SURFACE FLAW DETECTION WITH FERROMAGNETIC RESONANCE PROBES

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ABSTRACT

Small ferromagnetic resonators have been shown to provide effective electromagnetic detectors for surface flaws in magnetic and nonmagnetic metals. As such a resonator is moved along the surface of a test piece it experiences a frequency shift when it passes over a flaw. Two detection mechanisms are present: (1) an eddy current effect (2) a perturbation of the dc magnetic bias field used to tune the resonator. Results are given for experiments performed on machined slots in aluminum, titanium and steel and on tightly closed fatigue cracks in titanium. Results are also presented for some measurements on titanium aircraft fasteners.

INTRODUCTION

This paper is concerned with reporting progress made during the past year on ferromagnetic resonance probes for NDE, first reported at the Cornell Meeting last year. The program during this period has been a joint effort involving Stanford, where the focus has been on developing two concepts and performing preliminary experiments on various probe geometries, and the Rockwell Science Center, where attention has been directed to test sample preparation and the development of more sophisticated electronics.

The basic geometry is illustrated in Fig. 1 which shows a spherical sample of ferromagnetic crystal, yttrium iron garnet (YIG) or gallium-doped YIG, placed in a dc magnetic bias field and excited with a single-turn coupling loop containing $H_{dc}$ in its plane. It is the extreme simplicity of the structure that makes it attractive compared to a conventional eddy current probe and the rigidity of construction that gives it an advantage over a Hall probe for DC NDE applications (flux leakage and magnetic particle techniques). Resonance of the YIG sphere takes the form of a procession of its magnetic dipole moment about the dc magnetic field as shown in the figure. The resonant frequency is controlled by the strength of the dc field and lies typically above 2 GHz. At these frequencies the skin depth in a good conductor is of the order of microns, much smaller than the flaw dimensions. This means that the eddy currents do not flow in depth around the surface flaw, as in conventional eddy currents, but enter its interior from the surface. An advantage of the feature is that it concentrates the current at the flaw. The probe is a detector of surface topography, the frequency of the resonator being perturbed by the changes in the surface current pattern as they flow into the flaw. One of the purposes of the present research is to develop a theory relating detection signal and flaw dimensions in this type of eddy current system. The presence of the magnetic bias field in Fig. 1, and its frequency-determining character, account for the dc mode of flaw detection with a ferromagnetic resonance probe. If the test piece shown is a magnetic material, the dc field at the resonator will change and this will cause a shift in resonant frequency. Our initial experiments were performed on long machined slots in aluminum, as shown, but more recently a series of experiments has been made on EDM notches in titanium and steel and on tightly closed fatigue cracks in titanium.

THEORY

It is clear from Fig. 1 that a number of different probe configurations are possible depending on the orientation of the dc field - tangential or normal to the surface, parallel or perpendicular to the slot. A general theory for all geometries has been developed under support of the NSF Thrust Program on Nondestructive Evaluation at Stanford. The basis of this theory is the Lorentz reciprocity relation in its form applicable to gyromagnetic media.

$$\nabla \cdot (H_1 \times E_2 - H_2 \times E_1) = 0 \tag{1}$$

where subscripts 1 and 2 indicate two solutions to the field equations and the caret indicates that the magnetic bias field is reversed. This relation is integrated over the volume enclosed by a surface around the test piece, a surface enclosing the signal generator and a closure surface at infinity. In the vicinity of the resonator and the flaw the microwave magnetic field is represented by the quasistatic approximation, using a scalar potential $\phi$. This differs from the theory of conventional eddy current testing, where a vector potential is used, but it is standard in ferromagnetic response theory and poses no problems at microwave frequencies, where the currents are confined to the surface of the test piece and flaw. After performing the manipulations described in Ref. 1, one arrives at the following relation for the changes in resonator frequency and $Q$ due to the presence of a flaw

$$\frac{\delta \omega}{\omega_o} = \frac{160 \alpha_s}{20 \omega_o} \frac{\int_{S_F} \nabla \cdot \phi (2 \alpha_s/3\pi) \phi(2 \alpha_s/3\pi) ds}{2V}, \tag{2}$$

where $S_F$ is the surface opening of the flaw, the $1$ and $2$ potentials are in the absence and presence
of the flaw, respectively, the carat indicates reversed bias field, and $V$ is the stored energy in the resonator.

