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CHAPTER 4
EDDY CURRENT INSPECTION METHOD

SECTION I EDDY CURRENT INSPECTION (ET) METHOD

4.1 GENERAL CAPABILITIES OF ET.

4.1.1 Introduction to Eddy Current Inspection. This method is used to detect discontinuities in parts that are conductors of electricity. An eddy current is a circulating electrical current induced in a conductor by an alternating magnetic field. An eddy current instrument generates an alternating current that is designed to go through a coil of copper wire that has been placed in a holder called a "probe." This results in the coil producing an alternating magnetic field that when placed near a conductor, generates electrical currents within the conductor (Figure 4-1). When these eddy currents encounter an obstacle such as a crack, the normal path and strength of the currents is changed and this change is detected, processed and then displayed on the instrument display.

4.1.1.1 Eddy Current Inspection is a "reference" type inspection. The term "reference" means a standard is used to setup the equipment. Results are only as good as the reference standard(s) used. For flaw detection, a minimum of three flaws of varying sizes is recommended for setup. The three flaws represent a closer standardization method for inspection reliability and probability of detection (POD) data. Calibration standards are also used for thickness measurements and conductivity testing. The term "calibration" refers to the use of standards directly traceable to a National Institute of Standards and Technology (NIST) standard that is government controlled.

4.1.2 Definition of Eddy Current. Eddy currents are electrical currents induced in a conductor by a time-varying magnetic field. Eddy currents flow in a circular pattern, but their paths are oriented perpendicular to the direction of the magnetic field.

NOTE

When the ferromagnetic properties of the specimen are of interest, magneto inductive testing is the more appropriate term. For the purposes of this chapter, Eddy Current, Eddy Current Inspection, and/ET will be used.

4.1.3 Inspection With Eddy Current. The eddy current inspection method is a highly capable, reliable inspection method. When used by a trained technician, it can be used to detect surface and some subsurface cracks, determine material properties, and measure the thickness of thin materials, conductive coatings and non-conductive coatings on conductive substrates.

4.1.4 Advantages of the Eddy Current Method. The following are some advantages of the eddy current method:

- Instantaneous results
- Little part preparation
- No hazardous materials required
- Sensitive to small flaws
- Little to no operator danger

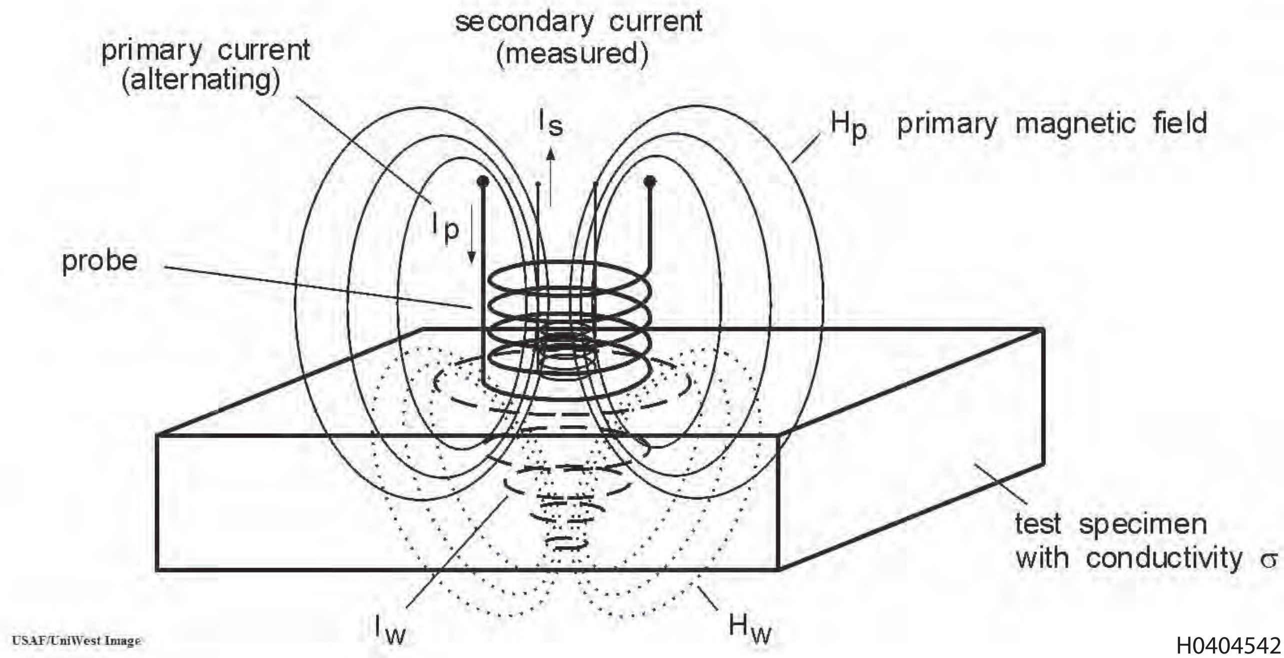


Figure 4-1. Generation of Eddy Currents

4.1.5 Limitations of the Eddy Current Method. The following are some limitations to the ET method:

- Inspection is limited to electrically conductive materials
- Flaws that run parallel to the surface are difficult to detect
- Ferromagnetic materials have permeability effects that conflict with conductivity
- Capability is related to the skill of the operator

4.1.6 Variables Affecting Eddy Currents. Inspection parameters such as the coil-to-specimen separation (also called lift-off or fill-factor, depending on the type of coil used) and coil assembly design may cause the eddy currents to vary. A consequence of this is often that eddy current for one condition (e.g. presence of discontinuities), can be hampered by variations in properties not of concern (e.g. specimen geometry). In most cases, the effects of variations in properties not of interest can be minimized or suppressed. The generation and detection of eddy currents in a part are largely dependent on:

- The inspection system
- Material properties of the part
- The test conditions

4.1.6.1 Effect of Conductivity on Eddy Currents. The distribution and intensity of eddy currents in non-ferromagnetic materials is strongly affected by electrical conductivity. In a material of relatively high conductivity, strong eddy currents are generated at the surface. In turn, the strong eddy currents form a strong secondary electromagnetic field opposing the applied primary field. As a result, the strength of the primary field decreases rapidly with increasing depth below the surface. In poorly conductive materials, the primary field generates small amounts of eddy currents, which produce a small opposing secondary field. Therefore, in highly conductive materials, strong eddy currents are formed near the surface, but their strength reduces rapidly with depth. In poorly conductive materials, weaker eddy currents are generated near the surface, but they penetrate to greater depths. The relative magnitude and distribution of eddy currents in good and poor conductors are shown in Figure 4-2.

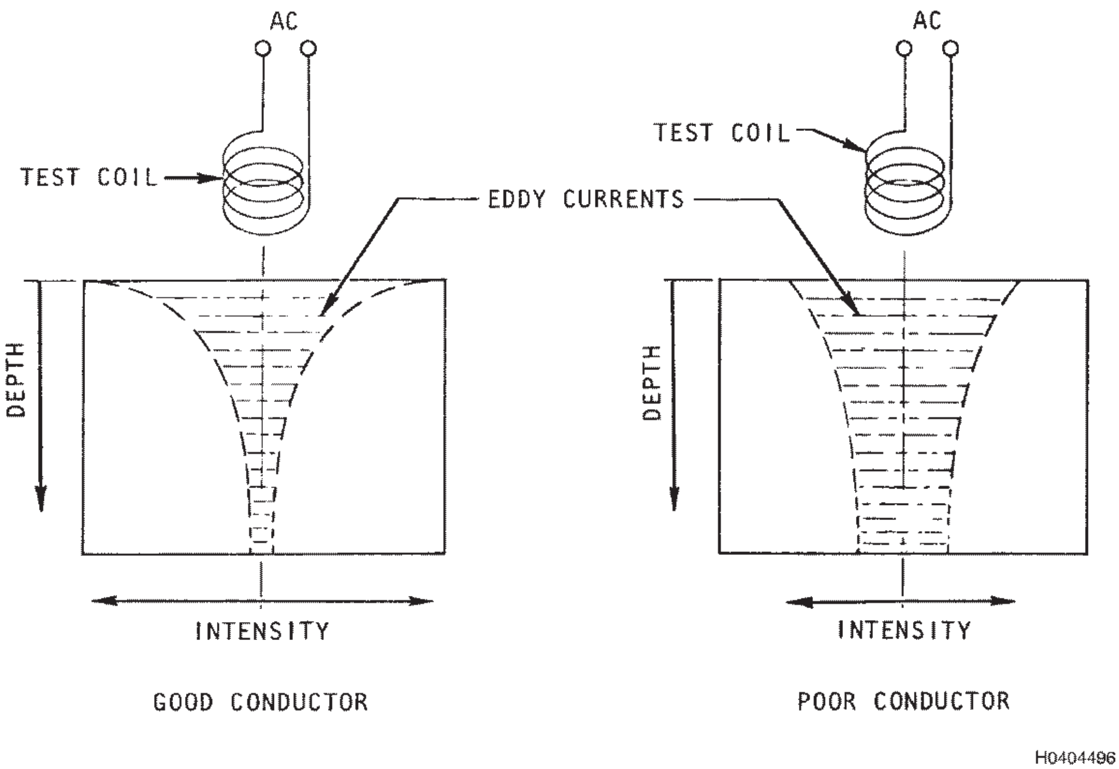


Figure 4-2. Relative Magnitude and Distribution of Eddy Currents in Good or Poor Conductors

4.1.6.2 Effect of Permeability on Eddy Currents. Eddy current testing of ferromagnetic parts is usually limited to testing for flaws or other conditions that exist at or very near the surface of the part. In a ferromagnetic material, as compared to a non-ferromagnetic material, the primary field results in a much greater internal field because of the large relative magnetic permeability. The increased field strength at the surface results in increased eddy current density. The increased eddy current density generates a larger secondary field that rapidly reduces the overall field strength a short distance from the surface. Consequently, the effective depth of penetration during ET is much less in ferromagnetic materials than in other conductive materials. The high relative magnetic permeability acts as a shield against the generation of eddy currents much below the surface in a ferromagnetic part. The relative effects of permeability variations on the depth of penetration and the intensity of the eddy currents are shown in Figure 4-3.

4.1.6.3 Magnetic Permeability. Relative magnetic permeability is the principal property of ferromagnetic materials that affects eddy current responses. The relative permeability depends on a wide variety of parameters; alloy composition, degree of magnetization, heat treat, and residual stress, to name a few. Variations in permeability due to non-flaw conditions may mask effects from discontinuities or other conditions of interest. There are some situations where the permeability in the area of interest is not an interfering parameter and eddy current inspection can be successfully applied. An increase in conductivity or a decrease in permeability causes a decrease in measured impedance. Conversely, a decrease in conductivity or an increase in magnetic permeability causes an increase in measured impedance.

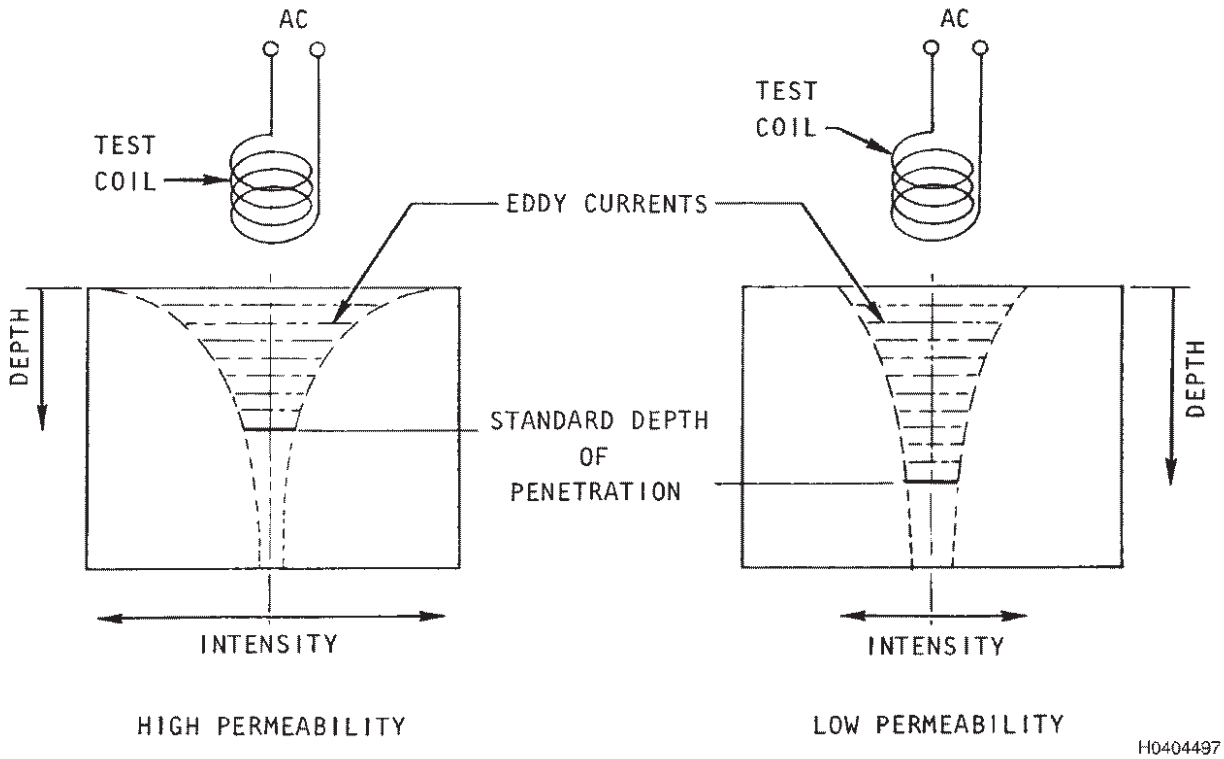


Figure 4-3. Relative Magnitude and Distribution of Eddy Currents in Conductive Material of High or Low Permeability

4.1.6.4 Geometry. Eddy currents occupy a volume in a conductive material that is relatively small. As indicated in Figure 4-2 and Figure 4-3, the volume is approximately conical and not very deep. The maximum diameter will be on the order of twice the diameter of the driving coil (which can be reduced by shielding) and the depth is estimated by the equation discussed in Section 4.8. In this respect, part geometry only becomes significant when this volume exceeds the volume available within the part. This happens when the thickness of the region of the part inspected is less than the effective depth of this conical volume or when an area near edges of the part is inspected.

