A SOLUTION TO THE PERMEABILITY AND LIFT-OFF PROBLEMS IN ELECTROMAGNETIC FLAW DETECTION

by

Ralph H. Kenton, Product Manager, Electromagnetic Systems

Magnaflux Corporation

7300 W. Lawrence, Chicago, Illinois 60656 U.S.A

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I. INTRODUCTION -- Electromagnetic nondestructive testing, often known as eddy current NDT, has been used successfully for dozens of years in the evaluation of most metallic materials. The three basic application groups include the detection of flaws at or near the surface, the evaluation of material properties, and in certain cases – the measurement of nonmetallic coating and metallic sheet thicknesses. Many important technological developments have created a significant increase in the industrial use of eddy current NDT during the past decade.

This method provides many distinct advantages over other techniques, such as high inspection rates and speeds, low testing costs, repeatability of indications, and versatility and simplicity of instrumentation. Equally important is the ease of interpretation and elimination of operator fatigue and possible errors in judgment. Finally, eddy current tests provide no hazard to the operator or contamination to the part under the test, and these methods usually require no part pre-preparation. While the detection of discontinuities in nonmagnetic metals has proven to be a rather straightforward application, the detection of similar flaws in magnetic metals provides a far greater challenge. The purpose of this paper is to describe a new solution to this problem utilizing a unique probe for the manual or automatic inspection of magnetic and nonmagnetic metals. The advantages of this system will be most easily understood after a brief review of eddy current fundamentals.

In the eddy current method, an alternating current is impressed upon the test probe or encircling coil. The alternating electromagnetic field thus created induces circulating eddy currents in the test parts. These currents react with the various properties of the test material, and in turn, create their own electromagnetic fields. It is the interaction of the test coil field and the eddy current field which gives the test coil a unique electrical property (impedance) for a given set of test conditions. As the probe is scanned along the surface of the test object, changes in the eddy current patterns ultimately create changes in the test coil impedance, through the interaction of the electromagnetic fields involved.

Four fundamental material properties will influence the eddy current distribution: the electrical conductivity; the magnetic permeability; the degree of homogeneity; and the mass, dimensions, or thickness. The basic problem in this NDT method involves the isolation of the desired property as it may relate to the specific application, simultaneous with the suppression of irrelevant variables.

This improvement in the "Signal/Noise" ratio is accomplished through proper adjustment of the test system parameters: frequency; coupling (known as "lift-off" when testing with probes); field strength; test coil type, resolution, and arrangement; circuit type; and readout device.

Flaw detection in magnetic materials presents a unique problem. Test coil impedance variations due to material permeability changes are usually much greater than impedance changes due to the interruption of induced eddy currents by typical defects. Although not completely satisfactory, several approaches have been developed in past years to suppress random permeability variations. By proper selection of test frequency, for example, the phase angle for permeability variations will lie in a somewhat different direction than the phase angle for discontinuities. In these cases, phase discrimination circuitry can be of some value. It is usually impossible, however, to develop a test system where changes in permeability, conductivity, and probe-to-metal spacing <u>all</u> produce a signal whose phase angle is sufficiently different from that created by the defects. Another approach is the simultaneous application of a strong steady-state (D.C.) biasing field which normalizes and reduces the random variations in material permeability. However, this technique is quite cumbersome and sometimes expensive.

Additional improvements in the Signal/Noise ratio also have been made through the application of time-rate-of-change or filtering circuits. These tend to exaggerate defect signals and suppress those from permeability changes. This technique requires a constant speed of scan and is therefore not always practical. These developments have generally employed the traditional type of test probe, of solenoid or pancake geometry and either using a ferrite or air core. In the search for further improvement in the Signal/Noise ratio, attention was turned toward the probe design itself.

II. PROBE DEVELOPMENT – Several goals were established for the development of an improved eddy current probe: surface and subsurface discontinuities should be detectable with maximum suppression of permeability variations and minimum signal interference from changes in lift-off (probe-to-metal spacing). The desired probe should be compact and low in cost and should work on both magnetic and nonmagnetic metals. The conventional single winding had obvious limitations and was immediately discarded. Several differential (series opposing) types were studied, and their limitations became obvious: in many applications, both probe coils could approach the same crack or seam simultaneously, thus offering little or no test signal. In addition, less than complete suppression of permeability was observed. In other applications, the development of two individual test signals (when each probe coil in turn passed over the same defect) created problems in interpretation when using typical circuits.