Equation (2) is an exact expression but, because of the complication of the geometry, it is necessary to use approximations in evaluating the potentials $\phi_1$ and $\phi_2$. From an electromagnetic point of view a small slot of finite length is a waveguide below cutoff, and certain characteristics of the system can be deduced directly from this fact. That is to say, the depth of a flaw can be determined only if it is less than the decay distance of the least cut-off mode. On the basis of an approximate wave theory one finds that the detectors limit for a deep slot, with 10-to-1 length-to-width ratio, is of the order of 0.002 inch, when using a 15 mil diameter YIG probe. For the long slot test geometry shown in Fig. 1, the length of the slot is not a relevant parameter, because the probe fields are concentrated only in its vicinity, Fig. 2b, and the slot can be considered to be of infinite length. In this case, it is appropriate to express the potentials $\phi_1$ and $\phi_2$ as Fourier integrals along the $z$ direction.

Since the potential $\phi_2$ within the slot is a solution to Laplace's equation, each component of the spatial Fourier spectrum is of the form

$$\hat{\phi}_2(k) = A(k) e^{-ikz} \quad (3)$$

This shows that the higher spatial frequency components decay more rapidly with flaw depth, indicating that the spatial frequency content of the probe fields should be carefully chosen to optimize the sensitivity to depth — which is the critical parameter in a surface flaw. Because of the normal derivative of the second factor in Eq. (2), the $k$-dependence of the detection sensitivity goes as $kA^2(k)$. Figure 2(b) shows that the quantity passes through a maximum as a function of $k$. In order to measure the depth of a relatively deep flaw, it is necessary that most of the spectral energy be concentrated at low values of $k$ and, as shown in Fig. 2, this feature is realized by using a spatially extended probe. From this general type of reasoning one may conclude that, in detecting a long slot with a spherical YIG probe, variations in depth do not become observable until it is less than the probe diameter. This effect will be noted in the experimental results of the next section. It should be noted in passing that the quasi-static potential approximation does not apply for all values of $k$ down to zero in Fig. 2. However, the interesting structure of the curves occurs for $k$'s of the order of (probe diameter)$^{-1}$, or 100 cm$^{-1}$, while the quasi-static approximation breaks down for $k$'s of the order of (EM wavelength/10)$^{-1}$, or 1 cm$^{-1}$.

All of our experiments to date have been performed with the one-port resonator system shown in Fig. 1. However, the electronics being developed at Rockwell Science Center is aimed at a two-port resonator circuit because of its advantages for separating changes in resonator frequency and $Q$. The theory for this case has also been treated in Ref. 1. Within either context the probe may be operated either passively, as a resonator whose reflection or transmission characteristics may be observed by sweeping either frequency or field and observing the resonance line on a scope, or actively, as a YIG-tuned oscillator. In the latter case, the minimum detectable frequency shift, and, consequently, the minimum detectable flaw size is reduced by the narrower spectral width of the active system.

**MEASUREMENTS ON LONG MACHINED SLOTS IN ALUMINUM**

The first series of measurements were made in the geometry$^3$ using the passive probe illustrated in Fig. 3. where the YIG sphere is seen as the black dot at the center of the aperture in the base. The resonator is protected by a layer of plastic tape, which also serves to define the lift-off distance. Orientation of the dc magnetic field, produced by samarium cobalt bars (the dark strips on either side of the resonator), is tangential to the surface. The resonator is pure YIG and operates at 3.6 GHz. Figures 4 and 5 show measured frequency shifts as a function of slot width and depth. Note that the depth begins to affect the frequency shift only below 10-20 mils, that is, at depths comparable to the 15 mil diameter of the YIG sphere.

The same series of slots were measured with an active probe consisting of a standard negative resistance type of YIG oscillator (Fig. 6), again with tangential field. This is not the optimum circuit design for the application but has the advantage of being easily constructed as a direct copy of existing devices. The experimental results in Figs. 7 and 8 show the same general type of depth behavior as the passive probe. It is evident that the frequency shifts are large, even compared with the natural resonance width ($\approx 3$ MHz) of the passive system. Measurements on more realistic models are reported below.