4.1.6.5 Lift-Off. As an eddy current probe is brought near a conductive part, you will note a change in the detected signal. With the probe near a part, a pronounced signal change will be observed in response to a small change in distance between probe coil and part. This effect is termed "lift-off." The signal change occurs because the intensity of the eddy currents in the part decreases considerably with a slight increase in coil-to-part spacing. This condition is demonstrated in Figure 4-4. Calibrated measurements of lift-off can be used to determine the thickness of non-conductive coatings on conductive parts. Lift-off is discussed more in paragraph 4.3.14.8.

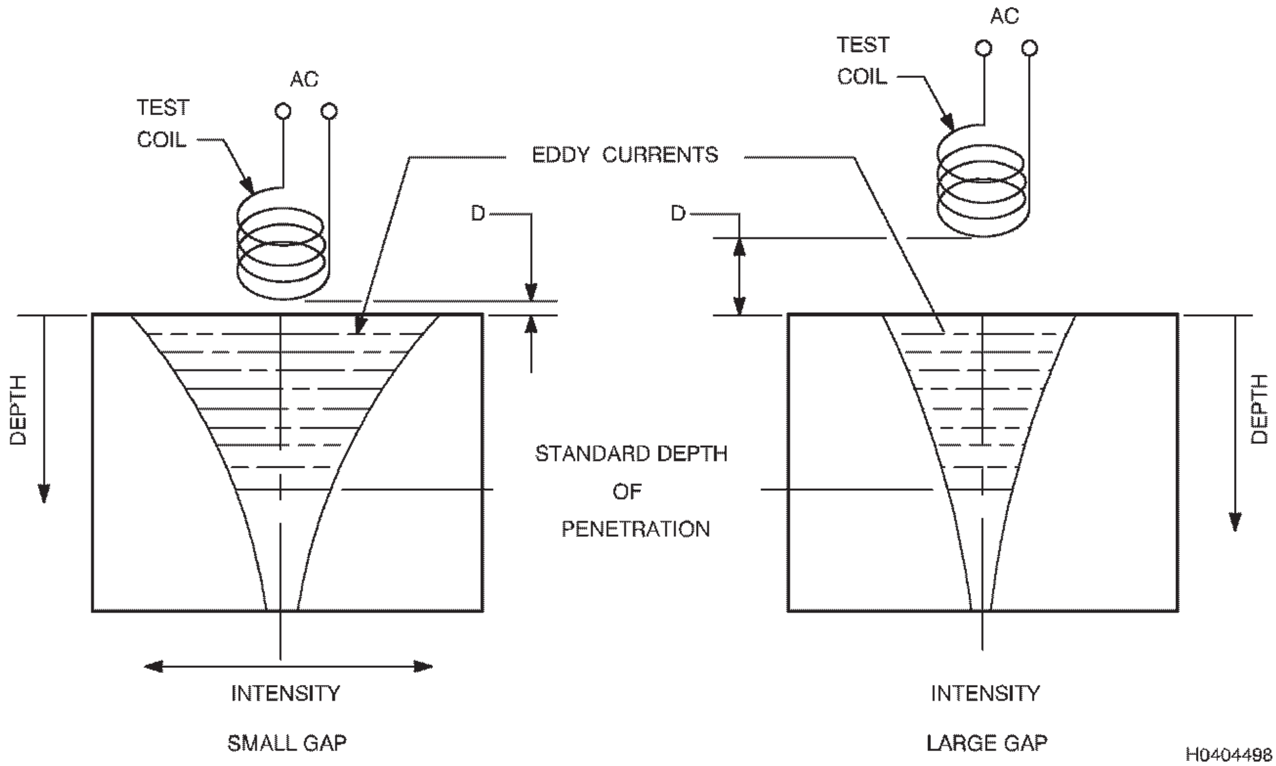


Figure 4-4. Relative Intensity of Eddy Currents With Variations in Lift-Off

4.1.6.6 Material Thickness. In sheet material with a thickness less than the effective depth of penetration (see paragraph 4.3.4.2), the electromagnetic field is not zero at the back surface. As the thickness decreases, the field at the back surface increases. And, as the thickness increases, the back surface field decreases. This provides a mechanism for thickness gauging of thin materials. Furthermore, a material of either lower or higher conductivity at the far side will change the magnitude and distribution of the eddy currents as shown in Figure 4-5. This provides a means for thickness gauging of thin, conductive coatings on underlying materials that are either more or less conductive than the coating.

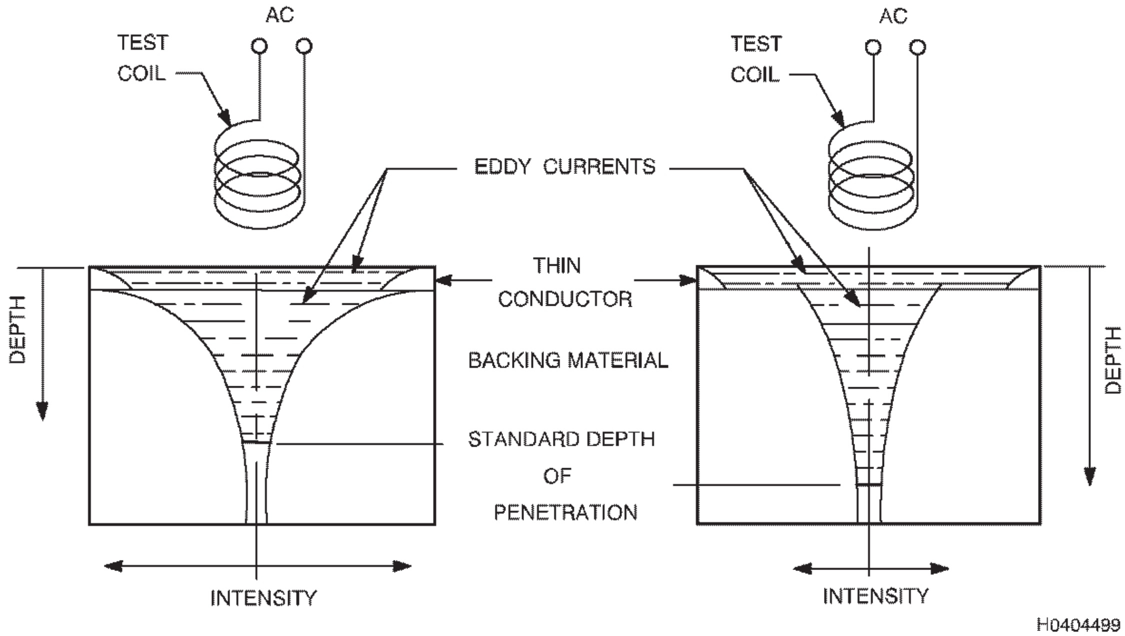


Figure 4-5. Distribution of Eddy Currents in Thin Conductors Backed by Materials of Different Conductivity

4.1.6.7 Heat Treat Condition or Hardness. Heat treating (or age hardening) a metal changes its hardness and its electrical conductivity. Just as above, the aluminum alloys have been the most investigated for the hardness/conductivity effect. Again, the impedance change is along the conductivity curve in the range of 25% to 65% International Annealed Copper Standard (IACS).

4.1.6.8 Temperature. Changing the temperature of a part changes its electrical conductivity. All metals become less conductive as temperature rises. This would be seen on the impedance plane as a movement along the conductivity curve toward the zero (air) end of the curve. For aluminum alloys, conductivity decreases about 1% IACS for a 20°F increase in temperature. If a conductivity meter is being used to check for proper alloy or heat treat condition, the temperature of all parts and calibration standards must be the same and kept constant. A change in temperature could be interpreted as a change in alloy or hardness, since all three factors may change the conductivity of a metal.

4.1.7 Eddy Current Techniques. There are a wide variety of Eddy Current techniques. A technique can be defined by the test frequencies, coil arrangements, data analyses, and data displays that are used. The techniques in (Table 4-1) are common applications used to measure or detect a variety of conditions. The table is categorized according to the actual material property or inspection parameter to be measured.

4.1.8 Field Application. The Eddy Current method is suited for detection of service-induced cracks in aircraft parts and related equipment. In addition, eddy current equipment is portable, with most systems using battery power. Eddy current applications are best suited for inspecting small localized areas. Scanning large areas for randomly oriented cracks is discouraged unless the system is automated. Eddy current can be more economical than other methods, because stripping and refinishing of surface coatings is not normally required.

SECTION II MATERIALS AND PROCESSES

4.2 MATERIALS AND PROCESSES.

4.2.1 Structure of Metals. The atoms of a chemical element have a nucleus or center with a positive charge. Around each nucleus are orbiting electrons. Each element has a different size nucleus surrounded by a characteristic number and arrangement of orbiting electrons. The distribution and number of the outermost electrons determine the properties of the element, including its metallic or nonmetallic nature. In a crystalline solid the atoms are stacked in an orderly arrangement called a lattice.

4.2.2 Mechanical Properties. Yield strength, tensile strength, and fatigue strength are determined by resistance to plastic deformation. Plastic deformation is permanent distortion of the metal and results from shearing along layers of atoms. Plastic deformation is made easier by the presence of localized imperfections in the lattice. These lattice imperfections are called dislocations and are present in great numbers in all commercial metals and alloys. If the resistance to movement of the dislocations can be increased, the strength of the metal can be increased.

4.2.3 Electrical Conductivity. Electrical conductivity is a measure of the ease with which electrons can move within a material. Good conductors of electricity have loosely bound electrons in the atomic lattice or crystalline structure and are relatively free of obstacles to the movement of those electrons. Metals have greater conductivity than nonmetals, but even within metals there is a wide range of conductivity. A perfect lattice is one in which there is no interruption in the orderly arrangement of the atoms making up the material. This situation offers the fewest obstacles to electron flow, and therefore, the highest conductivity. Any irregularity or distortion of the atomic lattice impedes the flow of electrons. Sources of such obstructions include atoms of alloying elements and grain boundaries (where lattice mismatches occur because of differing crystalline orientations). Additional obstructions are created when heat treat processes precipitate alloying elements at grain boundaries to increase strength. Cold working also creates obstructions to the flow of electrons, because of its disruption of the lattice structure. During NDI inspections it is important to note cracks and other discontinuities will also impede electron flow.

4.2.3.1 Conductivity and Mechanical Properties. The same variables of chemical composition, heat treatment, and metal working that determine the mechanical properties of a metal, also establish its electrical conductivity and magnetic permeability. As a result, correlation has been obtained between electrical conductivity and mechanical properties. This correlation does not mean the conductivity value of a metal will reliably measure its mechanical properties. However, for some metals, change of the measured conductivity from a specified conductivity range or excessive variation in conductivity within a given part or specimen indicates a probable change in properties. This change may be detrimental to the performance of the metal. It requires additional engineering investigation using hardness testing and other forms of testing to determine the magnitude of the change and disposition of the parts. The correlation of conductivity measurement with mechanical properties requires a clearly defined change in conductivity between the various alloys, tempers, or heat treatments involved. Differences in conductivity and/or permeability exist between alloys of many metals including aluminum, copper, magnesium, steel, and titanium. Not all alloys in each system are separable because of overlapping conductivity ranges. If one material has a relatively high conductivity and the other is relatively low within the given range, material separation is possible. Some metals have clearly defined differences in conductivity or permeability between the standard heat treat tempers. This situation exists for most structural aluminum alloys, many magnesium alloys, some copper alloys, and various steels. Little or no difference in conductivity is noted between the various heat treat conditions of titanium alloys.

4.2.4 Mechanical Properties of Pure Metals. A pure metal is one composed entirely of a single element. These metals are rarely used in structural applications and are usually difficult to prepare because of problems in removing all traces of other elements. They have relatively low resistance to deformation because there are few mechanisms to prevent the movement of dislocations through the metal. Two conditions can add to the strength of pure metals. Yield strength, which is a measure of the first detectable plastic deformation, can be increased very slightly by decreasing grain size. A grain is a small volume of the metal with the same three dimensional repetitive patterns of atoms. Most engineering metals are made up of a large number of grains fitted together along grain boundaries usually not visible to the unaided eye. Difference in lattice orientation in adjoining grains provides increased resistance to dislocation movement. A second strengthening mechanism for pure metals is cold working. Cold working multiplies the number of dislocations, and interaction between dislocations on different lattice planes increases the resistance to further deformation.

4.2.5 Alloys. Most engineering metals are alloys. An alloy is formed by adding one or more metals or non-metals to a base metal to form a metal of desired properties. Alloying elements are usually added during melting of a base metal and the quantities added are specified as a percentage range. The alloying elements can be in one or more forms in the solidified state depending on the amount added and the rate of cooling from the melting temperature. Some elements may occupy lattice positions normally occupied by atoms of the principle element in the material. The alloy thus formed is called a substitutional solid solution. Very small atoms such as those of carbon, nitrogen, and hydrogen take up positions between the base metal atoms to form interstitial solid solutions. This action can actually change the lattice structure, an example being the addition of carbon to iron to form steel. Alloying elements can also form new lattice structures which are continuous throughout the metal or distributed as small particles of various sizes throughout the metal. The distribution of the alloying elements is dependent on the amount of alloying elements that are added in relation to the amount that can be tolerated in the lattice of the base metal and their change in solubility with temperature.

4.2.5.1 Alloy Effects on Mechanical Properties. All of the alloying element distributions increase the resistance of a metal to deformation. Increased strength results from the interference of the alloying atoms of particles formed by the alloying atoms with the movement of dislocations or by the generation of new dislocations. This distribution can often be modified by heat treatment.

4.2.5.2 Alloy Effects on Conductivity. The conductivity of a metal is decreased as increasing amounts of alloying elements are added. Even small amounts of foreign atoms can greatly reduce conductivity. Some alloying elements have a much greater effect on conductivity than others. Generally, atoms that most severely differ in size and electron distribution from the base metal cause the greatest decrease in conductivity. The lattice distortion caused by the alloying atoms and particles of different chemical composition inhibits the flow of electrons through the lattice. Because of variations in chemical composition resulting from the tolerances in alloy additions, a conductivity range rather than a specific conductivity value is obtained for each alloy.

4.2.6 Heat Treatment. The properties of metals can be altered by changing the number and distribution of dislocations, alloying atoms, and particles of different composition. These changes can be accomplished through various types of heat treatment. The three principal types of heat treatment are: (1) annealing, (2) solution heat treatment, and (3) precipitation heat treatment or artificial aging.

