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PROPOSED METHOD OF CORRECTING MAGNETIC RECORDING BORESCOPE RESULTS FOR DETECTOR LIFT-OFF VARIATIONS

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Technical Report by

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ABSTRACT

The functional dependence of leakage field strength, associated with a crack-type defect, on the distance from the crack has been experimentally determined. Field strength measurements were used to generate empirical expressions relating the leakage field strength to lift-off distance. Equations were written for the normal and horizontal field components and the partial derivative of the horizontal component of the field strength with respect to horizontal distance from the crack, based on the assumption of a semicircular field pattern. Comparison of calculated values and the experimental data demonstrated that, over the range of interest, the semicircular field assumption adequately describes the field. Results of the analysis of the leakage field surrounding a crack suggested a method of correcting for the uncontrollable variations in lift-off which occur during magnetic recording borescope inspection of large caliber gun tubes. Curves required to make these corrections have been established for two specific types of detectors and a procedure for making the correction utilizing these curves is presented. Practical application of the correction to gun tube inspection is considered.

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INTRODUCTION

Recently there has been renewed interest in utilizing a magnetic scanning technique to nondestructively inspect the bore of large caliber cannon tubes for cracks running in the longitudinal direction. Although there are recognized limitations to the technique, there are also certain practical considerations which make it quite attractive, compared with other available methods, for quickly locating and determining the general severity of existing cracks in fired gun tubes. For example, a rather extensive portion of a premagnetized tube can be completely scanned in minutes and a permanent recording made which depicts the variation of magnetic leakage field intensity over the bore surface. At their present stage of development, other methods such as ultrasonics require access to the outside diameter which restricts their application on some tubes, notably the 175 mm.

Recurrence of the need to nondestructively examine the bore of cannon tubes for firing-induced fatigue cracks resulted in the development of a new scanning system designed specifically for inspecting the 175-mm gun tubes for firing damage. This scanning system was utilized in an extensive program conducted at Yuma Proving Ground and Aberdeen Proving Ground during the period from January 1967 through July 1967. The results of this test program and additional work that has been done more recently show conclusively that the system known as the magnetic recording borescope (MRB) is capable of detecting and showing the location, length, and relative amplitude of leakage fields caused by cracks in 175-mm gun tubes.[1] A description of the scanning system, inspection procedures, and a summary of the results of the test program are also given in Reference 1.

A major limitation of the magnetic method of crack detection is its inability to predict crack depth with the desired accuracy. An example of this is shown in Figure 1, where the signal amplitude of an inductive-type tape head detector is plotted as a function of the crack depth measured after the tube had been sectioned. Though there is a general trend between signal voltage and crack depth, the band over which data points fall is quite wide. There seem to be two major reasons for this scatter. First, variations in crack geometry, i.e., the width of the crack or effective air gap, the angle of inclination of the crack with respect to surface, and surface contour, effect the intensity and shape of the leakage field associated with the crack. The second, the effect of variations in lift-off of

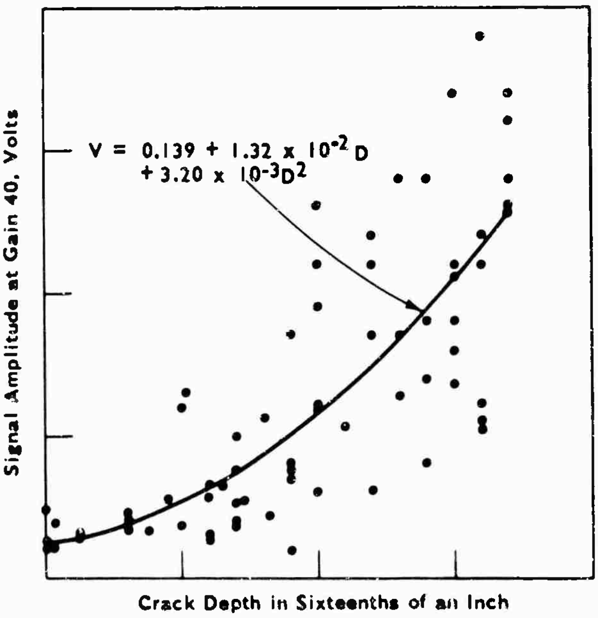


Figure 1. RELATION BETWEEN PEAK-TO-PEAK SIGNAL AMPLITUDE AND CRACK DEPTH MEASURED IN SIXTEENTHS OF AN INCH. Curve represents best fit by method of least squares where V is signal voltage and D is crack depth.

the tape head from the surface, is the source of error with which we will be concerned here.

The detailed design and performance description of the MRB scanning system are found in Reference 1. The only feature of the system that is relevant to the subject of this paper is the detector and the method by which it is maintained in contact with the bore surface. Figure 2 is a drawing of the detector head assembly. This assembly is held in contact with the bore surface by the centrifugal force developed by rotating the head at 300 rpm.

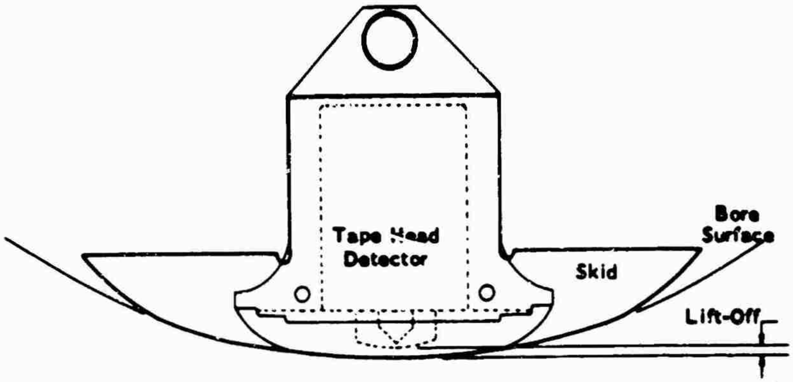


Figure 2. DETECTOR (TAPE HEAD) HOUSING ASSEMBLY OF THE MRB SCANNING UNIT

As long as a smooth bore condition exists, there is no problem in maintaining the detector at a fixed, predetermined distance from the bore surface and no errors result from this source. Unfortunately, erosion that occurs in the bore of a cannon often results in an undulating surface even after the rifling has been completely obliterated. When the rotating head assembly hits these surface irregularities it is quite apt to bounce off the surface a significant distance. The severity of the bouncing, which effects the signal voltage, depends on the material from which the skids of the detector housing are made and the roughness of the surface. During the test program previously mentioned, variations of up to 50 percent were observed in a single signal from one rotation of the head to the next. It has been general practice to use the highest amplitude signal since there is no way for the detector to get closer than the preset distance to the bore surface. However, the highest recorded amplitude of the defect signal may still represent the signal amplitude at some lift-off greater than the preset value because of surface irregularities.