**MEASUREMENTS ON EDM SLOTS AND TIGHT FATIGUE CRACKS IN TITANIUM**

These samples, which were fabricated by Murray Mahoney at the Science Center, were tested at Stanford - the EDM slots by Elston and the tight fatigue cracks by Elston and Fortunato. The notable features of these results (Fig. 9) are that shifts are very large for the slots and that the shift for the tight cracks is in the opposite sense (position) to that for the open slots. The latter effect is to be interpreted by opening the crack under load. It is also noteworthy that the first and fifth entries in the upper table indicate a distinct depth sensitivity, which is more pronounced in the perpendicular field configuration. The tight cracks were also tested with the passive probe, giving comparable results.

**MEASUREMENTS OF EDM SLOTS IN MAGNETIC STEEL**

The previous tangentially-magnetized probes cannot be used on magnetic test pieces because the high permeability path across the magnet poles pulls the field away from the YIG resonator and destroys the resonance. In this case it is necessary to use the normal field geometry shown in Fig. 10. Figure 11 illustrates one of two similar probes of this type. The miniature co-axial feed line passes through a hole drilled in the samarium cobalt magnet and the YIG resonator, seen as a black dot in the photo, is mounted on a straight wire or half-loop coupler. Figure 12 shows a spring-loaded micrometer controlled scan mount for this type of probe. Using the arrangement, the measurements shown in Fig. 13 were taken. By
shielding the microwave currents from the steel sample by means of an aluminum film of thickness greater than a skin depth, it was determined that the observed frequency shift was almost entirely due to the shift in dc magnetic field due to the pressure of the flaw. This phenomenon appears to offer great promise as a method for performing magnetic particle detection in a quantitative manner. YIG probes do not suffer from the mechanical fragility of Hall field probes. Figure 14 shows a calibrated series of lift-off and displacement measurements on steel using the arrangement in Fig. 12, giving an indication of the stability of the device. Some preliminary tests have been made with this probe on tight cracks in steel, provided by Phil Hodgetts of Rockwell International, Los Angeles Division. These have not yet been detected and further work is needed to reduce the resonance line width of the normal field probe which is not yet as good as for the tangential field probe.

AIRPLANE FASTENERS

Some initial measurements have also been made on flaws in titanium airplane fasteners, provided by K. J. Law. The longitudinal seam type of flaw (Fig. 15) was easily detected. They were estimated to be 8-10 mils wide and 5 mils deep and gave frequency shifts in the range of 6 to 9 MHz. The shear head cracks were not detected because a pronounced step at the crack edge made it impossible to traverse the crack with the type of mounting arrangement used. It is not, apparently, a difficult problem to solve but further study of mounting and scanning techniques will be required.

CONCLUSION

It has been demonstrated that the YIG ferromagnetic resonance probe is capable of easily detecting flaws of practical interest. Nevertheless, the work to date is still very exploratory in nature and more detailed calibration and comparison with theory will be required to accurately establish the limits. More complete measurements on loaded and unloaded fatigue cracks, as well as on fabricated slots of dimensions smaller than the probe will be required for this purpose. In addition, the theory needs to be extended to allow for the effects of material and contact losses in cracks and to explain the difference in behavior of open and closed cracks. Further parameters to be investigated are the influence of oscillator noise and lift-off fluctuations on the ultimate detection sensitivity and the effect of probe geometry on depth detection capability.

REFERENCES


Fig. 1 Ferromagnetic resonator configuration featuring in-plan dc magnetic bias and rf coupling loop.

Fig. 2 (a) Spatial Fourier eddy current distribution spectra for an extended and localized ferromagnetic probe. (b) Relative depth sensitivity functional for above.
Fig. 3 Passive YIG probe with tangential dc magnetic field bias viewed from the bottom.

Fig. 4 Measurements of cracks in aluminum samples using passive probe with field tangential to surface and parallel to face of crack. Operating frequency was 3600 MHz.

Fig. 5 Measurements of cracks in aluminum samples using passive probe with field tangential to surface and perpendicular to face of crack. Operating frequency was 3600 MHz.

Fig. 6 Negative resistance active YIG probe viewed from the top.