4.2.6.1 Annealing. In annealing, the metal is heated to a sufficiently high temperature to remove the effects of cold working by redistribution of dislocations and, in some instances, by the formation of new stress-free grains (re-crystallization). During the annealing of alloys, the temperature is selected sufficiently high to permit the alloying atoms to readily migrate. However, this selected temperature is sufficiently below maximum solubility to favor the formation of separate particles and compounds by the alloying atoms. Slow cooling from the annealing temperature encourages even more alloying atoms to move from their random position in the base metal lattice to aid in the growth of larger secondary compounds.

4.2.6.1.1 Annealing Effects on Mechanical Properties. Annealing removes many of the obstacles to plastic flow, such as interacting dislocations, the numerous individual alloying atoms, and fine particles that normally resist plastic deformation. These processes generally result in metals of lower strength and greater ductility after annealing.

4.2.6.1.2 Annealing Effects on Conductivity. The annealing process reduces obstacles to electron flow. Therefore, annealing improves the conductivity of a metal.

4.2.6.2 Solution Heat Treating. The minimum number of alloying atoms will occupy lattice sites of the base metal when a temperature slightly below melting point is reached. In interstitial solid solutions, the maximum number of atoms will occupy interstitial positions. As temperatures are lowered, the atoms of many alloying elements will tend to diffuse together and form separate compounds or regions with a different lattice. If the metal is cooled rapidly, the atoms do not have time to diffuse and are held in their original lattice positions (retained in solution). The process is called solution heat treating. Any delay in rapid cooling (delayed quench) or a slow rate of cooling will permit an increased amount of diffusion and reduce the number of alloying atoms held in solution.

4.2.6.2.1 Solution Heat Treating Effects on Mechanical Properties. The alloying atoms retained in base metal lattice positions by solution heat treating present obstacles to dislocation movement. The resistance to plastic deformation increases the strength of the metal. In many instances, more than one alloying element contributes to the higher strength of alloys. Slow rates of cooling from solution heat treating temperatures or too low a solution heat treating temperature can reduce the strength of the heat treated alloy.

4.2.6.2.2 Solution Heat Treating Effects on Conductivity. The distortion and stresses established by the substitution of alloying atoms for those of the base metal reduce the conductivity of the metal. The greater the number of solute atoms of a specific material, the greater the reduction there will be in conductivity. The presence of lattice vacancies, caused by solution heat treating, also disrupts the electronic structure of an alloy and contributes to lower conductivity.

4.2.6.3 Precipitation Heat Treatment. If an alloy has been solution heat treated to retain atoms in the same lattice occupied at high temperature, properties can be further modified by a precipitation or aging treatment. During a precipitation treatment, an alloy is heated to a temperature which will allow alloying atom diffusion and coalescence to form microscopic particles of different composition and lattice structure within the metal. The number, size, and distribution of the particles are controlled by the time and temperature of the aging process. Temperatures are much lower than those required for solution heat treating or annealing. Lower temperatures and shorter times result in smaller particle sizes. Higher temperatures favor the formation of fewer but larger particles.

4.2.6.3.1 Precipitation Treatment Effects on Mechanical Properties. Precipitation or aging treatments are generally designed to increase the strength of alloys, particularly the yield strength. The strengthening is accomplished by the formation of small particles of different composition and lattice structure from the original lattice. The small particles provide obstacles to the movement of dislocations in which planes of atoms slip one over the other causing plastic deformation. Greatest strengthening usually occurs at a specific range of particle size for a particular alloy system. In many cases, aging is performed under conditions designed to provide a specific combination of strength and ductility, or corrosion resistance. As aging increases beyond the optimum time or temperature, particle size increases and gradual softening occurs. When material has been aged for an excessive time or at too high a temperature, it is said to be over-aged.

4.2.6.3.2 Precipitation Hardening Effects on Conductivity. The removal of foreign atoms from the parent lattice during precipitation hardening removes much of the distortion of the electron distribution in the lattice. This action favors the movement of electrons through the metal and results in higher conductivity. As increased amounts of foreign atoms are removed from solution and particle growth occurs during over-aging, conductivity continues to increase.

4.2.7 Measurement of Mechanical Properties. The most common method of determining the strength of metals is by means of a tensile strength test. In the tensile strength test, a specimen is cut from the metal to be tested, machined to a specified configuration, and tested until it fails. This is accomplished by applying a known tensile force. Tensile force is the stress at which a known amount of plastic deformation occurs, and the breaking stress can then be determined. Many other destructive type tests can be performed to establish such properties as impact resistance, notch sensitivity and fatigue strength. All of these methods require destroying a section of the part to be tested and involve considerable time and expense.

4.2.7.1 Hardness Testing. An approximate measure of strength of metals may be established by hardness testing. Hardness is usually determined by the resistance of a metal to penetration by a rounded or pointed indenter pressed into the surface with a known static force. Measurement of hardness is based on the depth of penetration of the indenter, or the plane area of the indentation. For many metals, correlation has been established between hardness and tensile strength. Hardness supplies no information regarding ductility although portable hardness testers are available; access and geometry often limit their use.

SECTION III EDDY CURRENT PRINCIPLES AND THEORY

4.3 PRINCIPLES AND THEORY OF EDDY CURRENT INSPECTION.

4.3.1 Induction of Eddy Currents. As the electromagnetic field from a coil penetrates a conductor, it generates eddy currents parallel to the surface of the part and at right angles to the direction of the applied field (Figure 4-6). The frequency of eddy current flow is the same as the electromagnetic field.

4.3.2 Primary Electromagnetic Field. The primary electromagnetic field is the coil's magnetic field (Figure 4-6). This field is called electromagnetic because the magnetic field is produced from electricity rather than from a permanent magnet. The rate at which the electromagnetic field varies is called the frequency. The strength of the electromagnetic field at the surface of the conductor depends on the coil size and configuration, the amount of current through the coil, and the distance from the coil to the surface. The amount of eddy currents the primary field is able to generate is dependent upon the properties of the part under test and the strength of the secondary electromagnetic field that opposes the primary field.

4.3.3 Secondary Electromagnetic Field. Eddy currents also generate an electromagnetic field in the part. This field, called the secondary electromagnetic field, opposes the primary electromagnetic field (Figure 4-6) and is a consequence of Lenz's Law. Lenz's Law, as applied to this case, states induced currents (eddy currents) act to reduce the magnitude of the inducing current. The opposition of the secondary field to the primary field decreases the overall electromagnetic field strength and reduces both the current flowing through the coil and the resultant eddy currents. Changes to the properties of the inspection article produce changes to the eddy currents and thus their secondary magnetic fields. In this manner, changes in the inspection article produce effects that can be detected by monitoring either the source of the primary electromagnetic field or the overall electromagnetic field.

4.3.4 Depth of Penetration. The intensity of eddy currents decreases exponentially with depth in a material. The intensity at any given depth is affected by the same variables that influence the surface intensity of eddy currents, although not always in the same manner or by the same amount. To put it another way, the depth of penetration of a specific intensity of eddy currents is affected by the variables, as indicated in Table 4-3 in paragraph 4.8. Generally, any parameter that increases the depth of penetration would increase the detectability of discontinuities deeper in the part.

4.3.4.1 Standard Depth of Penetration. Three of these variables (conductivity, relative magnetic permeability, and frequency) are used to define the standard depth of penetration. Standard depth of penetration is the depth below the surface of the inspection article at which the magnetic field strength, or the intensity of the induced eddy currents, is reduced to 36.8-percent of the value at the surface. The standard depth of penetration is expressed by the following formula in paragraph 4.8.7. Since the depth of penetration is related only to a percentage of surface field strength (eddy current intensity) some test variables are not included in the formula. Coil configuration, size, current, and magnetic coupling are not considered in this formula. These variables affect the absolute magnitude of the eddy currents at a specified depth but not the standard depth of penetration. The standard depth of penetration values for select frequencies for various alloys, bare aluminum alloys, and clad aluminum alloys are shown in Table 4-5 and Table 4-6 in paragraph 4.8.

4.3.4.2 Effective Depth of Penetration. Effective depth of penetration is the depth in the inspection article at which the magnetic field strength or the intensity of the induced eddy currents is reduced to 5-percent of the value at the surface. This depth is approximately 3 times the standard depth of penetration (According to ASTM E1004, the effective depth of penetration used for the purposes of conductivity testing is 2.6). The effective depth of penetration is used to determine test frequency when working with thin materials, so the overall electromagnetic field does not extend beyond the back surface of the test part so thickness variation effects can be suppressed. The minimum material thickness required for conductivity testing various alloys at 60 kHz and 480 kHz using the ASTM values of 2.6 is shown in Table 4-3 in paragraph 4.8.

4.3.4.3 Temperature and Depth of Penetration. For most applications, temperature is not a major factor in determining depth of penetration. However, if necessary the effects of temperature would be included as adjustments to the values for conductivity and relative magnetic permeability used in the formula to calculate the standard depth of penetration.

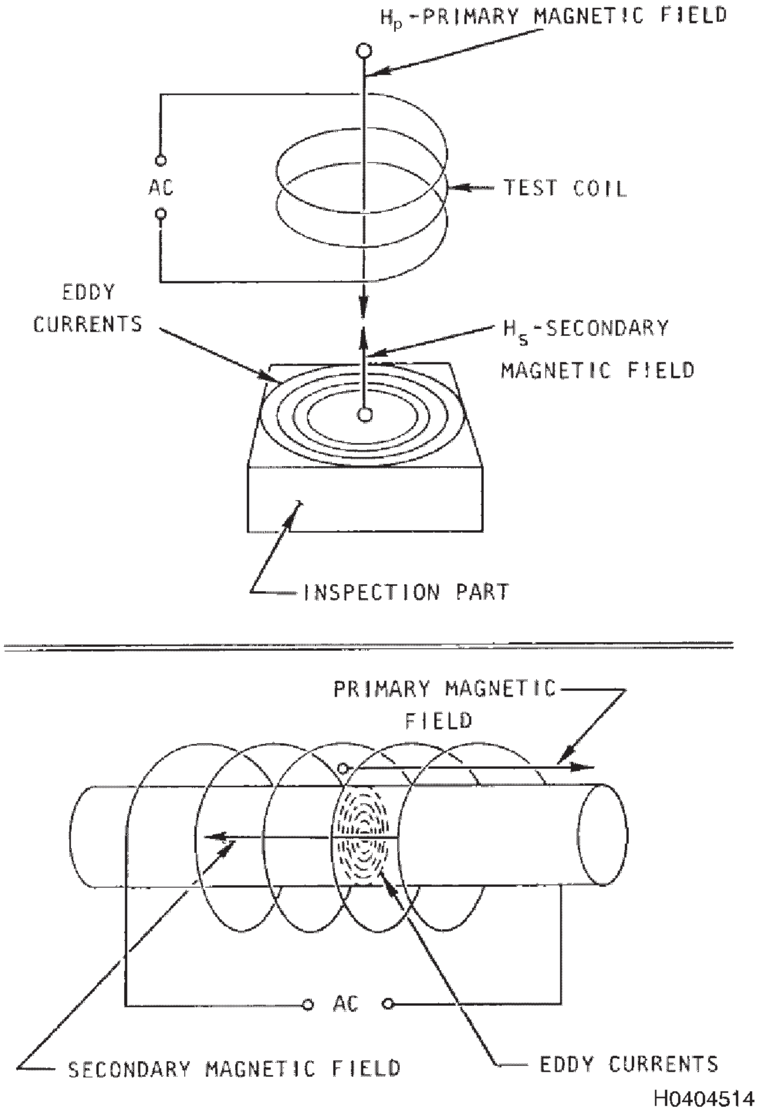


Figure 4-6. Primary and Secondary Magnetic Fields in ET

4.3.5 Impedance. Impedance is the total opposition to the flow of current represented by the combined effect of resistance, inductance and capacitance of a circuit.

4.3.6 Sensitivity. The ability of an eddy current instrument to detect small variations in test coil impedance is a measure of its sensitivity. This quality is interrelated with the properties of the test coil and the operating frequency. Therefore, instrument sensitivity to a particular flaw condition or material property SHALL be established from reference standards representing this condition.

4.3.7 Resolution. The ability of a test system to separate the signals from two indications that are close together is defined as "resolution." This property plus sensitivity must be considered in every flaw evaluation situation. Probe design, test frequency, and instrumentation design are all factors in determining the resolution of an eddy current system.

4.3.8 Measurement of Resistivity. Electrical resistance is a measure of the resistance to the flow of electric current in a conductor. Resistance depends on the length and area of the current path, and the conductivity of the conductor. Resistance is commonly measured in ohms. If a material allows one volt (electric potential) of driving force to push one ampere of current through a conductor, the electrical resistance of the conductor is defined as one ohm of resistance. Resistivity is a material parameter independent of the size of a material sample and is related to resistance. Resistivity is defined as ohms times cross-sectional area divided by unit of length (paragraph 4.8.1.3).

4.3.9 Measurement of Conductivity. Electrical conductivity is the reciprocal of electrical resistivity. The reciprocal of the "ohm" is commonly called the "mho." Conductivity is commonly expressed in units of mho's per unit length; such as mho/inch or mho/meter. The relationships between conductivity, resistivity, and resistance are expressed by the equations in paragraph 4.8.12.

4.3.9.1 Conductivity Based on the Percentage of International Annealed Copper Standard. (%IACS). An alternative way of expressing conductivity is a percent of the conductivity of a known material. The International Electro-technical Commission has designated the conductivity of a specific grade of high purity copper to be the standard for this alternative method with a conductivity of 100-percent. It is called the International Annealed Copper Standard (IACS). The conductivity of all other metals is then expressed as a percentage of this standard.

NOTE

Values of conductivity of some commonly used engineering materials are listed in Table 4-2 and Table 4-7 in paragraph 4.8. Percent IACS is the usual way of expressing conductivity in aerospace NDI.

4.3.10 Overview of Signal Detection, Processing, and Display.

4.3.10.1 Signal Sources. When performing an eddy current technique, material changes can be detected by monitoring the alternating current in the coil (single coil arrangement) or using a separate sensing coil to monitor the resultant electromagnetic field. These signals can be analyzed for information relevant to the inspection being conducted. The important thing to note is the coil that is acting as the receiver is producing an electrical current that either leads or lags the instruments oscillator current. The difference in this "leading" or "lagging" is the phase angle.

