially important in fracture mechanics experiments.

The spatial resolution of the FMR probe is also much higher than that of the standard eddy current probes tested (Fig. 13). A trial with a high-resolution differential probe gives somewhat improved results, although the differential nature of the probe tends to obscure the response; resolution of the device examined was still much less than FMR. The FMR probe is much easier to produce than any low-frequency probe we know of which approaches its resolution.

A situation commonly encountered in NDE is a crack at a corner or edge. Often, special eddy current probes are designed for this type of detection, since the coupling to the sample decreases as one approaches the edge. This effect is also present in the FMR probe. The use of smaller (higher spatial resolution) probes enables us to see an edge crack 1.7 mm by 0.5 mm in a Ti alloy bar (Fig. 14). This crack is particularly interesting because it was not intentionally initiated. The other feature in the map has no optical counterpart in microphotographs of the flawed region; we speculate that it may be a subsurface inclusion related to the initiation of the edge crack.

**Fig. 12.** Low frequency and FMR responses to crack opening. The low frequency signal is almost the same for a fatigue crack and a saw cut, while the FMR signal for the saw cut is 20 times larger!

**Fig. 13.** Spatial resolution of a typical low-frequency probe operating at 1 MHz, and the FMR probe. The sample was an aluminum bar with slots cut 0.02" apart. The low-frequency probe totally fails to resolve the slots.
APPLICATIONS

The primary advantages of this type of probe over other NDE methods are:

1) Accessibility to confined areas of complex geometries: Probes can be made smaller than 1 mm in diameter.

2) Probes are sensitive to small flaws, and give quantitative flaw parameters. Spatial resolution is high.

Thus, the primary application is in the testing of complex nonmagnetic parts; these are typically found in aircraft turbine engines. The probe has proven its usefulness as a means of studying fracture mechanics in the laboratory. Yet another potential application would be as a proximity tester. Because the probe is scanned mechanically, its ideal environment is in a computer-controlled robot system, where precision positioning and signal interpretation would be performed by the same computer.

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REFERENCES


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SUMMARY DISCUSSION

Jim Martin, Chairman (Science Center): Thank you very much, Frank. Those are pretty results.

Are there any questions?

Frank Muennemann (Stanford University): We'll take theoretical questions.

Amrit Sagar (Westinghouse Electric): Talking about resolution, have you tried current density probes at low frequencies? Because I'm surprised the resolution you show is not very good.

Frank Muennemann: The two-megahertz probe we used was one which was especially designed for GE. It's a differential probe which has two coils very tightly wound. It was designed for high resolution.

Amrit Sagar: The other question is: How close to the boundaries can you pick up the cracks?

Frank Muennemann: The crack in the titanium was directly at the edge. It is primarily because we have a small probe that we can see this crack. It is only 1.7 millimeters long; we can detect flaws correctly up to an inch.

Amrit Sagar: Supposing we have a cube and the crack is close to the edge of the cube. Can you pick it up?

Frank Muennemann: Yes, we can pick it up.

Unidentified Speaker: You said your nearest scan was 15 millimeters from the edge?

Frank Muennemann: Yes.

Al Bahr (SRI): Do you every let your probe touch the surface as you scan, or does that introduce a lot of noise?

Frank Muennemann: Yes, it does touch the surface during the scan. Actually we use it as a means of calibrating the lift off. When the probe touches the flaw there is a slight deformation since it is set in epoxy. A fairly large signal results. You cannot let the probe actually drag on the surface.

Jim Martin, Chairman: One more question and I would like to move on.

Bill Reynolds (AERE, Harwell): Have you thought of using this probe for examining carbon fibre reinforced plastic?

Frank Muennemann: We thought of it. We do not have any samples at the moment. However, it should be pointed out that this will work best in high conductivity materials.

Bill Reynolds: Low frequency eddy current probes are usable in FRP.

Frank Muennemann: That might be encouraging.

Jim Martin, Chairman: Thank you, Frank.