Fig. 7 Measurements of cracks in aluminum samples using active (YIG oscillator TOR) probe with field tangential to surface and parallel to face of crack operating frequency was 1900 MHz.

Fig. 8 Measurements of cracks in aluminum samples using active (YIG oscillator TOR) probe with field tangential to surface and perpendicular to face of crack. Operating frequency was 1900 MHz.
<table>
<thead>
<tr>
<th>TITANIUM SAMPLES</th>
<th>(CRACK WIDTH = 10 mils)</th>
<th>( \text{CRACK LENGTH (mils)} )</th>
<th>( \text{DEPTIMILS} )</th>
<th>( \text{FREQUENCY SHIFT WITH FIELD PERPENDICULAR TO CRACK (MHz)} )</th>
<th>( \text{FREQUENCY SHIFT WITH FIELD PARALLEL TO FACE OF CRACK (MHz)} )</th>
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<th>CLOSED CRACKS</th>
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<td>46 133 2</td>
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Fig. 9 "Open" crack measurements taken using passive probe operating at 3600 MHz. "Closed" cracks measured using active (YIG oscillator) probe operating at 1900 MHz. Field is tangential to surface in both probes.

Fig. 10 Detection of an open crack using a spherical ferromagnetic resonator with normal DC magnetic field bias.

<table>
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<tr>
<th>STEEL SAMPLE</th>
<th>(CRACK WIDTH = 5 mils)</th>
<th>( \text{CRACK DEPTH (MILS)} )</th>
<th>( \text{CRACK LENGTH (MILS)} )</th>
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Fig. 11 Detail of the miniaturized probe with normal DC magnetic field bias.

Fig. 12 Spring loaded scan mount for YIG probes.

Fig. 13 Data from steel sample using passive point probe with field normal to surface at a frequency of 1900 MHz.
Fig. 14 Frequency shift over steel as a function of lift-off and distance from the crack. Field is normal to surface. Operating frequency was 2200 MHz. Data was taken using the miniatuerized probe shown in Fig. 11.

Fig. 15 Longitudinal seam type flaw in titanium airplane fasteners.
DISCUSSION

Tom Moran (AFML): What would be the natural line width of the apparatus?

B. A. Auld (Stanford University): If you use a good, uniform field, the line width is less than an oersted.

Tom Moran: What was the measured line width?

B. A. Auld: To give you an example, and I see Chris Fortunko has his hand up (he may give you a better answer than I), the last probe that we measured had a 12 megahertz line width. On the other hand the first probe I showed, the 3600 gigahertz probe with two magnets on the sides, had a width of three oersted, which is, maybe, not more than a factor of two above that of the material. You raise a good point. You must be careful of the magnetic field.

Don Forney (AFML): Bert, what would your YIG sphere see if you brought it next to the surface of a magnetized steel part where the strength of the field varied from point to point?

B. A. Auld: It would move it around a great deal. The frequency would shift. Roughly, it would shift about three megahertz for every oersted change in the field. So it would be very, very sensitive to these changes in the field.

Don Forney: Perhaps you might have a device that could measure variation in field strength from point to point that might do a better job than a Hall device. Is that a fair statement?

B. A. Auld: It certainly could be used for that purpose. On the other hand, these YIG spheres have been around for a while and people still use all probes. I think the accuracy of a Hall probe is better.

Chris Fortunko (Science Center): I would like to point out that when you pass the YIG sphere over a non-uniform magnetic field, then the shape of the line also changes because other modes may be excited and that may be an indication of a sudden change in the magnetic field. We did see that at the Science Center when the YIG sphere was mounted on a substrate with a cobalt lead-in wire.

B. A. Auld: The lines distort and you can also see, as Chris pointed out, that the height of the line changes. Seeing Chris standing up there talking reminds me of something I forgot to say. The tightly closed fatigue cracks that Chris brought up and measured with Ellston showed that with an open crack or slot the frequency shifted down, and with a tightly closed crack it moved up. We have no idea why that happens, but it seems to be something very significant.

Robert E. Green (Johns Hopkins): That would apply to a certain type of crack that won't be detected at all.

B. A. Auld: Nature being what she is, I would believe that.

William Lord, Chairman: At this point we'd better move on to the last paper today.