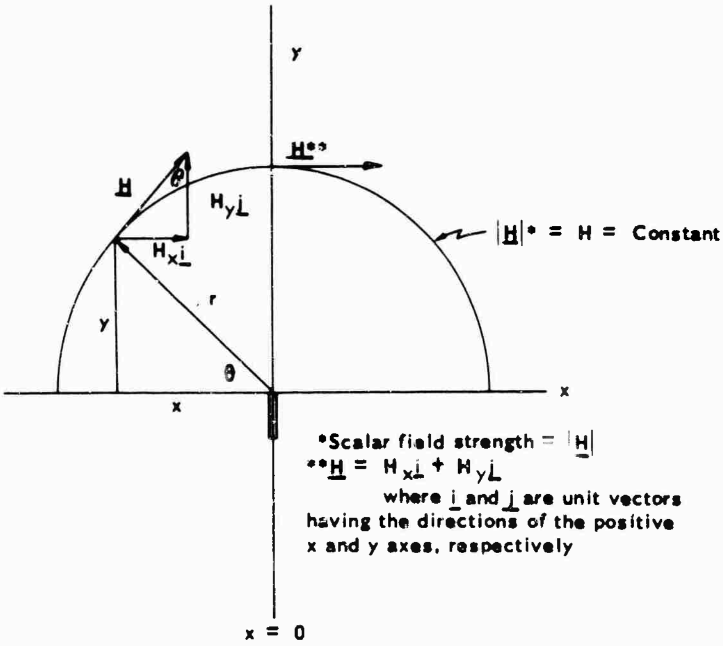
Under the conditions normally encountered in a fired gun tube, small variations in the lift-off distance cannot be eliminated. Because even small changes in the lift-off of the detector can cause rather large variations in signal voltage, a means of making corrections for this effect would be very desirable. The purpose of this paper is to show how such a correction might be made and applied to the gun tube problem under conditions where the rifling has been nearly or completely obliterated by erosion.

BACKGROUND

Recently Gericke[2] carried out an analysis based on an inverse-square-law variation of field strength and a semicircular field pattern about a crack. The coordinate system shown in Figure 3 was used in making the calculations. One of the important results of his analysis was that the ideal time or distance separation between the maxima and minima of the voltage developed in a tape head detector was found to be directly related to the lift-off distance. This result was especially valuable because it suggested a means of correcting crack signal amplitudes, measured during MRB inspection of gun tubes, for errors resulting from uncontrolled variations in lift-off. The development of such a procedure was the main objective of this investigation.

The field around a current-carrying wire has been found to be a useful analog to the field around a crack. From Ampere's law, the magnetic field intensity due to an incremental length of current-carrying wire varies as $1/r^2$, whereas for an infinitely long straight wire the field intensity is proportional to $1/r$.[3] Because the cracks encountered in a gun tube are generally quite long with respect to the lift-off distance at which the field is measured, the field strength would be expected to vary approximately as the reciprocal of r. It is also expected that this relation between H and r will break down at small lift-off distances.

To establish this relationship it was decided that high resolution measurements of the variation of magnetic leakage field intensity around crack-type defects should be made. These measurements would be used to establish



*Scalar field strength = $|\underline{H}|$

$^{**}\underline{H} = H_x\underline{i} + H_y\underline{j}$

where $\underline{i}$ and $\underline{j}$ are unit vectors having the directions of the positive x and y axes, respectively

Figure 3. COORDINATE SYSTEM FOR ANALYSIS OF FIELD STRENGTH AROUND A CRACK BASED ON ASSUMPTION OF SEMICIRCULAR LINES OF EQUAL FIELD STRENGTH

empirical expressions for the change in leakage field intensity with distance from the crack which could then be used to make lift-off corrections.

PROCEDURE

Hall Element Probes and Probe Calibration

The measurable leakage field associated with cracks on the inside diameter of circumferentially magnetized gun tubes extends only a few tenths of an inch from the center of the crack. To make measurements of the variation of leakage field intensity with distance from the crack with the required resolution, Hall elements with a small active area must be used. Figure 4 shows the configuration of the two Hall element probes used to make measurements of the x and y (tangential and normal) components of leakage fields. These are the smallest probes that could be obtained that were compatible with available gaussmeters.

The calibration of the probes is easily checked at relatively high field intensities by means of commercially available calibration magnets. However, these were not adequate for the present work because the field strengths to be measured were generally well below the field strength of the calibration magnet and more than a single calibration point was desired. To obtain a known low intensity field uniform over a relatively large volume, a Helmholtz coil was constructed. The field strength at the center of symmetry of the coil in air is given by[4]

$$H = (0.899)\ Ni/a$$

where N is the number of turns of wire in *each* coil, i is the current flowing in the coils in amperes, and a is the radius of the coil in centimeters.

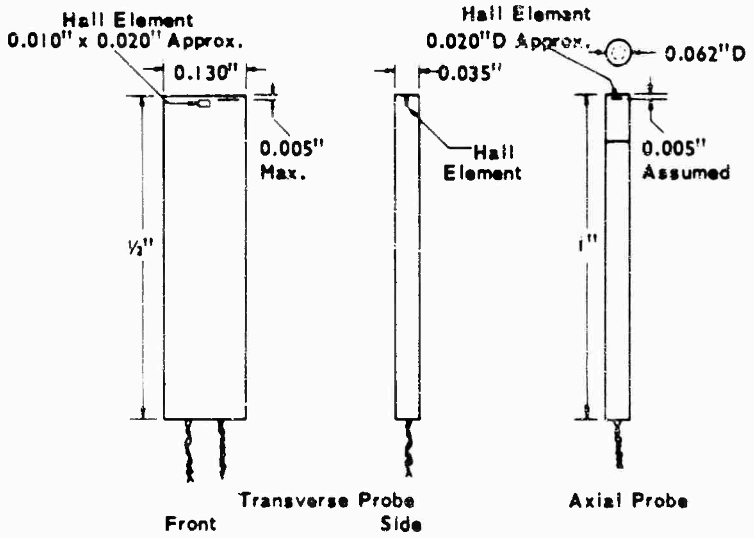


Figure 4. CONFIGURATION OF HALL ELEMENT PROBES USED TO MEASURE LEAKAGE-FIELD STRENGTH AROUND CRACKS

The radius of the calibration coil was 10.35 centimeters and 150 turns of number 18 magnet wire were wound on each coil. For these parameters, the equation for field strength reduces to

$$H = (13.0)i.$$

Table I shows the calculated field strength and the measured field strength for each of the two probes used to make leakage field measurements. Figure 5 is a photograph of the Helmholtz coil assembly.

Table I. CALCULATED AND MEASURED FIELD STRENGTHS

Current (i)	Field Strength (oersted)		
	Calculated	Measured	
		Transverse Probe	Axial Probe
0.5 amps	6.5	6.7	5.8
1.0	13.0	13.2	13.0
1.5	19.5	20.0	19.0
2.0	26.0	26.2	25.5
2.5	32.5	33.0	32.0
3.0	39.0	39.5	38.0
3.5	45.5	46.0	46.0
4.0	52.0	53.0	52.0

Test Specimen

The specimen was a 3-inch-long cylindrical cross section with an outside diameter of 12-5/16 inches and an inside diameter of 6-11/16 inches. Actually the specimen was a composite assembly which consisted of an outside retaining ring of 2-3/8-inch wall thickness into which a second ring comprised of three equal segments was press-fitted. The wall thickness of the second ring was 0.50 inch and this ring was divided into thirds to facilitate the cutting of simulated longitudinal cracks in the otherwise smooth bore surface. Milled slots were used to simulate cracks. They ranged in depth from 0.010 to 0.250 inch and in width from 0.004 to 0.010 inch. Furthermore, the joints between the three press-fit segments of the inner ring were used to simulate tight cracks. More complete details of the specimen characteristics may be found in Reference 5.