4.3.10.2 Signal Detection. A simple but effective signal detection technique is to use a bridge circuit as illustrated in (Figure 4-7). With current flowing through the test coil and the coil positioned on a flaw-free or reference area, the variable impedance Z_1 can be adjusted so zero current flows through the amplifier. This adjustment is termed either "balancing" or "nulling" the bridge. When the coil is placed on a flawed or damaged area, the resultant change in current through the coil “unbalances” the bridge and current flows through the amplifier. This current is the inspection signal. The signal has the same frequency as the current through the coil. The phase and amplitude of this signal contains information on the condition that caused the bridge unbalance.

4.3.10.3 Signal Analysis. In the simplest type of instrumentation, analysis of the signal consists of measuring the change in magnitude of the current flowing through the bridge. Changes in the magnitude of the alternating current are amplified and converted to a direct current for display or readout. In more sophisticated instrumentation, both amplitude and phase are measured.

4.3.10.4 Displays. The method by which eddy current signals are presented is dictated by the type of information required and the complexity of the instrumentation. When only signal amplitude is measured, meters, alarm signals, or recorders are commonly used. When both amplitude and phase information are to be displayed, a two-dimensional display device is normally used.

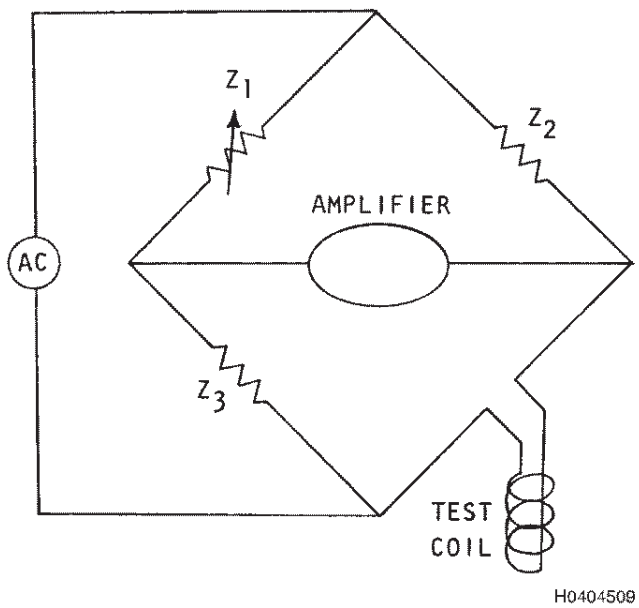


Figure 4-7. Simplified Bridge Circuit

4.3.10.4.1 Amplitude Display. Meters may be analog (needle moving over a fixed numerical scale) or digital. Audible or visual alarms may be set to trigger when the signal amplitude exceeds a predetermined threshold. A recorder presents a continuous record of the signal amplitude during an inspection for subsequent analysis.

4.3.10.4.2 Impedance Plane Display. Defects or other variations in material characteristics will alter the strength and distribution of an induced eddy current flow. Changes in the eddy current flow will result in changes in the inducing coil or sensor coil currents. These changes can be expressed as an apparent change in the coil's electrical impedance. This makes it possible to associate changes in material properties with specific changes in the apparent impedance of either the excitation or sensor coils. The two-dimensional display that permits this is the most commonly used and is called an impedance plane display. The impedance plane is discussed further in paragraph 4.3.10.8.2.

4.3.10.5 Impedance Changes. The impedance of a coil appears to change when it is placed adjacent to an electrically conductive or ferromagnetic part. The secondary electromagnetic field created by the induced eddy current in the part opposes the primary field. This opposing field also induces a current flow in the coil in opposition to the primary current. If the part is not ferromagnetic, the net magnetic field resulting from the combination of the primary and secondary fields is decreased in magnitude, as is the current flow in the coil. This is equivalent to decreasing the inductance and increasing the resistance of the coil. If the part is ferromagnetic, the net magnetic field is increased because of the magnifying effect of the relative magnetic permeability, but the current flow in the coil is decreased because of the opposing effect of the secondary magnetic field from the induced eddy currents. This is equivalent to increasing both the inductance and resistance of the coil. In this manner changes in a part that affect either the strength of the magnetic field at the surface of the part or the strength and distribution of the eddy currents in the part, change the apparent impedance of the test coil(s). These variations in current flow, both phase and amplitude, can be detected, amplified, displayed, and analyzed as eddy current test results. The amplitude and phase changes in the signals can be related to changes in the parts inspected.

4.3.10.6 Inductance of a coil. The inductance of a coil depends upon the number of turns in the coil, the size of the coil, the permeability of the material within the coil (e.g., the core of the coil), and total magnetic flux through the coil. An alternate method of expressing self-inductance (L) is:

$$L = n \Phi / I$$

Where:

X_L = Inductive reactance (Ohms)
π = 3.141596
f = frequency (Hertz)
L = Inductance (Henrys).

4.3.10.7 Inductive Reactance. The measure of the amount of opposition or resistance (Ohms) to alternating current flow due to inductance in a coil is called inductive reactance. Inductive reactance is dependent upon the value of the inductance of the coil and the frequency of the alternating current. The inductive reactance increases as the inductance or frequency increases. This can be stated by the following equation:

$$X_L = 2 \pi fL$$

Where:

X_L = Inductive reactance (Ohms)
π = 3.141596
f = frequency (Hertz)
L = Inductance (Henrys).

4.3.10.7.1 The inductive reactance results from the electromotive force generated across a coil by the alternating current. The instantaneous value of this induced voltage, increases and decreases as the rate of change of the applied alternating current increases and decreases as shown in Figure 4-8. The voltage is at its maximum value when the rate of current change is at its maximum; this occurs when the current value is at zero. Conversely, the voltage is zero when the rate of current change is zero; this occurs when the current is at its maximum value. Considering 360-degrees to be one complete cycle, the induced voltage leads the current (e.g., is out of phase with the current) by 90-degrees as illustrated in Figure 4-8. The induced voltage is in opposition to the electromotive force applied to the coil, reducing the amplitude of the resultant current.

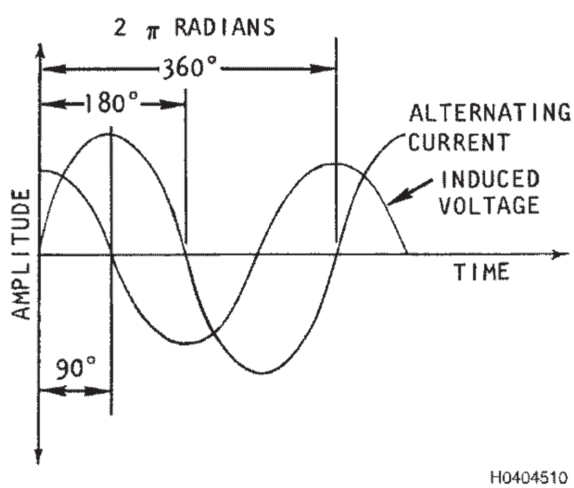


Figure 4-8. Sinusoidal Variation of Alternating Current and Induced Voltage in a Coil

4.3.10.8 Combining Out of Phase Quantities. A real coil has a resistive component of the impedance in addition to the inductive reactance. They can be combined to describe the net impedance. A coil can be considered to be a resistor in series with an inductor. Applying an alternating current to this series circuit will result in two voltages, one across the resistor and another across the inductor. The net voltage across the combination of the resistor and inductor (e.g., across a real coil), will be the combination of the two voltages. The voltage across the resistor will be in phase with the current while the voltage across the inductor will lead the voltage across the resistor by 90-degrees. The combination of the two voltages, as illustrated in Figure 4-9, results in a voltage that will be out of phase with the current but not by a full 90-degrees.

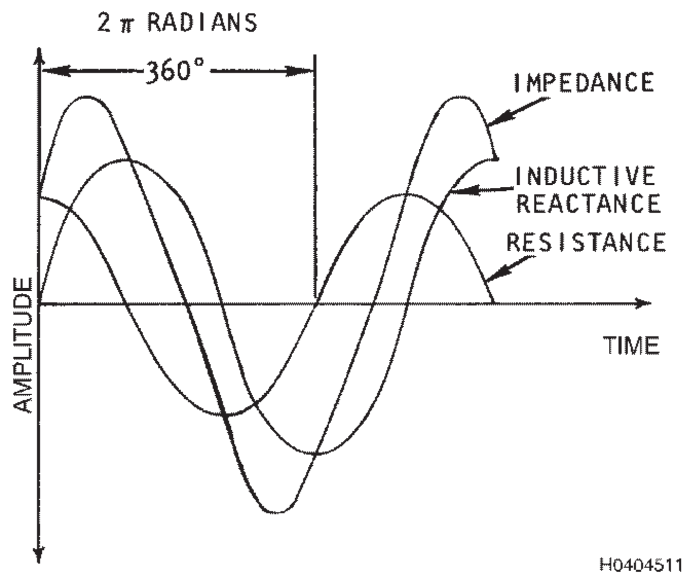


Figure 4-9. Combining of Out-of-Phase Voltages

4.3.10.8.1 X-Y Plot Representation. Another way to illustrate the combination of out-of-phase quantities in a coil is illustrated in Figure 4-11. Here the two voltages drop; one across the resistor (V_R) and the other across the inductor (V_L) are plotted at right angles to each other. This represents the two quantities being 90-degrees out of phase. The combination of the two quantities is represented by the diagonal line OA that is at the angle "θ" with respect to the voltage drop across the resistor.

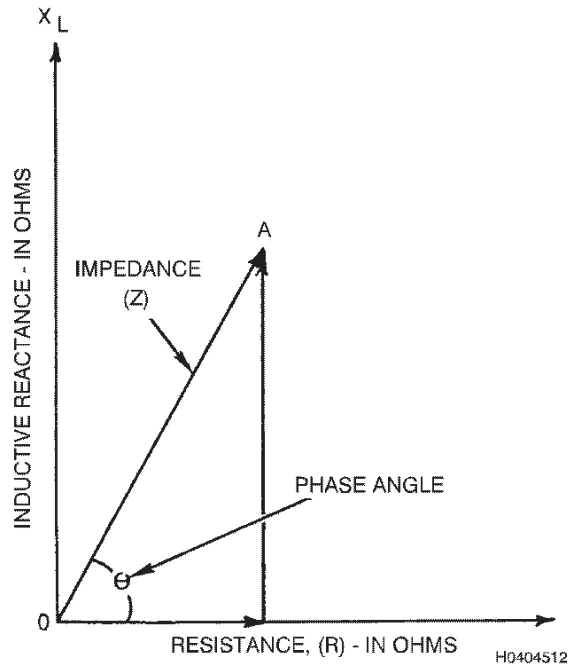


Figure 4-10. Vector Diagram Showing Relationship Between Resistance, Reactance, and Impedance

4.3.10.8.2 Impedance Plane Representation. Just as the two voltages can be combined to produce the net voltage across a coil (Figure 4-11); the resistive and inductive impedance components can be combined to produce the net impedance of a coil. In Figure 4-10, inductive reactance (X_L) is plotted on the y-axis and resistance (R) is plotted along the x-axis. These two values define the impedance that is represented by the vector OA. The value of the angle "θ" for the net impedance is the same as the angle "θ" illustrated in Figure 4-11 for the net voltage. This is important because it shows that the impedance of a coil can be displayed as the combination of two out-of-phase voltage drops. The amplitude of the impedance may be determined from the known values of resistance and inductive reactance according to the following formula:

$$Z = (X_L^{\ 2} + R^2)^{1/2}$$

Where:

Z = Impedance magnitude (ohms)

X_L = Inductive reactance (ohms)

R = Resistance (ohms)

X_c = O Capacitive reactance is negligible.

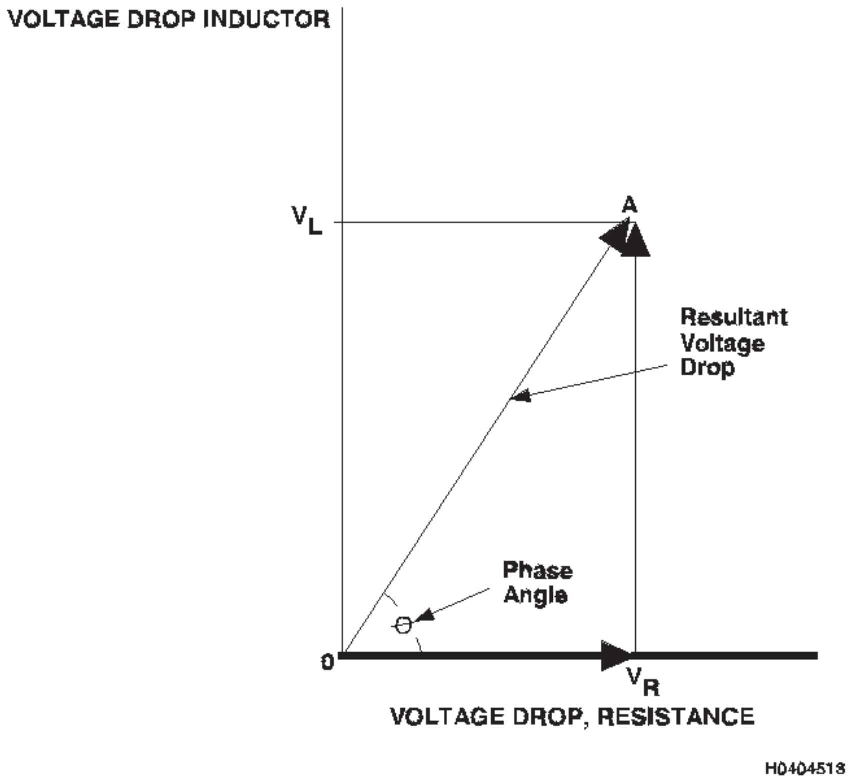


Figure 4-11. Diagram Showing Relationship of Voltage Drops Across Coil Resistance and Coil Reactance

4.3.10.8.3 The phase angle (θ) of the impedance can be calculated from the values of resistance and inductive reactance as follows:

$$\tan \theta = X_L / R$$

Where:

θ = Phase angle (degrees)
X_L = Inductive reactance (ohms)
R = Resistance (ohms)

4.3.11 Impedance Diagrams.

4.3.11.1 Purpose. The impedance diagram shows how changes in eddy current test variables change the apparent impedance of a coil. Typical variables displayed are electrical conductivity, relative magnetic permeability, fill-factor or lift-off, part thickness, and test frequency. Impedance diagrams are very useful in determining optimum inspection parameters and understanding eddy current results when more than one variable is changing. The vector representation of inductive reactance on the y-axis and resistance on the x-axis of Figure 4-12 is the basis of the impedance diagram. Let point A represent the impedance of a test coil while on a part. If the probe is moved to a place on the part with a flaw, the impedance will change. This new impedance can be represented by the point B, as shown in Figure 4-12. Each change in the impedance will create a new point on the diagram.