It was next decided to study the possibility of developing a differential coil arrangement wherein both elements scanned essentially the same test area rather than adjacent areas. The idea of using core materials was discarded, and that of developing a pair of orthogonal windings was investigated. (See Figure #1.) Two pancake coils were wound, one inside the other, with their axes mutually perpendicular. The windings were connected differentially and applied to a special bridge. The results were quite encouraging, since the signals created by the disruption of eddy currents at a discontinuity appeared to be additive to those signals caused by this same localized interruption in the magnetic permeability. Permeability suppression was fair, although lift-off compensation was not too good.

It was obvious that the change in each test winding impedance was not identical with increasing probe-to-metal spacing. A special proprietary technique (for which a patent application has been made) was then developed which vastly improved the balance of the two coil elements, thus overcoming this limitation. Many additional months of investigation and experimentation yielded improved assembly techniques which maintained the degree of balance required. The final product was a critically balanced orthogonal probe pair.

This development has completely met the goals originally established. The change in impedance for each of the orthogonal windings is virtually identical as the probe passes over zones of changing permeability, conductivity, and thickness. In addition, infinite lift-off compensation has been obtained. In other words, the impedance of each winding changes at a uniform rate with increasing probe-to-metal spacing. A technique has been developed for making such probes completely interchangeable with suitable instrumentation. Ceramic wear shoes are provided for long life, and the air gap thus created does not decrease flaw detection sensitivity to any great extent. Because of this tolerable air gap, carbide wear shoes can also be developed for extremely rough surfaces. The overall coil bobbin diameter can be as small as 0.25 inch (6.4 millimeters), and the resulting coil assembly is essentially spherical in shape.

The single limitation of this probe style is the need for relative orientation with respect to the defect direction. However, most defects which occur in industrial processing have a known or preferred direction, and so this has been no serious stumbling block to date in the majority of applications. The change in test coil impedance created when passing over a given discontinuity is proportional to $|\sin \varphi - \cos \varphi|$, where φ is the angle between a given test coil plane and the defect plane. (See Figure #1.) In practical testing, the Signal/Noise ratio is quite high, thus allowing the use of sensitivities adequate to detect most defects lying at an angle φ up to approximately 30^o, and sometimes greater.

A variety of surface probes, varying principally in size, has been developed. The orthogonal probe is basically high resolution in nature, and the larger diameter probes primarily offer the advantage of grater surface area of continuous manual inspection of rough surfaces. Small probe bobbins have been developed in spherical-tipped probe housings for the inspection of radii in channels, etc. Additional probes have been fabricated for the inspection of fastener holes in aircraft, oil holes in crankshafts, etc.

III. INSTRUMENTATION -- Parallel to the probe refinement portion of this program, a project was initiated to develop suitable test instrumentation. Goals included the engineering of a compact, portable, stable instrument providing high Signal/Noise ration combined with simplicity of operation. The operating test frequency was selected with several criteria in mind. The first was that of effective depth of penetration. Most industrial application suggested that a frequency be chosen high enough to reliably detect seams and cracks in magnetic materials which were approximately 0.005 inch (0.13 millimeter) deep and greater. Some ability to discriminate various defect depths was desired up to approximately 0.065 inch (1.7 millimeters). A second consideration in selecting test frequency was to choose a value high enough to create a sufficient change in impedance when scanning the defect, using the small coil windings developed. A third criterion was the choice of a frequency which provided maximum phase angle separation of discontinuities on one hand from changes in permeability, conductivity, and lift-off on the other. After a careful review of these parameters, a test frequency of 100 kHz was selected.

Because of the probe features described above, a special bridge circuit was chosen as the ideal design for the system. Each coil winding forms one arm of the bridge, with the Balance Controls contained within the instrument forming the remaining two arms. The block diagram shown in Figure #2 further describes the nature of this circuit. Battery operation was easily facilitated by the liberal use of integrated circuits and other solid state components throughout. The final system is shown in Figure #3, depicting hand scanning with a large area probe. Other surface probes have been developed with housing diameters as small as 0.31 inch (8.0 millimeters).

IV. SYSTEM OPERATION AND PERFORMANCE -- Instrument set-up procedure is quite straightforward. The two Balance Controls are adjusted alternately until a minimum reading is obtained on the front panel meter when the probe is in contact with sound material. The Sensitivity Control is adjusted for the level of inspection required, and testing may immediately commence. Line power may be used to recharge the batteries, and operate a threshold circuit. This circuit flashes a front panel indicating lamp and closes a pair of relay contacts when the defect signal exceeds a preset value. Thus, the system may be adapted to the automatic testing of various materials on a production line basis.