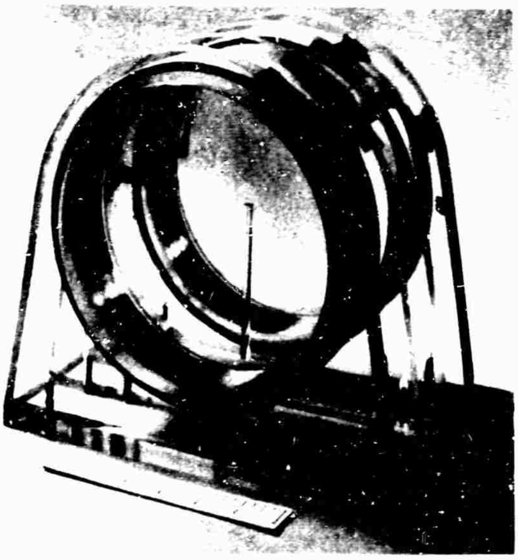


Figure 5. HELMHOLTZ COIL FOR CHECKING CALIBRATION OF GAUSSMETER PROBES

Scanning System

To make precise measurements of field strength as a function of position around the crack, a motor-driven, micrometer, x-y-z platform was constructed. With this arrangement it was possible to move the Hall element probe either parallel or normal to the bore surface and, by means of a gear-driven sweep potentiometer, the variation of field strength with position was displayed on a storage oscilloscope. A photograph of the setup appears in Figure 6.

Measurement

The starting point of the experimental measurements was a determination of the dependence of leakage field strength on the distance from the center

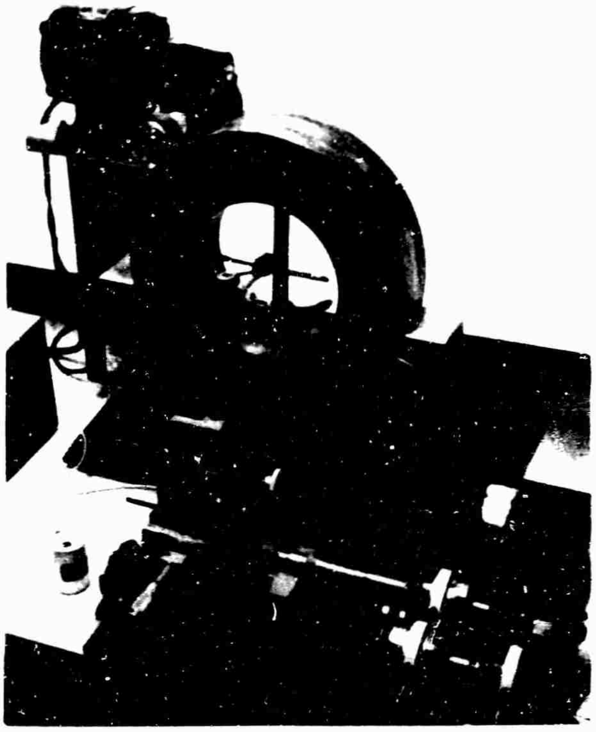


Figure 6. SCANNING SYSTEM FOR MEASURING VARIATIONS IN THE INTENSITY OF MAGNETIC LEAKAGE FIELDS AROUND A CRACK

of the crack. Measurement of this relationship was based on the assumption that the field vector H is parallel to the surface at all points directly above the center of the crack as indicated in Figure 3. If a Hall probe, sensitive to the horizontal component of the magnetic field, is placed over the center of the crack, the variation of total leakage field strength with distance from the crack may be obtained by moving the probe in the vertical plane and simultaneously recording the measured field strength. This type of measurement was made for several of the simulated cracks in the previously described test specimen.

The data acquired in this manner were used to develop empirical expressions for the variation of the field from the center of the crack by making the assumption that lines of equal scalar field strength are semicircular as depicted in Figure 3. The empirical expressions obtained in this manner were then used to derive equations for the variation of the horizontal component (H_x), the normal component (H_y), and the derivative of H_x with respect to x ($\partial H_x/\partial x$) as a function of the horizontal distance x. Experimental measurements were made to test the validity of the derived equations based on the assumption of semicircular lines of equal field strength.

The measurements made with Hall probes were used as a basis of comparison for similar data obtained from magnetic tape heads. The direct output of the tape head, for example, is analogous to the $\partial H_x/\partial x$ versus x curve while the integrated tape head output should be directly related to the curve of H_x versus x.

RESULTS AND DISCUSSION

Relation of Field Strength to Distance from the Crack

Positioning the transverse Hall probe shown in Figure 4 as close as possible to the test surface places the center of the active element at a lift-off distance of 10 mils. Starting at this point, variation of the field strength with lift-off was recorded. Data for a number of such measurements were compiled and normalized to a value of unity at a lift-off distance of 10 mils. The data are tabulated in the Appendix and are plotted in Figure 7.

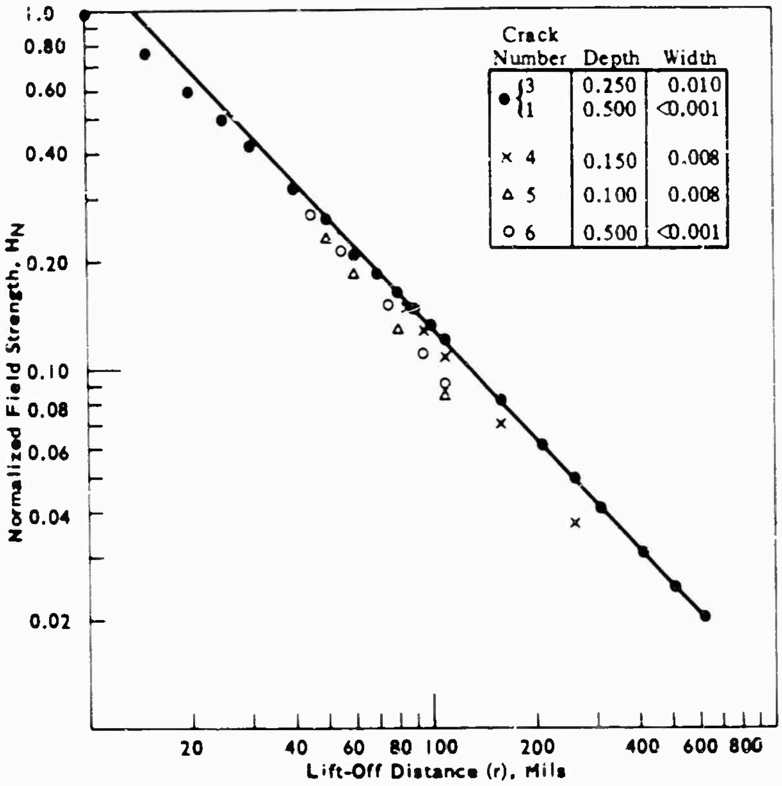


Figure 7. RELATION BETWEEN NORMALIZED FIELD STRENGTH AND LIFT-OFF DISTANCE FOR CRACK NUMBERS 1, 3, 4, 5, AND 6 IN SPECIMEN SS03

Represented in this plot are cracks ranging in depth from 0.1 to 0.5 inch and in width from <0.001 to 0.010 inch.

Although initially the slope of all the data is nearly the same, at a lift-off of 50 mils the data for individual cracks begin to diverge, and at approximately 100 mils a 50 percent difference exists in the value of the normalized field strength. The cause of these differences appears to be relatively weak long-range stray fields that are superimposed on the leakage fields due to the crack. It was found that the value of these long-range fields could be measured on either side of the crack at the appropriate lift-off and at sufficient distance from the crack that crack leakage is nil. The bias field can then be added or subtracted from the apparent leakage associated with the crack depending on its sign. If this is done, the spread in the data is considerably reduced as in Figure 8a. The effect of these stray fields is more serious as the absolute value of the crack-associated leakage field becomes smaller. Therefore, the data for cracks with high leakage fields are considered more reliable. The table in the Appendix shows that the value of the stray fields varies considerably from point to point. The origin of these fields, which are also found in gun tubes, needs clarification.