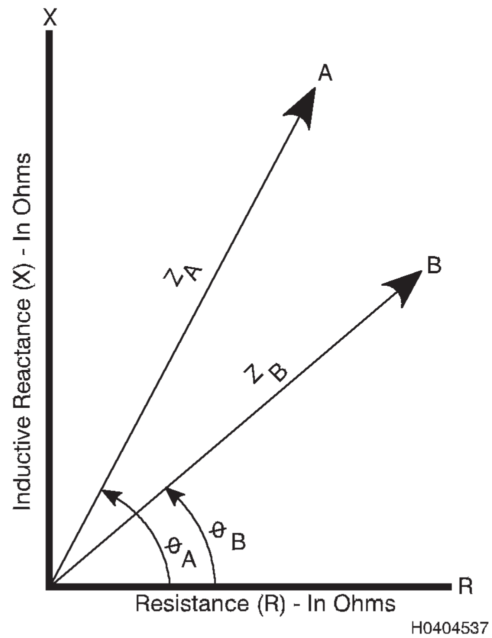


Figure 4-12. Vector Representation of Impedance

4.3.11.2 Development of an Impedance Diagram. To make the impedance diagram into a useful tool for understanding eddy current testing, it is necessary to systematically change a single test parameter such as conductivity, and observe the changes in the impedance. Using an eddy current instrument with a two-dimensional graphical display, a surface probe, a piece of ferrite (a nonconductive, ferromagnetic ceramic) and several nonmagnetic metal specimens representing a range of conductivity's from low (titanium, Inconel) to high (copper, silver), approximate impedance diagrams can be developed and demonstrated. The specimens must have clean, flat, and bare surfaces. When the eddy current probe is held away from the part (in the air) and the instrument is nulled, an indication (dot) will appear on the display. The null point can be repositioned near the upper left hand corner of the display, as indicated by point A in Figure 4-13 and Figure 4-14. The null point in air will be used as a point of reference for the rest of the diagrams. Next, the ferrite specimen is used to establish the direction of inductive change. Place the probe on the ferrite and adjust the phase control so that the change from air to ferrite is vertical (parallel to the y-axis). When the probe is placed on the copper specimen, the point will move to a new location on the screen, represented by point I in Figure 4-14. As the probe is lifted from the specimen, the point will move back to the air null point (A), as shown in Figure 4-13 and Figure 4-14. The path that the indication follows as the probe is moved onto and off the specimen is called the lift-off trace/line.

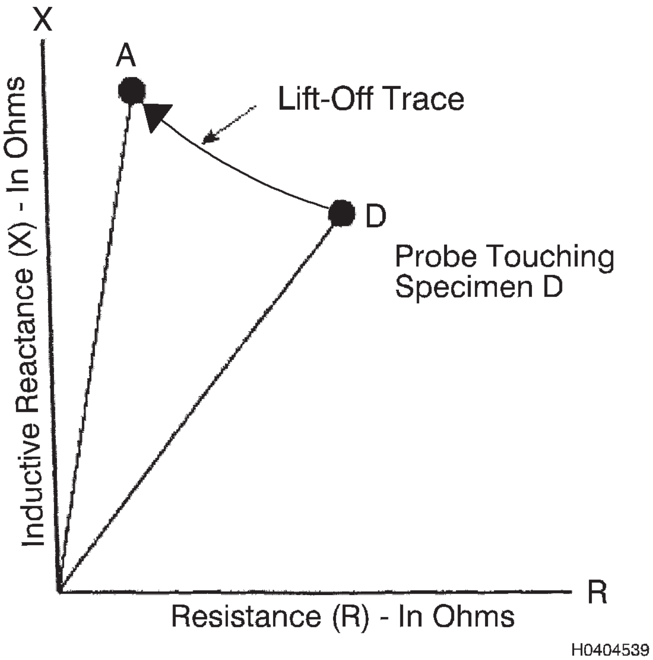


Figure 4-13. Vector Representation of an Impedance Change due to Lift-Off

4.3.11.3 Typical Uses of an Impedance Diagram. The impedance diagram (shown in Figure 4-14) illustrates the conductivity curve can be used to measure the relative conductivity of an unknown material by comparing the position of its indication on the conductivity curve to the positions of indications from known materials. Notice also the lift-off lines are in a different direction than the conductivity line. Changes in conductivity and lift-off are said to have different phase angles. This phase angle difference is further illustrated in Figure 4-15. The lift-off curve can also be used to measure the thickness of non-conductive coatings on a conductive surface. This is done by comparing the length of lift-off line for an unknown coating thickness to the lengths of lift-off lines for known thickness.

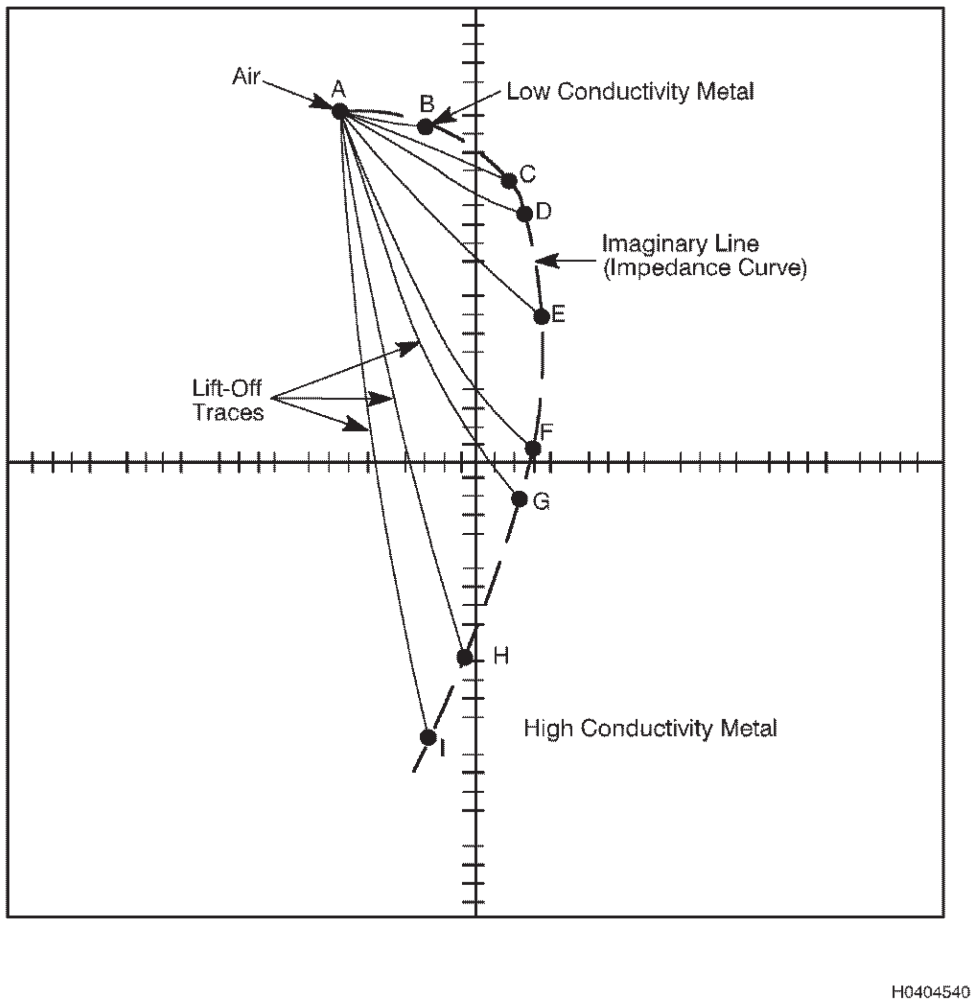


Figure 4-14. Impedance Diagram Illustrating Effects of Variable Conductivity

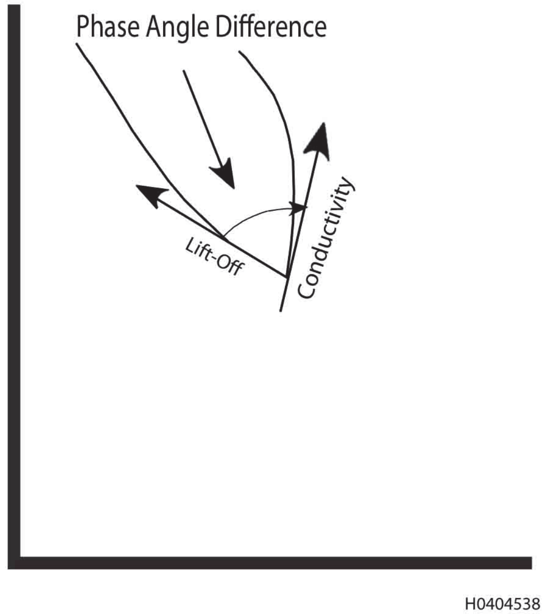


Figure 4-15. Phase Angle Difference between Lift-Off and Conductivity

4.3.11.4 Thickness Variations. When the part thickness is less than the effective depth of penetration of the test coil at the inspection frequency employed, the impedance curve departs from the conductivity curve as shown in Figure 4-16. Typically, there is an increase in the resistive component of the impedance with thinner parts, as compared to parts that have thickness equal to or greater than the effective depth of penetration. As the thickness of the parts increase and approach more closely the effective limit of penetration, the curve tends to spiral as it approaches the end point (T=1) on the conductivity curve, where T equals the ratio of the specimen thickness to the effective depth of penetration in that specimen.

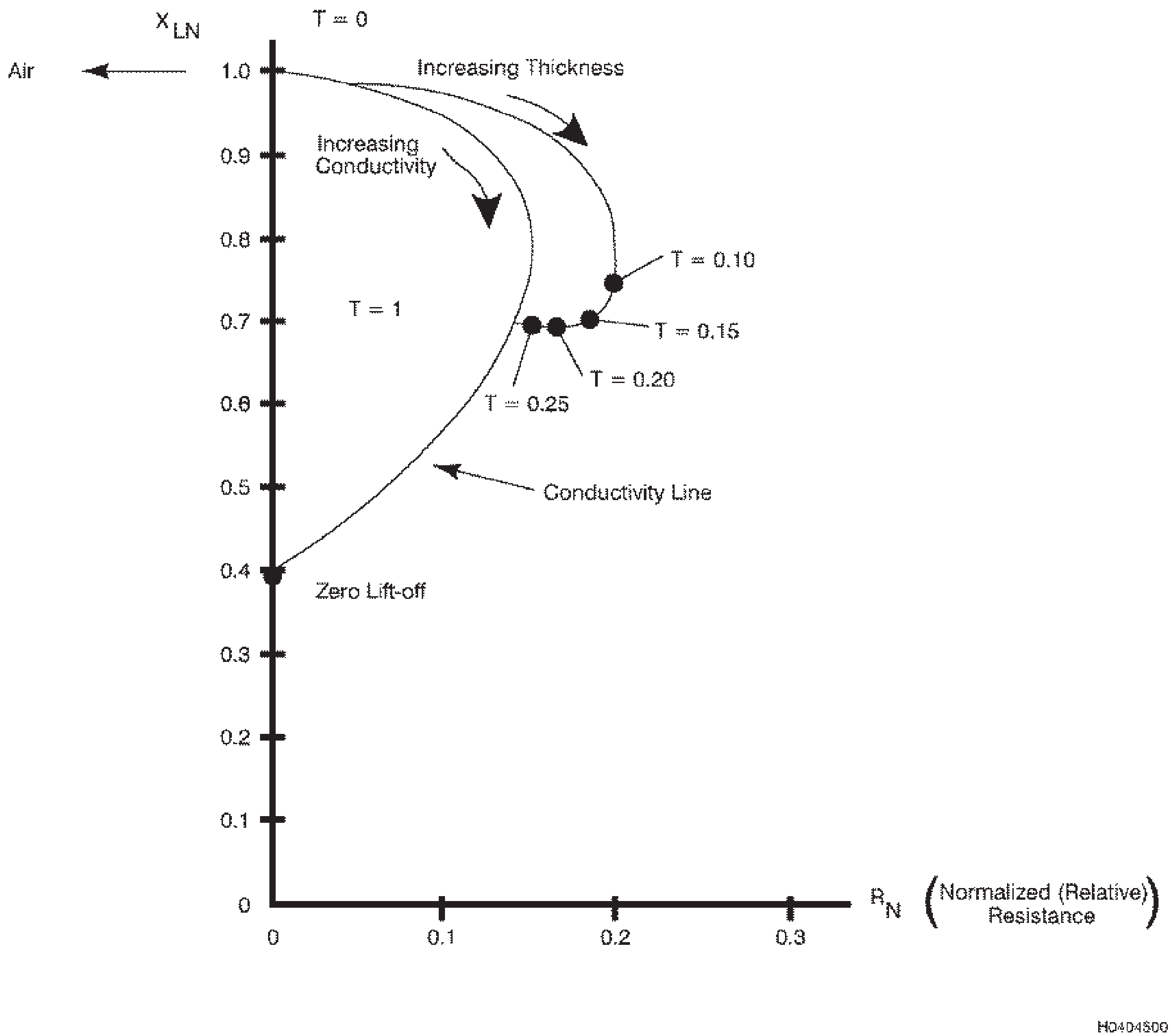


Figure 4-16. Impedance Diagram Showing the Effect of Specimen Thickness

4.3.11.5 Conductive Layers. The impedance curve for thin conductive layers on a substrate of different conductivity is also represented as a change in the impedance curve for conductivity. The impedance for the layered material departs from the conductivity curve at the value corresponding to the substrate conductivity and forms a loop that rejoins the conductivity curve at the conductivity of the metal in the outer layer. Increasing thickness of the outer layer corresponds to a clockwise direction along the loop. The point at which the loop rejoins the curve represents the effective depth of penetration in the coating.