System sensitivity is excellent on virtually all magnetic and non-magnetic metals. For example, a defect approximately 0.005 inch (0.13 millimeter) deep can usually be detected with good Signal/Noise ratio. Although sensitivity is decreased proportionately, good test results also can be obtained with lift-off gaps as large as 0.039 inch (1 millimeter), and sometimes greater. Suppression of permeability changes is excellent. For example, at normal operating sensitivity levels, the test probe may be moved from a nonmagnetic part to one made of wrought steel, and then to a magnetic casting, with virtually no deflection apparent on the front panel meter. Thus, only slight adjustments on the front panel Balance Controls are necessary when changing test materials.

Although accurate crack depth measurement is general is a difficult application in magnetic steel parts, this system provides some degree of defect depth discrimination. The ability of any instrument to measure the depth of a discontinuity is of course dependent upon the geometric, electrical, and magnetic boundary conditions for such defects. Depth discrimination of this system is equal to or better than that of other systems studied, most of which are far more complicated in design and operation.

The probe developed in this project is quite high in resolution with the effective test area being approximately 0.06 inch (1.5 millimeters) in diameter. Although this provides excellent sensitivity to short discontinuities, careful and complete area scanning is therefore required.

Because of the coil design employed, infinite lift-off compensation is also obtained. When slowly removing the probe from the test part to an infinite distance, virtually no front panel deflection is observed at the normal sensitivity levels used. For magnetic materials, the instrument is generally used at approximately 10 – 15% of its maximum available gain. Nonmagnetic parts also can be tested, although at increased sensitivity.

System setup usually takes less than one minute, and requires only minimal training of the operator. Speed response is uniform up to scanning speeds of approximately 3 feet /second (0.92 meter/second) using the internal threshold circuit. Special external threshold circuits have been developed to increase this scanning rate by a factor of 10X or more. Probe cables approximately 75 feet (23 meters) long, are possible due to the high sensitivity of this system.

Of great interest is the ability to detect natural defects far below the surface of magnetic materials. For example, a defect on the reverse side of a steel plate 0.25 inch (6.4 millimeters) thick, has been detected. This is accomplished through the simultaneous magnetization of the test object in a direction perpendicular to the discontinuity. It is believed that this excellent subsurface sensitivity is obtained through distortion of the magnetizing field around the discontinuity, and the resulting anisotropic change in the permeability of the zone between the defect inner edge and the test probe surface.

For similar reasons, the test probe is sensitive to the existence of stray fields within magnetic objects. Such fields create random deflections of the front panel meter as the probe is scanned across the surface. If an unsatisfactory Signal/Noise ratio is obtained for this reason in flaw detection, a simple demagnetization of the part beforehand will remedy this situation. Occasionally, improvement in the Signal/Noise ratio also can be made by magnetizing the part prior to inspection.

V. APPLICATIONS -- Typical applications of this system are many, and a few representative examples will be reported here:

1) hand scanning of forging billets for seams in the stockpile area;
2) detection of cracks in pipe ends;
3) location of thermal cracks in railroad locomotive and car wheels on the truing machine in the wheel shop;
4) location of surface discontinuities and fastener hole fatigue cracks in aircraft structures and rotating members;
5) detection of fatigue cracks in plant maintenance applications involving crankshafts, pressure vessels, etc.;
6) automatic scanning of automotive components such as gear blanks, wrist pins, suspension studs, large cap screws, and sintered metal parts for various discontinuities;
7) automatic inspection of hot rolled bar stock in screw machining operations;
8) location of fatigue cracks in helicopter blade spars;
9) automatic detection of drilled collar/pipe joints in oil drilling operations;
10) measurement of field strength within magnetic test parts, either on a continuous or residual basis;
11) determination of the degree and direction of grain orientation in either magnetic or nonmagnetic materials (by using a deliberately unbalanced probe).

Many more application problems have been solved using this probe, but are far too numerous to report here.

VI.SUMMARY -- A unique orthogonal probe design, precisely balanced, has allowed the development of a test system meeting the design criteria specified above. Extremely good Signal/Noise ration has been obtained for flaw detection on both magnetic and nonmagnetic materials. Excellent suppression of permeability variations has been combined with infinite lift-off compensation and ease of operation. This unique probe element has allowed the use of a circuit which simplifies setup procedure and reduces the need for sophisticated operator training. This solution therefore promises to be a most useful tool in the detection and classification of various discontinuities in virtually all phases of industrial nondestructive testing.