The results of the measurements summarized in Figures 7 and 8 show no significant variation in the relation between field strength and lift-off due to crack parameters such as width and depth. It is evident that measurement

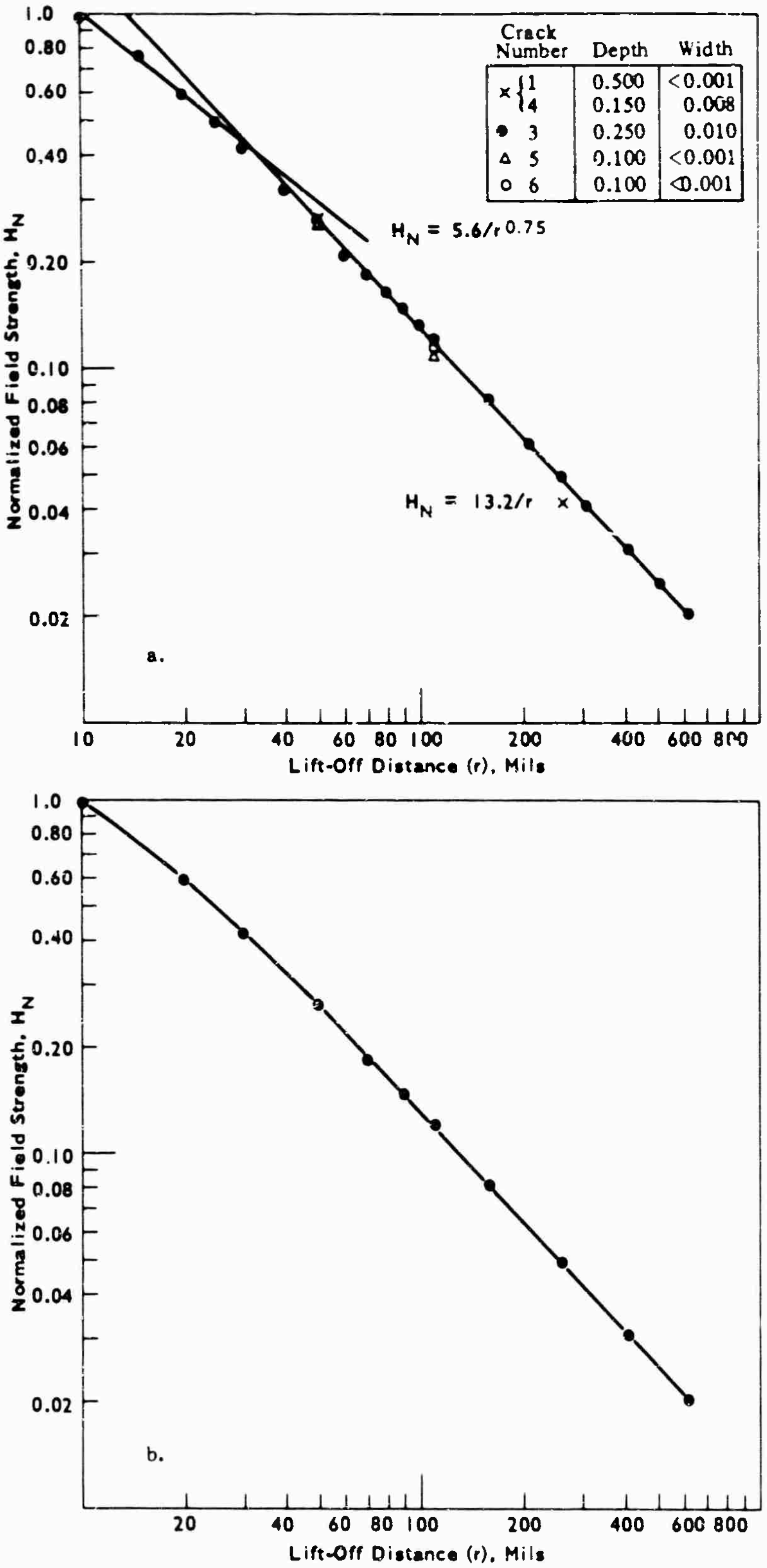


Figure 8. RELATION BETWEEN NORMALIZED FIELD STRENGTH, CORRECTED FOR THE EFFECTS OF LONG-RANGE BIAS FIELDS, AND LIFT-OFF DISTANCE.

of the field gradient above the crack can provide no separation of the individual contributions of crack depth and width on the total magnitude of the leakage. On the other hand, the constancy of the relation permits one to obtain empirical expressions on which corrections may eventually be based.

Figure 8a shows that the log-log plot of H versus lift-off can be approximately expressed as two separate straight lines which have the basic form of

$$\log H = \log H_0 - m \log r$$

where r is the radial distance to the crack in mils. This reduces to

$$H = H_0/r^m.$$

The slope m of the initial part of the curve can be made -0.75 which is valid to a lift-off of 30 mils where it intersects with the second straight line having a slope of -1 which is in agreement with the current-carrying wire analog. The constant H_0 has values of 5.6 for the first straight line and 13.2 for the second. Therefore, the following equations are obtained.

$$H = 5.6/r^{0.75} \quad (10 \leq r \leq 30 \text{ mils})$$

$$H = 13.2/r \quad (30 \leq r \leq 620 \text{ mils}).$$

The region of the curve of most interest is that between 10 and 100 mils of lift-off because, in order to get crack indications of adequate amplitude, this is the area in which one must often make measurements. In an attempt to get a more exact expression for the variation of field strength in this region, a computer-generated best-fit polynomial curve by the method of least squares was obtained for the data shown for crack number 3 in the Appendix. These data were selected as the most reliable because the leakage field strength around this crack was the greatest.

The data were put in the form of ln H versus lift-off. The polynomial was carried out to the third order to give an expression of the form

$$\ln H = \ln H_0 - (ar + br^2 + cr^3)$$

which reduces to

$$H = H_0\, e^{-(ar + br^2 + cr^3)}.$$

The value of the constant H_0 and the coefficients of this equation are as follows:

$$H_0 = 1.63$$

$$a = 5.84 \times 10^{-2}\ \text{cm}^{-1}$$

$$b = -5.41 \times 10^{-2}\ \text{cm}^{-2}$$

$$c = 2.03 \times 10^{-6}\ \text{cm}^{-3}$$

Field Pattern Around a Crack

Using these basic expressions for the variation of field strength with distance from the crack, one can write equations for the components of the field (H_x and H_y) at any point (x, y) as well as the $\partial H_x/\partial x$ at constant y by using the coordinate system shown in Figure 3 and making the following substitution:

$$r = (x^2 + y^2)^{1/2} \qquad \text{(assuming semicircular flux lines)}$$

$$H_x = H \sin\theta = yH/(x^2 + y^2)^{1/2}$$

$$H_y = H \cos\theta = xH/(x^2 + y^2)^{1/2}.$$

If this is done for the three basic expressions for the variation of H with r, the following equations result:

I

$$H = H_0/r^{0.75} \qquad (10 \leq r \leq 30 \text{ mils}) \tag{1}$$

$$H_x = yH_0/(x^2 + y^2)^{0.875}$$

$$H_y = xH_0/(x^2 + y^2)^{0.875} \tag{2}$$

$$\partial H_x/\partial x = -1.75\, xyH_0/(x^2 + y^2)^{1.875} \tag{3}$$

II

$$H = H_0/r \qquad (r \geq 30)$$

$$H_x = yH_0/x^2 + y^2 \tag{4}$$

$$H_y = xH_0/x^2 + y^2 \tag{5}$$

$$\partial H_x/\partial x = -2xy\, H_0/(x^2 + y^2)^2 \tag{6}$$

III

$$H = H_0\, e^{-[a(x^2+y^2)^{1/2} + b(x^2+y^2) + c(x^2+y^2)^{3/2}]} = H_0\, e^{-[f(x,y)]}$$