4.3.11.6 Normalization of Impedance. To illustrate general principles of eddy current inspection or to present data in a universal form independent of specific coil impedance values, impedance diagrams are usually normalized. In normalization, the inductive reactance and the resistance of the coil on the part are divided by the value of the inductive reactance of the coil in air. Therefore, the vertical axis of the impedance diagram equals the relative inductive reactance (XLN) of the test coil; and the horizontal axis of the impedance diagram equals the relative resistance (RN) of the test coil. Normalization is a convenient method to allow comparisons of eddy current data from a large number of tests using different probes and materials. The shapes of the impedance diagrams remain the same. However, the air null point A in Figure 4-17 becomes 1 on the y-axis of the impedance diagram after normalization. The impedance diagrams in this manual will all be represented by the normalized reactance (XLN), on the y-axis and normalized resistance (RN) on the x-axis.

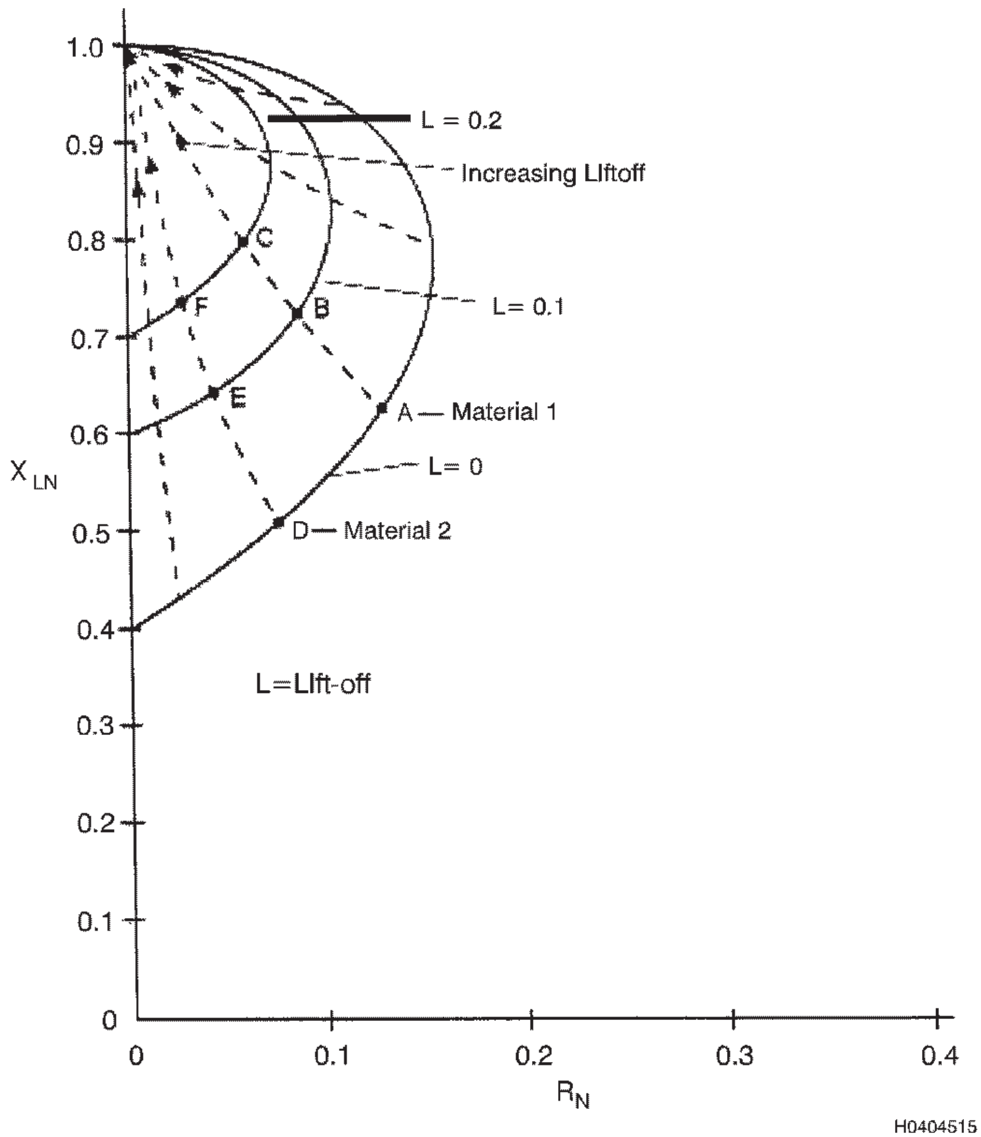


Figure 4-17. Impedance Diagram Showing the Effect of Lift-Off

4.3.12 Impedance Plane Analysis. Most eddy current applications have two major problems to overcome. The first is to ignore changes in parameters not of interest during the test; an example is lift-off variation while inspecting for cracks. The second is to recognize valid indications while other changes are occurring. Another way of stating this is insignificant variations such as those associated with lift-off should not be mistaken for valid defect indications, and valid defect indications should not be hidden by nonrelevant changes such as lift-off. Impedance plane analysis, also called phase analysis, is a tool that is effective in solving these problems.

4.3.12.1 Phase Detection. Phase angle measurements are a good way to detect a variety of flaw conditions. The information in the vector diagram (Figure 4-10) illustrates this. Decreases of conductivity (e.g., cracks) and permeability could produce the same signal amplitude, and it would be difficult to differentiate between cracks and normal permeability changes in a part. However, the phase angle of a conductivity change is very different from a permeability change if the correct test frequency is chosen. Using phase detection techniques, it becomes a simple matter to detect the difference between permeability variations and cracks. This also applies to determining the depth of a flaw, which is phase sensitive, or separating lift-off effects from flaw conditions. Phase sensitive detectors use a variety of techniques such as phase splitters, phase shifters, averaging, half-wave and full-wave detection, sampling, and subtractive and additive techniques. The presentation of the impedance plane on waveform display eddy current instrument; uses two-phase sensitive detectors to provide horizontal and vertical phase detection. This information is combined to produce a dot or point on the screen which represents the relative phase and amplitude of an eddy current signal. Some types of meter instruments utilize an adjustable phase control or phase gate to allow only signal detection at a particular phase angle of interest.

4.3.12.2 Cracks, Lift-Off, and Conductivity. The impedance changes due to surface cracks of different depths. The change for cracks will lie between the lift-off and conductivity. As the crack depth increases, the response moves farther from lift-off and closer to decreasing conductivity.

4.3.12.3 Crack Detection in Non-Ferromagnetic Materials. The amplitude of the response from a surface crack increases as the crack gets deeper. When the crack reaches three standard depths (paragraph 4.3.4.1) it is interrupting essentially all of the eddy current flow and no increase in amplitude is seen as it gets still deeper. Besides an amplitude increase for deeper cracks, the phase angle of the crack indication changes. A shallow crack interrupts little of the eddy current flow, so the amplitude of its signal is small. Also, it is essentially a surface condition, so the direction (phase) of the signal response is very close to that of lift-off (Figure 4-18). A deeper crack interrupts more of the eddy current flow, so its signal has greater amplitude. It extends well below the surface, the direction (phase) of its signal is farther away from lift-off (Figure 4-19). The three standard depths crack has the largest amplitude response. It interrupts the eddy currents as far down in the metal as the test can sense, it looks like a change in the bulk property of lower conductivity, and the crack signal direction (phase) is along the conductivity curve (Figure 4-20).

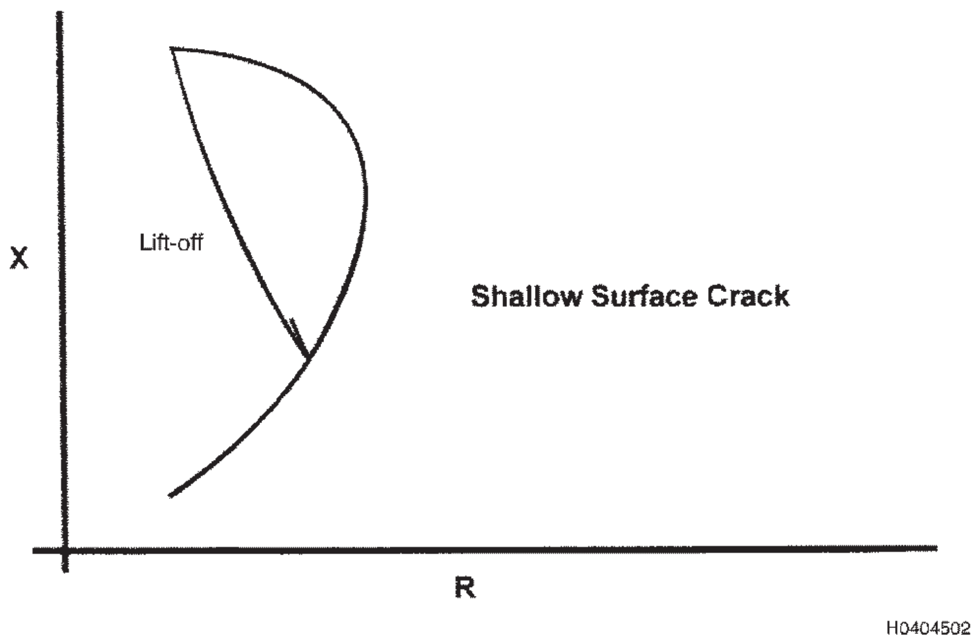


Figure 4-18. Shallow Surface Crack

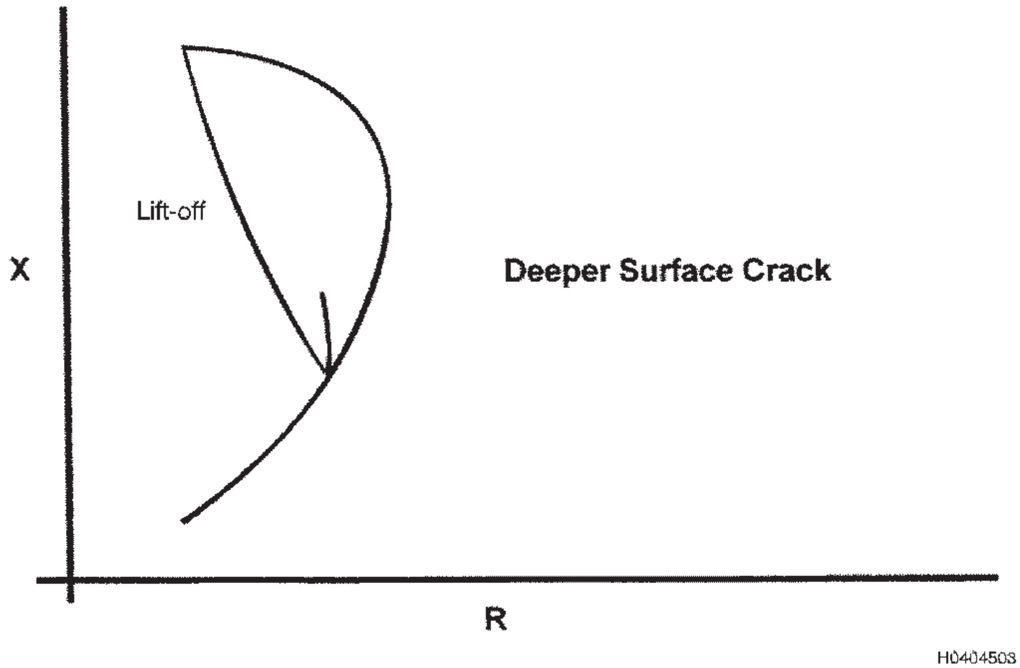


Figure 4-19. Deeper Surface Crack

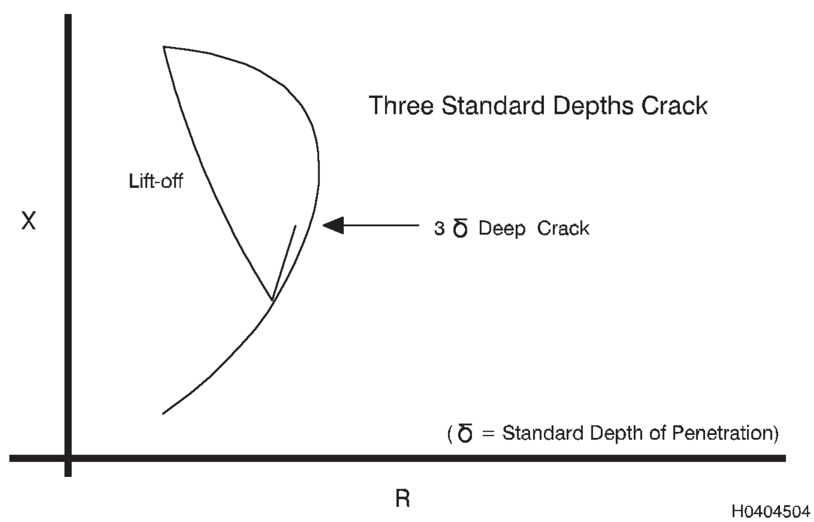


Figure 4-20. Three Standard Depths of Penetration

4.3.12.3.1 Making the three standard depths crack deeper will not change the signal response because there will be no eddy current flow for it to interrupt. However, there will be a change in the signal response for a subsurface crack. First, eddy currents will flow over the top of the crack (at the surface), the subsurface crack will not block as much of the eddy current flow and the amplitude of the signal must decrease. Second, the crack is now farther away from the surface so its phase angle must still be further away from lift-off (Figure 4-21).

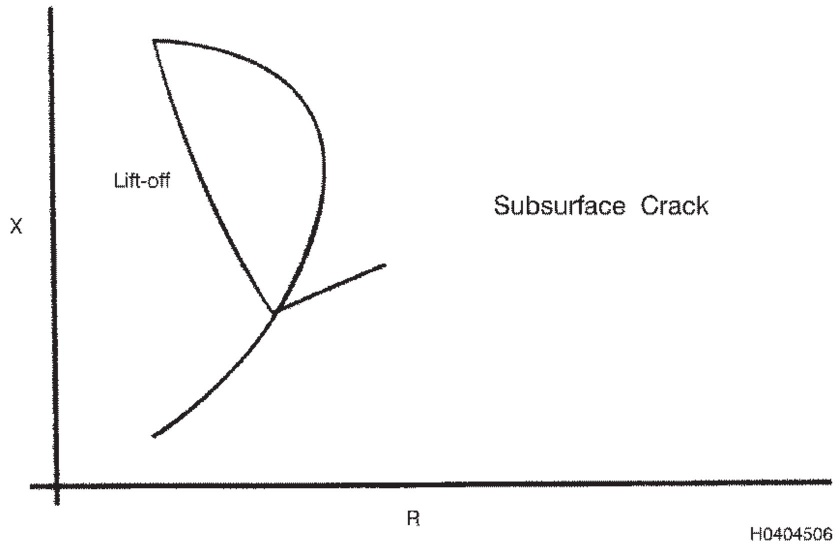


Figure 4-21. Subsurface Crack

4.3.12.3.2 Signal response decreases as the depth of the crack below the surface increases. As the subsurface defect gets further away from the surface, the signal amplitude gets smaller and the phase angle rotates clockwise, away from lift-off (Figure 4-22).