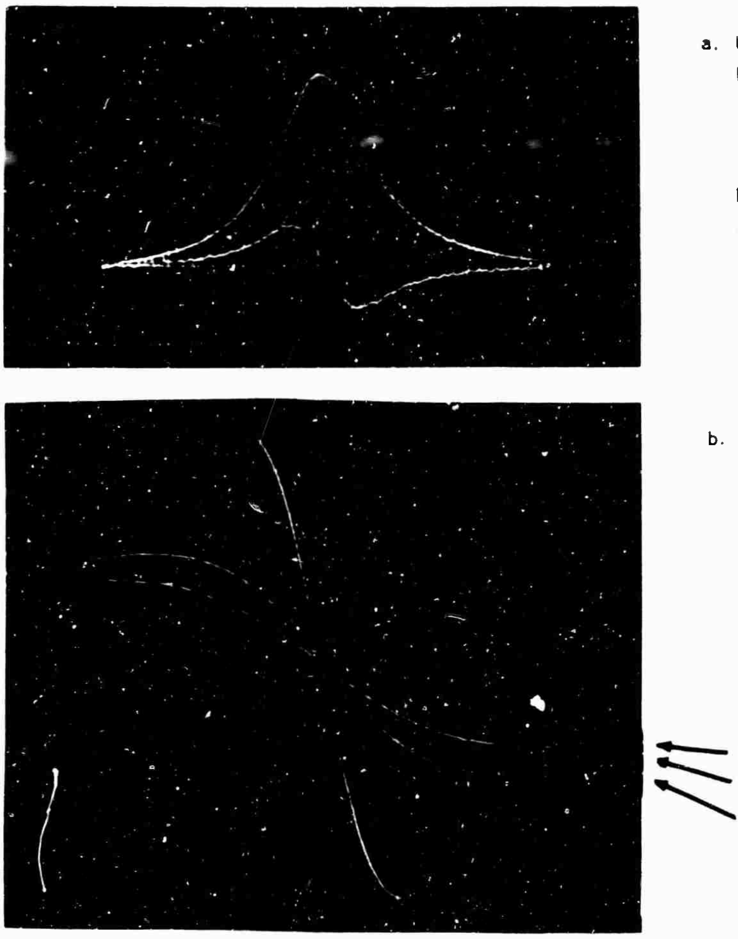
$$H_x = yH_0\, e^{-[f(x,y)]}/(x^2 + y^2)^{1/2} \tag{7}$$

$$H_y = xH_0\, e^{-[f(x,y)]}/(x^2 + y^2)^{1/2} \tag{8}$$

$$\frac{\partial H_x}{\partial x} = -\frac{2xy\, H_0\, e^{-[f(x,y)]}}{(x^2+y^2)^{1/2}}\left[\frac{a}{(x^2+y^2)^{1/2}} + b + \frac{3c}{2}(x^2+y^2)^{1/2} + \frac{1}{x^2+y^2}\right]. \tag{9}$$

The field components, H_x and H_y, and the $\partial H_x/\partial x$ can be measured experimentally with Hall probes to test the validity of the assumption that lines of equal field strength are semicircular.

Equations 1 through 9 were solved for a number of values of x and y and the resulting curves were compared with experimental curves measured with Hall probes. Figure 9 shows the form of curves representing the variations



a. Upper Curve - H_x Versus x
Lower Curve - $\partial H_x/\partial x$ Versus x

Horizontal - 0.050 in/cm
Lift-off - 0.034 in

b. H_y Versus x

Horizontal - 0.025 in/cm

Curve 3. Lift-off = 0.075 in
Curve 2. Lift-off = 0.050 in
Curve 1. Lift-off = 0.025 in

Figure 9. PHOTOGRAPHS OF OSCILLOSCOPE RECORDINGS OF H_x, H_y, AND $\partial H_x/\partial x$ VERSUS X FOR CRACK NUMBER 3, SPECIMEN 5503.

of H_x, H_y, and $\partial H_x/\partial x$ with distance from the center of a crack. A normalized experimental curve for H_x at a lift-off y of 35 mils is compared in Figure 10 with points calculated from (1), (4), and (7). The comparison is excellent for (4) and (7) indicating that the assumption of the semicircular field pattern is valid. The relation from which (1) was derived holds only for small distances from the center of the crack.

The close correspondence between the experimental and the predicted curves demonstrates that the leakage field around a crack has been empirically defined. With this established, we can go on to consider the features of these relationships which make possible the indirect measurement of the lift-off distance.

If (3) or (6) is differentiated with respect to x and the derivative set to zero, solution of the resulting equation for x yields the values at which the maxima and minima of the $\partial H_x/\partial x$ occur at a given lift-off. If this is done, the following relations are obtained:

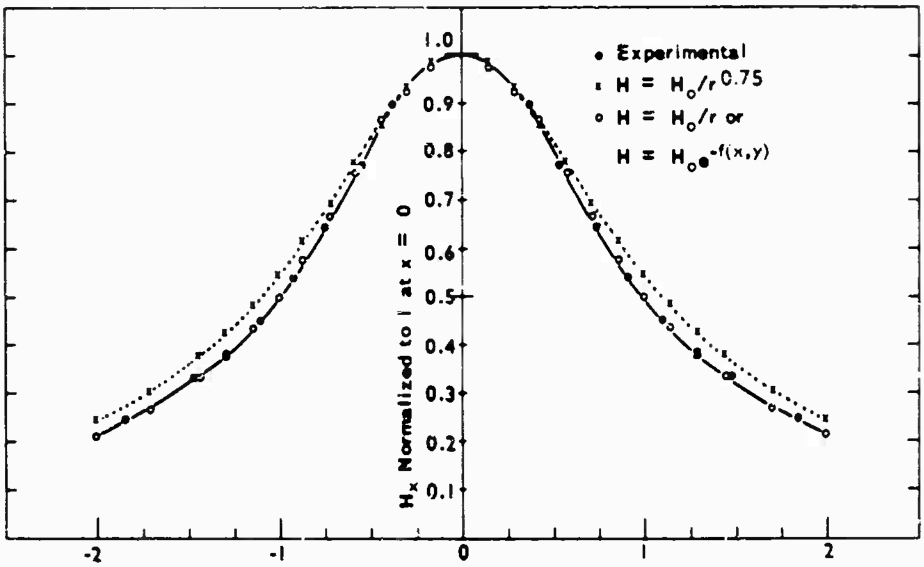


Figure 10. COMPARISON OF EXPERIMENTAL AND CALCULATED RELATION BETWEEN H_X AND s AT CONSTANT LIFT-OFF

For $$H = H_0/r^{0.75},$$

$$\partial(\partial H_x/\partial x/\partial x) = 0 = -1/(x^2 + y^2)^{1.875} + 3.750\, x^2/(x^2 + y^2)^{2.875},$$

$$\therefore x = \pm\, 0.60\, y.$$

For $$H = H_0/r,$$

$$\partial(\partial H_x/\partial x)/\partial x = 0 = -1/(x^2 + y^2)^2 + 4x^2/(x^2 + y^2)^3,$$

$$\therefore x = \pm\, 0.58\, y.$$

Thus, it is immediately apparent that if one measures the distance between the peaks of the curve of $\partial H_x/\partial x$, the result should be equal to 1.2 to 1.16 times the lift-off distance, with 1.2 being most valid at small values of lift-off. One can derive a similar relation in the time domain between the separation of peaks in the output voltage of a rate-sensitive detector, such as a tape head, and lift-off by making the substitution

$$x = vt$$

where v is surface speed in inches per second and t is measured time between peaks in seconds. Therefore, the time between the peaks in the output of the tape head should also be a measure of the lift-off. The relation between the separation of the peaks of the curve $\partial H_x/\partial x$ versus x and the lift-off was measured experimentally and the results are shown in Figure 11. A linear relationship was found with a slope of 1.15 which is in close agreement with the value of 1.16.

It follows intuitively that the width of the curve of H_x versus x at any preselected fraction of the maximum amplitude should be proportional to lift-off. A number of such curves were recorded for various cracks and the width of the curve at the 1/4 amplitude points was measured. It was found, as shown in Figure 12, that again there was a linear variation with respect to lift-off. Within the resolution of the measurements, there was no effect due to the crack parameters of width and depth except for the intensity of the leakage field. Therefore, the curve of either H_x versus x or $\partial H_x/\partial x$ versus x can be used to measure lift-off.

Equations 2 and 5 for the vertical component of field strength (H_y) can be differentiated with respect to x and the result set to zero in a manner similar to that already shown for 3 and 6. If this is done, it is found that for (2)

$$\partial H_y/\partial x = 0 = H_0/(x^2 + y^2)^{0.875} - 1.75\, x^2\, H_0/(x^2 + y^2)^{1.875},$$

$$\therefore x = \pm\, 1.15\, y;$$

and for (5)

$$\partial H_y/\partial x = 0 = H_0/(x^2 + y^2) - 2x^2\, H_0/(x^2 + y^2)^2,$$

$$\therefore x = \pm\, y.$$

Examination of Figure 9b shows that, at a lift-off of 25 mils, the peaks do occur at very nearly ± 1.15 y, whereas at 75 mils lift-off, where H is

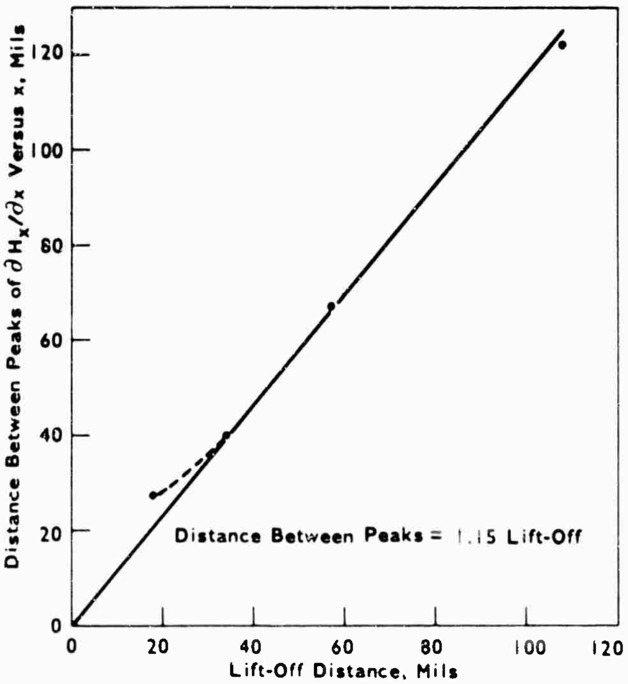


Figure 11. EXPERIMENTALLY MEASURED RELATION BETWEEN PEAK SEPARATION AND LIFT-OFF DISTANCE FOR THE CURVE OF $\partial H_x/\partial x$ VERSUS x.

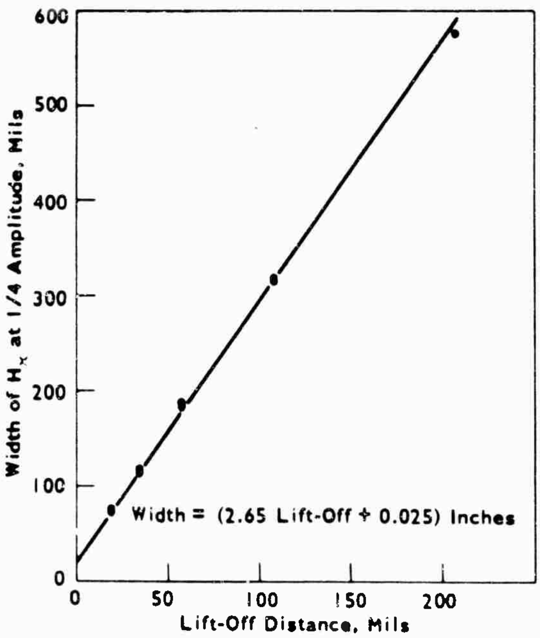


Figure 12. EXPERIMENTALLY MEASURED RELATION BETWEEN WIDTH OF THE CURVE OF H_x VERSUS x AT THE 1/4 AMPLITUDE POINTS AND LIFT-OFF DISTANCE.

proportional to the reciprocal of lift-off, the peaks are at ± y. This gives further evidence that the semicircular field is valid.

Correction for Lift-Off Variations

Now consider how these relations can be used to correct a peak value of field strength, measured by a Hall element scanning the bore of a tube at some unknown value of lift-off to the field strength at the correct lift-off distance. If the measured signal is presented on a time base, the actual width of the curve of H_x versus x or the separation between the peaks of the $\partial H_x/\partial x$ versus x can be determined from the relation $x = vt$ providing a constant surface velocity is used. Once this has been established, Figures 10 or 11 can be used to find the lift-off. Using this lift-off one finds the value of the normalized H in Figure 8b and then the value of normalized H at this correct lift-off distance. If the measured value of H_x was at a lift-off of y and the correct value of H_x to be determined is y_0 then

$$H_{x(y_0)} = H_{x(y)} \left[\frac{H_N\ (y_0)}{H_N\ (y)} \right].$$

An example will illustrate the procedure in detail. Suppose that a peak leakage field of 55 gauss is measured for a particular defect. The width of the signal at the 1/4 amplitude points is found to be 181 mils. From Figure 12 the corresponding lift-off is 60 mils. At this lift-off the normalized value of H is found in Figure 8b to be 0.22. Suppose further that the correct lift-off is 18 mils. The normalized field at this lift-off is 0.64. Therefore, the corrected value of H_x is

$$H_{x_{18}} = 55\ (0.65/0.22) = 160 \text{ gauss.}$$

The measured value of this leakage field at a lift-off of 18 mils was 160 gauss. It appears that by using this procedure the corrected values of H_x may be determined to within 10 percent of the actual value.

It should be emphasized that this type of correction has been demonstrated only for the smooth bore case. Attempts to make such corrections on a partially eroded bore surface have not been undertaken primarily because of a lack of suitable samples containing cracks.

Now that it has been shown feasible to correct for lift-off variations if Hall probes are used, let us turn to a consideration of the tape-head detector.

Correction for Tape Heads

The tape head is comprised of core of high permeability ferromagnetic material and, therefore, is not passive to the leakage field but distorts the field by its presence. Based on this, one would not expect exactly the same results from tape head and Hall element probe detectors. Nevertheless, it is possible to make corrections in the manner already outlined by drawing analogies between the tape-head output and Hall probe output. Ideally, it is the horizontal component (H_x) of the leakage field that induces the flux in the core of the tape head. The output is proportional to the time rate of change of induced flux which can be written as

$$V_0 = K(dH_x/dt) = Kv(dH_x/d_x) = K'(dH_x/d_x)$$

which has the same form as $\partial H_x/\partial x$ versus x for Hall probes. It follows that the horizontal interval between peaks of the tape-head output voltage and lift-off should show a relation similar to the one shown in Figure 11. Figure 13 shows a curve of peak-to-peak horizontal separation of the direct output of a tape head, similar to the one being used in the present MRB scanning system, versus the lift-off distance measured to the surface of the tape head. It will be noted that the slope of the curve is much greater than the similar curve obtained from Hall probe data. The greater slope indicates that the maxima and minima are farther apart for any given lift-off or that the leakage field is broadened by the effect of the ferromagnetic tape head.