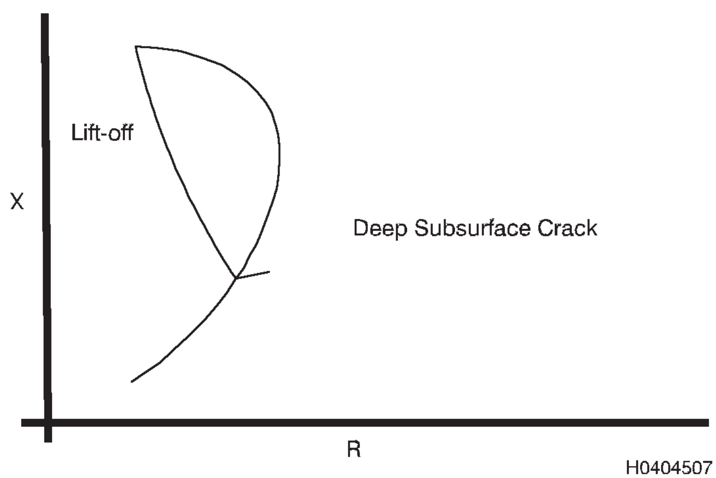


Figure 4-22. Deep Subsurface Crack

4.3.13 Phase Lag at Depth. A phase angle shift can occur and change the eddy current field time and travel distance. Changes at the surface of the part are seen immediately by the coil, while disturbances to the field at some depth in the part require some travel time to return to the surface where they are seen by the coil. Electrically, this is described as phase lag at depth, and the amount of phase lag is 1 radian (57°) per standard depth of penetration Figure 4-23). This phase lag from the lift-off (surface) signal may be used to measure the depth of defects. The phase angle of a defect signal correlates to defect depth.

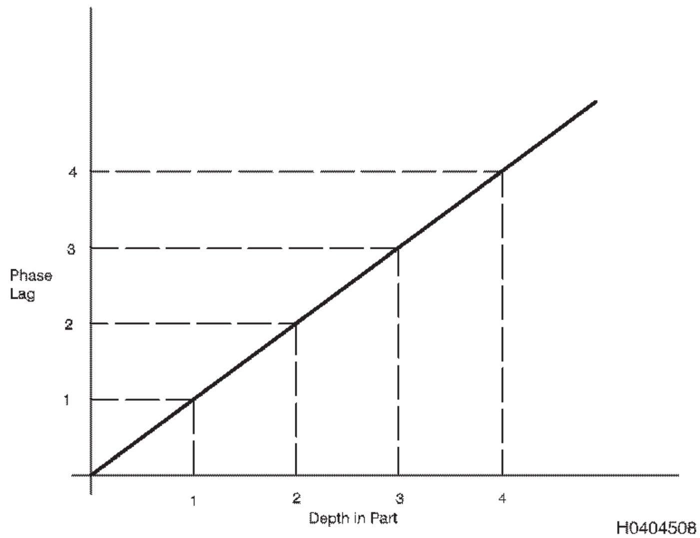


Figure 4-23. Phase Lag and Depth in Part

4.3.14 Effects of Inspection Conditions on Eddy Currents.

4.3.14.1 Frequency. The magnitude of the induced eddy currents in the part increases as the frequency of the inducing current increases. In turn, the higher intensity eddy currents generate a stronger opposing magnetic field, reducing the penetration of the primary field. Therefore, all other factors remaining constant, higher frequencies result in shallower depths of penetration as shown in Figure 4-24.

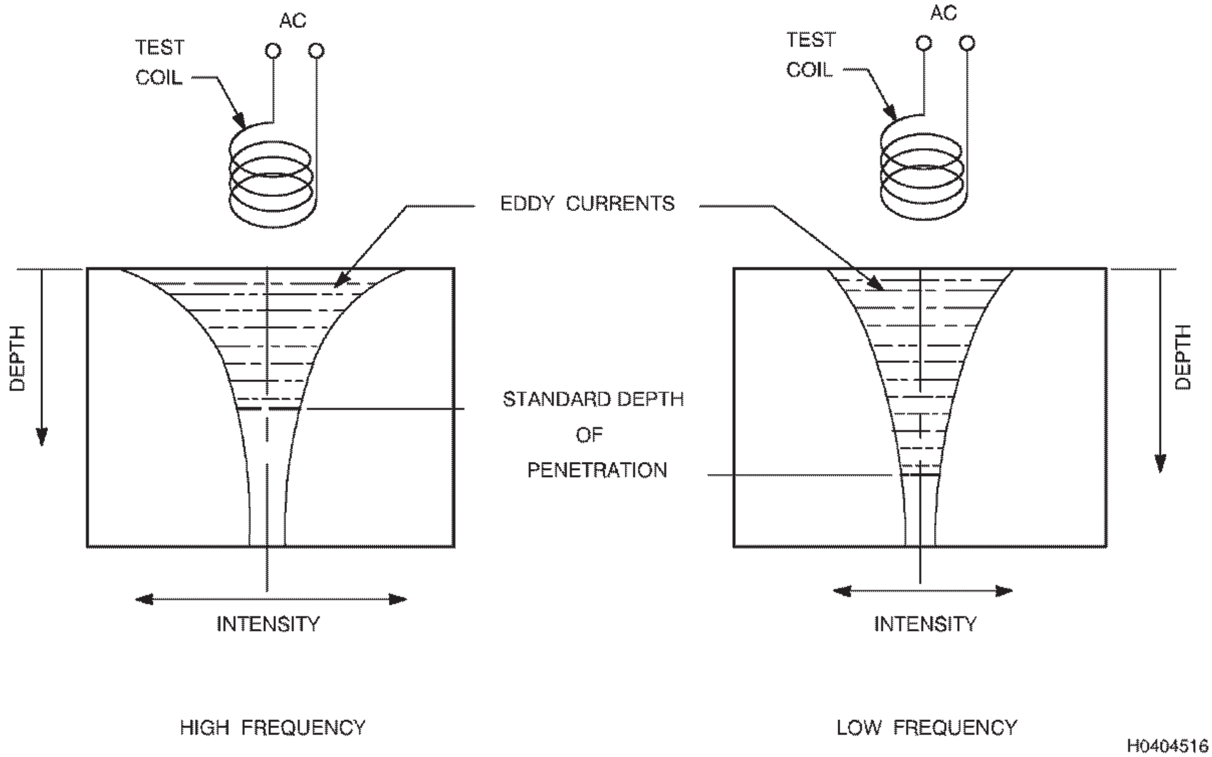


Figure 4-24. Relative Effect of Frequency on Depth of Penetration

4.3.14.2 Conductivity and Frequency. There is a relationship between conductivity and optimal inspection frequency. As an example, an eddy current inspection for cracks in aluminum alloy 7075-T6, with a conductivity of about 30% IACS uses a frequency of 200 kHz. To perform an inspection with comparable depth of penetration on a titanium alloy, TI 6Al-4V with a conductivity of about 1% IACS, a frequency of about 6 MHz would be required.

4.3.14.3 Electromagnetic Coupling. The interaction between the primary electromagnetic field generated by the coil and the inspection article is referred to as electromagnetic coupling. Because the field decreases in strength with increasing distance from the coil, resultant eddy currents at the surface of the part will also decrease in intensity. An electrical engineering term that could also be used is inductive coupling.

4.3.14.4 Fill-Factor. When an encircling coil is used to inspect a cylindrically shaped part, the degree of magnetic coupling is dependent upon the difference between the internal diameter of the coil and the external diameter of the part. This effect is termed fill-factor. For internal coils, electromagnetic (inductive) coupling is determined by the air gap between the external diameter of the coil and the internal diameter being inspected. Fill-factor is calculated using the basic formula, but in this case "d_i" is the inside diameter of the part and "D_0" is the outside diameter of the coil placed in the part (paragraph 4.8.3).

4.3.14.5 Coil Current. With all other factors constant, an increase in current flowing through the coil results in a higher magnetic field strength.

4.3.14.6 Temperature. The temperature at which an inspection is performed affects both the electrical conductivity and the ferromagnetic properties of the inspection article. Electrical conductivity generally decreases with increasing temperature, and conversely increases with decreasing temperatures. The reduction at higher temperatures occurs because of the scattering of conduction electrons by atoms moving with increased thermal oscillations. Temperature effects on the ferromagnetic properties of a material are generally negligible with one exception. Above a specific temperature called the Curie temperature (about 1400°F or 760°C), ferromagnetic properties disappear. Because of the thermal effects on conductivity, increasing temperature of the inspection article slightly decreases the intensity of eddy currents at the surface of a part and slightly increases the depth of penetration. Temperature variations also affect the inductance of the coil. Remember, changes in temperature affect ET results. Therefore, during inspections, time SHOULD be allowed for the test system and the test part to stabilize to the ambient temperature. An example test would be to see if part and standards feel the same to the bare hand.

4.3.14.7 Geometry. Geometric features such as edges, curved surfaces, changes in thickness, and non-conductive coatings (such as paint) on surfaces affect the distribution and strength of eddy currents. As a probe approaches an edge the eddy current response is known as edge effect and appears similar to a response from a crack. Similarly, curved surfaces and non-conductive coatings can vary the distance between the probe coil and the part. These changes are known as lift-off, and the consequent effects on the eddy current signal are called lift-off effects. Lift-off usually cannot be completely prevented; therefore compensating for some lift-off is part of the setup procedure. Part thickness variations can also produce an interfering response in some eddy current units when the thickness is in the range of the depth of penetration of the eddy current field.

4.3.14.8 Lift-Off. The effects of lift-off can be used to measure coating thickness. Changes in lift-off can be calibrated to allow measurements of nonconductive coating thickness. Fill-factor applies to parts passed through an encircling coil and, in a manner similar to lift-off, can be used to gauge some dimensions. As a test coil is moved away from a part (increasing lift-off) the coupling between test coil and inspection part is decreased. The magnitude of the impedance change for a specific change in an inspection variable is also decreased. For probe coils, the dotted lines connecting points representing the same material properties but with various amounts of lift-off have some curvature as shown in (Figure 4-17). The line A-B-C represents the increase lift-off for material one. Line D-E-F represents the increased lift-off for material two. The line from point A to point D represents the increase in conductivity of material two compared to material one at one lift-off value. Lift-off lines B-E and C-F are increasingly shorter, indicating a smaller change in the conductivity.

SECTION IV EDDY CURRENT EQUIPMENT

4.4 ET EQUIPMENT.

Most eddy current nondestructive test instruments for field use are portable AC or battery powered units. They are generally lightweight, less than 6 lbs., with batteries that provide up to 12 hours of operation. They can have a liquid crystal display (LCD), or electroluminescent (EL) displays. Some units have dual frequency operations with interchangeable display features. Newer units have state-of-the-art circuitry with advanced microprocessors. Frequency ranges of approximately 100 Hz to 6 MHz for detection of large and minute discontinuities. These units can be used to inspect first and second layer cracks, coating, plating thicknesses, and conductivity testing.

4.4.1 Components of an Eddy Current System. In its simplest form, an eddy current inspection system consists of the following components:

- An oscillator
- A coil assembly
- A bridge circuit
- Signal processing circuits
- An output display (readout/screen)

A block diagram of an inspection system is shown in Figure 4-25 with the coil applied to a test part. Systems may be constructed for multiple purposes or for very specialized functions. In general, instruments designed for specific tasks, such as measuring coating thickness or electrical conductivity, are easier to calibrate and operate than general-purpose instruments but also are limited to their designed application.

4.4.1.1 Oscillator. The oscillator provides an alternating current of one or more frequencies to the test coil. The frequency used is determined by the intent of the inspection and the material being inspected. Frequencies used for ET range from less than 100 Hz to greater than 6 MHz.

4.4.1.2 Coil Assembly (Probe). The coil assembly induces eddy currents into the part being inspected and detects changes in eddy current flow. For some applications, a single coil is used for both functions. More commonly, multiple coils are employed in an assembly. A common configuration has one coil inducing the eddy current flow and separate coils used as detectors. Another configuration uses one coil as both an inducer and a detector on the test part.

4.4.1.3 Bridge Circuit. The bridge circuit converts changes in eddy current magnitude and distribution into signals that are ultimately processed and displayed. A common mode of operation is to have the output of the bridge equal zero for a "good" or "non-flaw" condition. Presence of a flaw or an "other-than-good" condition results in an unbalance of the bridge, thus producing a relatively small signal. This signal becomes the input to subsequent circuits.

4.4.1.4 Signal Processing Circuits. The processing of the signal from the bridge circuit depends on the type of information to be displayed. Simple eddy current devices can be built that detect and amplify the signal or convert the signal into digital format (e.g., a conductivity value). More sophisticated systems can process the complex electromagnetic signal into amplitude and phase, and provide filtering to suppress unwanted signals. Details of the processes are discussed further in later sections.

4.4.1.5 Output Display. Eddy current test data can be presented in analog or digital format. Some common output devices are meter readout, a strip chart, an X-Y recorder plot, an oscilloscope display or a video screen presentation. Meters are suitable for performing specific types of tests requiring a measurement of signal amplitude only. Strip charts, X-Y recorders, and digital storage allow the signal amplitude to be displayed and correlated with some other parameter such as time or position. Eddy current instruments with a two-dimensional graphical display are used where both the eddy current signal amplitude and phase must be measured. These are the most common instruments available, and provide the inspector with the greatest capability to interpret results.