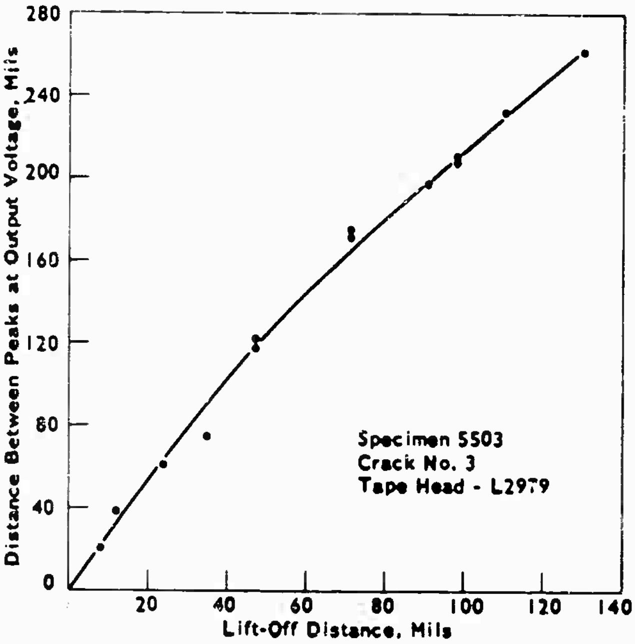


Figure 13. MEASURED RELATION BETWEEN SIGNAL PEAK SEPARATION AND LIFT-OFF DISTANCE FOR TAPE HEAD DIRECT OUTPUT

If the output voltage of the tape head is integrated, the result should be analogous to the curve of H_x in Figure 10. The integration was accomplished using operational amplifiers and, by expanding the time base of the oscilloscope presentation, the width of the defect indications at the 1/4 amplitude points was measured. The result is shown in Figure 14. Evidence of a spreading of the leakage field is again found by comparing the curve from tape-head data with the one obtained from Hall probe measurements.

Now, a relationship between the direct and/or integrated output voltage and lift-off is required. The measured variation for these two parameters as a function of lift-off distance is shown in Figure 15. Using these curves together with Figures 13 and 14, it is possible to make corrections in the output voltage of a tape-head detector in a manner similar to that outlined in the preceding section.

Again let us take an example. Suppose that the separation between the peaks of a crack signal as recorded by the direct output of a tape-head detector is 0.12 inch and the peak-to-peak amplitude is 0.11 volt. From

Figure 13 it is found that the lift-off was 47 mils. Entering Figure 15 at 47 mils a normalized direct output voltage of 0.255 is obtained. Suppose that the preset lift-off were 12 mils. The normalized direct output voltage is 0.92. The corrected value of the crack signal voltage is

$$V_{(yo)} = V_{(y)} \left[V_{N(yo)}/V_{N(y)}\right] = 0.11\ (0.92/0.255) = 0.395 \text{ volts.}$$

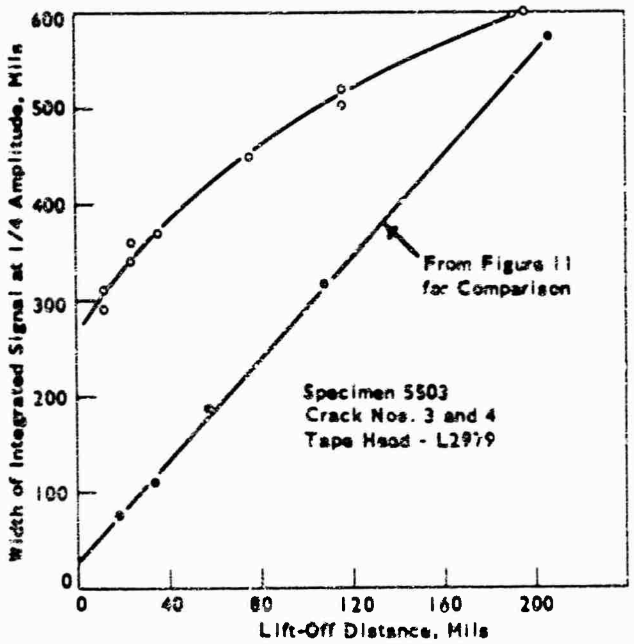


Figure 14. MEASURED RELATION BETWEEN WIDTH OF THE INTEGRATED TAPE HEAD OUTPUT VOLTAGE WAVEFORM AT THE 1/4 AMPLITUDE POINTS AND LIFT-OFF DISTANCE

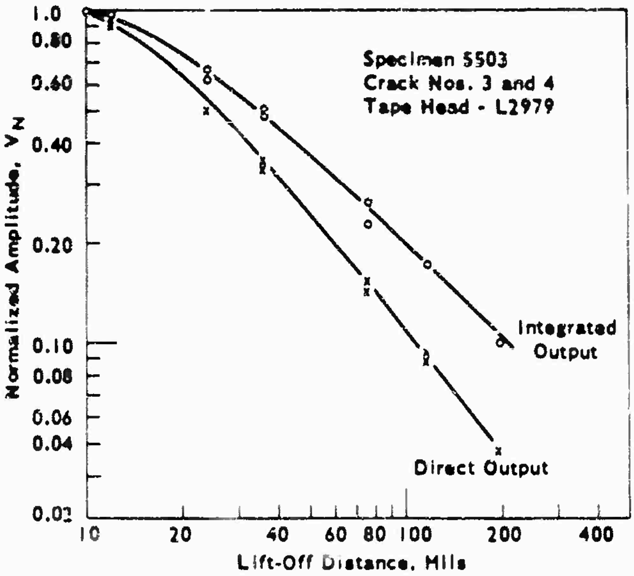


Figure 15. MEASURED DEPENDENCE OF TAPE HEAD DIRECT AND INTEGRATED OUTPUT AMPLITUDE ON LIFT-OFF DISTANCE

The measured value at 12 mils was 0.37 volt. Corrections can be made using the integrated output of the tape head detector in a similar manner.

Practical Application to Gun Tube Inspection

A correction procedure of the type described requires a certain amount of time to perform. Therefore, it does not seem feasible to apply the correction to each indication found during an inspection. In the performance of a routine examination it is anticipated that only the few highest amplitude indications will be of primary interest. To get the best possible measure of crack depth from these indications, the lift-off distance should be accurately known. The lift-off can be measured indirectly as previously outlined by utilizing an expanded time base on an oscilloscope presentation combined with a delay generator. If the lift-off determination by this procedure is within a predetermined percent of the nominal lift-off, no correction may be necessary. If, on the other hand, the lift-off is found to depart significantly from the nominal value, one proceeds with the correction. This is, of course, based on the premise that application of this correction procedure will reduce the scatter in the correlation between signal amplitude and crack depth shown in Figure 1.

CONCLUSIONS

The leakage field associated with a crack-type defect on the inside diameter of a large-caliber, smooth-bore tube has been experimentally defined. This was accomplished by measuring the change in field strength with distance directly above the crack to determine the functional dependence of H on the lift-off r. The leakage field strength was observed to decrease approximately as $r^{-0.75}$ between 10 and 30 mils from the surface, but approached an r^{-1} dependence at lift-off distances greater than 50 mils. A semicircular field pattern was assumed as a basis for calculating the variation of the field components H_x and H_y, and $\partial H_x/\partial x$ with distance from the crack. The calculations based on this assumption were in very close agreement with experimental data.

The analysis of the leakage field around a crack suggested a procedure of correcting defect indications, measured during magnetic recording borescope inspection of gun tubes, for the error produced by uncontrollable variations in detector lift-off. Such a correction procedure has been developed and demonstrated by laboratory measurements. Using curves contained in this report, corrections can be made to the field strength measured by a Hall-element probe or the output voltage of a tape-head detector. It should be emphasized, however, that the curves shown here are valid only for the specific types of detectors employed in this investigation. If different detectors are employed new curves should be established. With the proposed method of correction, it appears possible to correct signal amplitudes measured at an unknown lift-off distance to within 10 percent of the correct value at the nominal lift-off.

Although the correction procedure is somewhat tedious to carry out it should be worth the extra effort if it leads to increased confidence in the predicted crack depth. In practice, crack depth prediction may be required for only a few of the most significant indications which would make this procedure quite feasible.

RECOMMENDATIONS

1. Investigate the variations of bore conditions over which the proposed method of making lift-off corrections can be applied. Among the factors that must be considered are the influence of the rifling at various stages of erosion and the effect of unsymmetrical defect signal waveforms.

2. Determine the influence of this correction procedure on the correlation between defect signal and crack depth. This can be accomplished only by making measurements on samples of gun tubes containing cracks produced by actual firing damage.

3. Execution of recommendations 1 and 2 depends entirely on the availability of samples containing various degrees of firing damage and fatigue cracks. Every effort should be made to obtain a number of representative samples.

APPENDIX A

Table A - I. VARIATIONS OF LEAKAGE FIELD STRENGTH WITH DISTANCE DIRECTLY ABOVE CRACK, SPECIMEN 5503

Lift-off, y (mils)	Crack No. 1, 0.500"/<0.001"				Crack No. 3, 0.250"/0.010"				Crack No. 4, 0.150"/0.008"			
	H_x		Corrected H_x		H_x		Corrected H_x		H_x		Corrected H_x	
	(Oe)	Normalized	(Oe)	Normalized	(Oe)	Normalized	(Oe)	Normalized	(Oe)	Normalized	(Oe)	Normalized
10	125	1	126	1	540	1	545	1	250	1	255	1
15	95	0.760			410	0.759			190	0.760		
20	75	0.600			320	0.593			150	0.600		
25	62.5	0.500			265	0.491			123	0.493		
30	53.5	0.428			225	0.417			105	0.420		
35	46.5	0.372			195	0.361			90	0.360		
40	41	0.328			172	0.318			80	0.320		
45	37	0.296			155	0.287			71	0.284		
50	33.5	0.268	33.5	0.261	140	0.260	142	0.261	64	0.256	68	0.266
55	31	0.248			130	0.241			58	0.232		
60	28	0.224			118	0.218			53	0.212		
65	26	0.208			110	0.204			49	0.196		
70	24.3	0.194			100	0.185			45	0.180		
75	22.7	0.182			95	0.176			42	0.168		
80	21.3	0.170			88	0.163			39	0.156		
85	20	0.160			84	0.156			37	0.148		
90	19	0.152			79	0.146			35	0.140		
95	18	0.144			75	0.139			32	0.128		
100	17.2	0.1375			71	0.132			31	0.124		
105	16.5	0.132			68	0.126			28.5	0.114		
110	15.7	0.126	15	0.119	65	0.120	65	0.119	27	0.108	30.5	0.120
160					44	0.0815			17.5	0.070		
210					33	0.0611			12.3	0.0492		
260					26.5	0.0491			9.2	0.0368	10.7	0.042
310					22	0.0407						
360					19	0.0352						
410					16.5	0.0306						
460					14.5	0.0269						
560					12	0.0222						
610					11	0.0204						

Bias Field Measurement (oersted)									
Lift-off (mils)	Left Side	Right Side	Correction	Left Side	Right Side	Correction	Left Side	Right Side	Correction
10	+1	-2.5	+0.7	-5	-5	+5	-5	-6	+5.5
50	+1	-1	0	-2	-2.5	+2	-4	-5	+4.5
110	+2	+0.5	-0.7	+1.5	-1.5	0	-3	-4	+3.5
260							-1.5	-1.5	+1.5

Table A - I. VARIATIONS OF LEAKAGE FIELD STRENGTH WITH DISTANCE DIRECTLY ABOVE CRACK, SPECIMEN 5503 *(continued)*

Lift-off, y (mils)	Crack No. 5, 0.1"/0.008"				Crack No. 6, 0.500"/<0.001"			
	H_x		Corrected H_x		H_x		Corrected H_x	
	(Oe)	Normalized	(Oe)	Normalized	(Oe)	Normalized	(Oe)	Normalized
10	137	1	144	1	130	1	136	1
15	100	0.730			96	0.738		
20	79	0.576			75.5	0.581		
25	64	0.467			62	0.477		
30	53	0.387			52	0.400		
35	51	0.372			45	0.336		
40	40	0.292			39.5	0.304		
45	35	0.256			35	0.269		
50	31.5	0.230	36.5	0.254	31	0.239	36	0.264
55	27.7	0.202			27.7	0.213		
60	25	0.183			25.2	0.194		
65	23	0.168			23	0.177		
70	21	0.153			21	0.161		
75	19.2	0.140			19.5	0.150		
80	17.7	0.129			18	0.139		
85	16.3	0.119			16.5	0.127		
90	15.2	0.111			15.5	0.119		
95	14	0.102			14.3	0.110		
100	13	0.095			13.3	0.102		
105	12.2	0.089			12.5	0.096		
110	11.5	0.084	15.5	0.108	11.7	0.090	15.7	0.115

Bias Field Measurement (oersted)

Lift-off (mils)	Left Side	Right Side	Correction	Left Side	Right Side	Correction
10	-7	-7	+7	-7	-5	+6
50	-5	-5.5	+5	-5.5	-5	+5
110	-4	-4	+4	-4	-4	+4

LITERATURE CITED

1. FOWLER, K. A. *Detection of Fatigue Cracks in the M113 175-MM Gun Tube.* Proceedings of the Sixteenth Defense Conference on Nondestructive Testing, 26-28 September 1967, p. 59-97. Available from U. S. Naval Ordnance Laboratory, White Oak, Maryland, ATTENTION: E. L. Criscuolo.

2. ARMY MATERIALS AND MECHANICS RESEARCH CENTER. *Preliminary Results of Magnetic Recording Borescope Inspection of the M113 175-MM Gun Tube.* Materials Testing Laboratory Letter Report, 25 July 1967, p. 6-7.

3. SUYDAM, V. A. *Fundamentals of Electricity and Electromagnetism.* Fifth Printing, D. Van Nostrand Company, Inc., New York, 1948, p. 314.

4. BOZORTH, R. M. *Ferromagnetism.* Third Printing, D. Van Nostrand Company, Inc., New York, 1955, p. 840.

5. McELENEY, P. C. *Crack Depth Leakage Flux Characteristics in Ferromagnetic Materials.* Army Materials and Mechanics Research Center, WAL TR 148-1/1, April 1960.

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13. ABSTRACT

The functional dependence of leakage field strength, associated with a crack-type defect, on the distance from the crack has been experimentally determined. Field strength measurements were used to generate empirical expressions relating the leakage field strength to lift-off distance. Equations were written for the normal and horizontal field components and the partial derivative of the horizontal component of the field strength with respect to horizontal distance from the crack, based on the assumption of a semicircular field pattern. Comparison of calculated values and the experimental data demonstrated that, over the range of interest, the semicircular field assumption adequately describes the field. Results of the analysis of the leakage field surrounding a crack suggested a method of correcting for the uncontrollable variations in lift-off which occur during magnetic recording borescope inspection of large caliber gun tubes. Curves required to make these corrections have been established for two specific types of detectors and a procedure for making the correction utilizing these curves is presented. Practical application of the correction to gun tube inspection is considered. (Author)

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