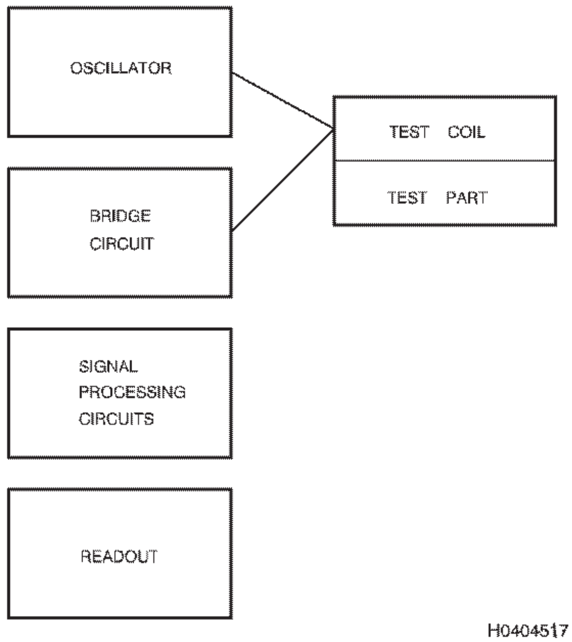


Figure 4-25. Block Diagram of ET System

4.4.2 Eddy Current Subsystems. Eddy current systems generally consist of three subsystems. One is the probe or probe subsystem. Second is the eddy current instrument. The third is the accessory subsystem. Scanners and recorders are included with some subsystems and are considered to be accessories.

4.4.2.1 Probes (Coil Assemblies). Eddy current probes consist of one or more coils designed to induce eddy currents into a part being inspected and detect changes within the eddy current field. A fundamental consideration in selecting an eddy current probe is its intended use. A small diameter probe or narrow encircling coil will provide increased resolution of small defects. A larger probe or wider encircling coil will provide better averaging of bulk properties with a loss in sensitivity to small defects. Also the probe or coil must match the impedance range of the eddy current instrument with which it is to be used.

4.4.2.1.1 Probe Shielding. Probe shielding is used to prevent or reduce the interaction of the probe's magnetic field with nonrelevent features in close proximity of the probe. Shielding could be used to reduce edge effects when testing near dimensional transitions such as a step or an edge. Shielding could also be used to reduce the effects of conductive or magnetic fasteners in the region of testing. Eddy current probes are most often shielded using magnetic shielding or eddy current shielding.

4.4.2.1.1.1 Magnetically shielded probes have their coil surrounded by a ring of ferrite or other material with high permeability and low conductivity. The ferrite creates an area of low magnetic reluctance and the probe's magnetic field is concentrated in this area rather than spreading beyond the shielding. This concentrates the magnetic field into a tighter area around the coil.

4.4.2.1.1.2 Eddy current shielding uses a ring of highly conductive but nonmagnetic material, usually copper, to surround the coil. The portion of the coil's magnetic field that cuts across the shielding will generate eddy currents in the shielding material rather than in the nonrelevent features outside of the shielded area. The higher the frequency of the current used to drive the probe, the more effective the shielding will be due to the skin effect in the shielding material.

4.4.2.1.2 Classification of Probes. Eddy current probes and coils can be classified by mode of operation, application, or design.

4.4.2.1.2.1 Mode of Operation. There are three general modes of operation for eddy current coil assemblies; absolute, differential, or driver/receiver (also called reflection).

a. The most common type of eddy current probe used in field applications is the absolute probe. Absolute probes consist of a single coil that is placed in contact with, or adjacent to, the part being inspected. Since any changes in the area interrogated by the coil produce a response, absolute probes can be used to measure specific materials properties such as electrical conductivity and magnetic permeability. They may have other discrete electrical elements such as capacitors included in the probe housing for matching to specific equipment requirements.

b. Differential probes contain two or more coils and are intentionally designed to produce a response when changes are sensed by the active coil only. Consequently, if the differential probe has two coils mounted side by side, gradual changes in electrical conductivity or magnetic permeability would be sensed by two coils simultaneously and no response would occur. On the other hand, if an abrupt change in conductivity should occur, localized to where it can be sensed by only one coil at a time, then there would be a response. Normally, in both surface and bolt hole differential probes, two small sensing coils are wound side-by-side in the shape of two back-to-back capital D's. They are wired in series, with one wound clockwise and the other counterclockwise. This produces an indication from a crack that deflects first one way, then the opposite way, while producing little or no indication from conditions that affect both coils equally, like lift-off or conductivity change.

c. Reflection probes can have a wide variety of configurations, but all have a driver coil wired separately from one or more receiver coils. A probe with one receiver coil is called "reflection-absolute", and a probe with two receiver coils is "reflection-differential". Reflection probes generally deliver better signal-to-noise levels, but are harder to make and therefore more expensive.

A fourth type of probe, remote field, has two or more coils, with the driver coil being a distance from the receiver coil(s). Remote field eddy current probes are used for deep penetration into thicker structures.

4.4.2.1.2.2 Method of Probe Application. Eddy current probes can also be classified by the method of application Figure 4-26). The most common application is the contact or surface probe used for flat or relatively flat surfaces of a part. Eddy current probes used to encircle a part are called encircling coils. Eddy current probes completely encircled by the part are called ID coils or bobbin coils. Through-transmission probes, which utilize a coil on each side of a part (a sheet of aluminum for instance) is another method of application. All of these probe applications can be operated in absolute or differential modes (Figure 4-27). Eddy current probes can also be classed according to the shape or some other prominent feature of the probe. Very thin probes are called pencil probes. Probes with special electromagnetic shielding are called shielded or focused probes. Probes used in rivet or bolt holes are called bolt hole probes. Certain types of probes with shaped ferrite cores may be referred to as E-core, U-core, and pot or cup core probes.

4.4.2.1.2.3 Probe Design Considerations and Limitations. Eddy current probes have several conflicting requirements. First, they must be a reasonable match to the electrical impedance requirements of the instrument to which they are connected. The closer the impedance match, the higher the signal-to-noise ratio. Also, the coils need to be designed for the flaw size to be detected. Smaller flaws require smaller coils. Most eddy current testing in the field is accomplished with surface probes. The surface probe is used on plates, sheets, irregularly shaped parts, and in holes. The extent of the area to be tested by the probe is controlled by the coil diameter and by the presence of coil shielding. When the area to be scanned is large, pancake-type surface coils or overlapping multi-coil probes can be used to reduce the time required to inspect the part. When small flaws must be detected, coils, as small as 1/32 inch in diameter, can be used to examine limited areas.

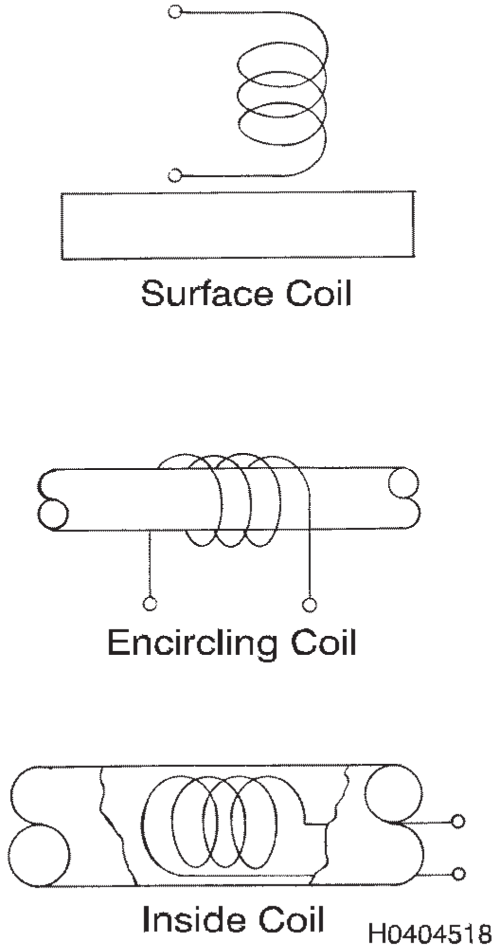


Figure 4-26. Basic Coil Configurations

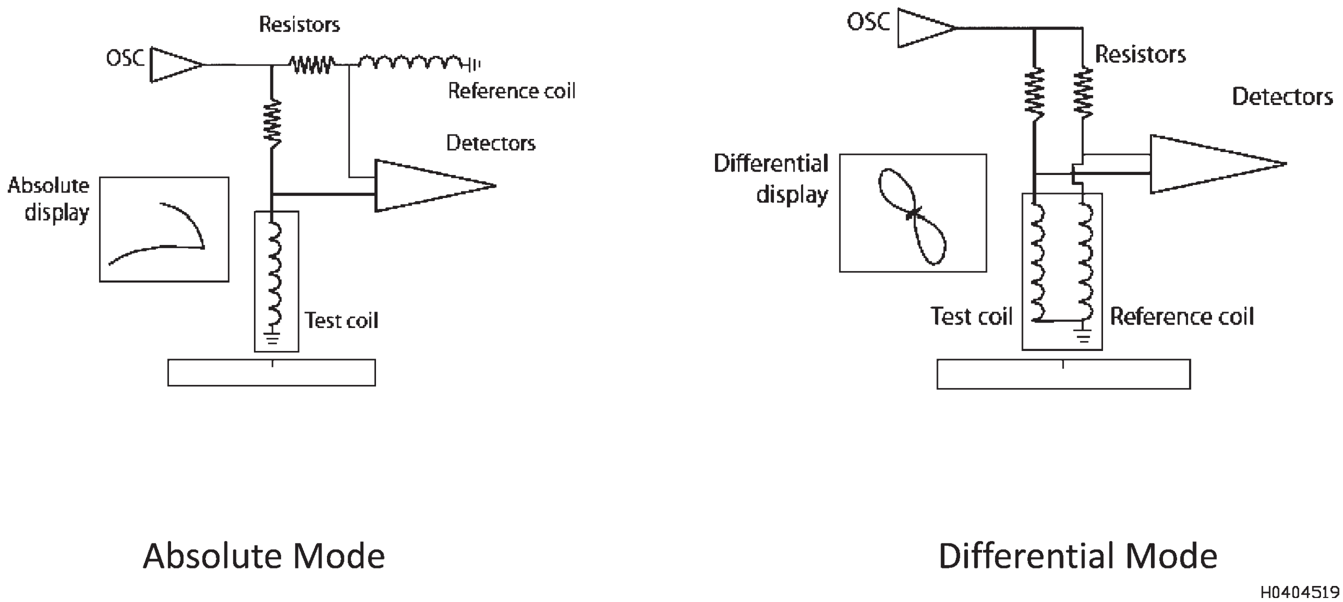


Figure 4-27. Example of Absolute and Differential Mode

4.4.2.1.2.4 Use and Limitations of ID and Encircling Coils. An inside diameter (ID) coil may be used on tubes, pipes, or other cylindrical parts where the geometry is regular and the interior is accessible. The ID coil should nearly fill the part opening in order to provide a high fill-factor for maximum test sensitivity. The use of ID coils can be restricted by bends or non-uniform diameters. Encircling coils are used primarily for inspecting rods, tubes, cylinders, or wire in manufacturing applications. With both encircling and inside coils, the entire circumference of the specimen is evaluated at one time. Consequently, while the axial location of defects (along the part length) can be determined, circumferential location (around the part) cannot be defined.

4.4.3 Functions of the Eddy Current Instrument. The eddy current test instrument performs three basic functions. First, it generates the alternating current that induces the eddy current flow in the part to be inspected. Second, it processes the responses to the induced eddy current flow. Third, it displays the responses in a manner to aid interpretation.

a. Current Generators. The current generator is usually a variable frequency oscillator operated at a single frequency for any given inspection. Most instruments have the capability of operating at frequencies from 100Hz to 6 MHz. Newer instruments have the ability to provide multiple frequencies to the test coil(s), either sequentially or simultaneously.

b. Processing. The processing function of the eddy current instrument includes a number of sub-functions. Most instruments include some form of a balancing or compensating circuit which is adjusted to provide essentially a zero output for non-flaw conditions. The signal from the bridge circuit is amplified before proceeding to the detector and/or analysis circuitry. Signals can be analyzed for their amplitude and phase. The output from the analysis circuits may be further filtered to assist interpretation before display.

c. Display Methods. The primary display method of most eddy current devices is either one dimensional, such as a meter, or two-dimensional, such as a CRT or an LCD screen. The outputs can also be transferred to X-Y recorders, strip chart recorders, magnetic storage media or even computers to both generate inspection records as well as aid in the analysis of the eddy current signals.

4.4.3.1 General Requirements. Eddy current instrumentation is the core of an eddy current system, whether the system is a simple instrument/coil combination or a fully automated scanning inspection station. To assure reliable operation, the instrumentation must have the capabilities described below:

a. Sensitivity. A term that refers to the instruments capability to find the most difficult to locate flaws; with reference to the size and type that need to be detected.

b. Low Noise. The noise should be low enough so the signal from the smallest flaw to be found (or smallest calibration flaw) is at least three times the noise level of the instrumentation.

c. Response Time. The response time of the circuitry must be fast enough to process and display signals at the required scanning rate.

d. Selectivity. The instrumentation should be immune to external sources of electromagnetic interference.

e. Stability. The instrumentation display should remain frequency drift-free, during the required testing period.

f. Ruggedness. The instrumentation must be capable of operating in the test environment. This may include a variety of environmental extremes of temperature, humidity, dust, and vibration.

4.4.3.2 Specific Instrumentation Requirements. Choice of an eddy current test instrument must take into account the type of flaw to be detected, the permeability of the material (nonferromagnetic or ferromagnetic), type of probe to be used, display method (meter, CRT, digital display, recorders, etc.), test frequency, and signal processing requirements, portability, if needed, and any accessories to be used.

4.4.3.3 Instrumentation Components. In general, most eddy current instruments consist of an oscillator, a bridge circuit or similar null balancing system, and a variety of other circuits for processing and display of the eddy current signal. Units will vary depending upon the complexity of the instrumentation and the requirements of the test.

4.4.3.4 Variable Frequency Oscillator. A basic eddy current instrument, while operating at a single frequency during a particular test, usually has an operating frequency range that is adjustable to meet a large variation of inspection situations. Low frequencies increase depth of penetration and consequently would be used for subsurface flaw detection in high conductivity materials. Higher frequencies limit depth of penetration and thus are used for low conductivity materials as well as for detecting smaller flaws. Some instruments also incorporate a fine adjustment of frequency as a mechanism for suppressing lift-off. These instruments incorporate the probe coil in parallel with a capacitor as one leg of a bridge. The coil/capacitor combination is resonant near the intended operating frequency. The frequency selected for operation causes a meter deflection off-resonant enough to where lift-off causes less of an impedance change than caused by a defect and the impedance change for increasing lift-off is opposite to that for a defect.

4.4.3.5 Bridge Circuit. A basic bridge circuit is shown in Figure 4-28. In this example, a voltage is applied at points E1 and E2 to the bridge containing impedances Z1, Z2, Z3, and Z4. Z1 and Z4 are fixed impedances of the same value; Z3 is an adjustable impedance; and Z2 the unknown or test probe impedance. Initially, Z3 is adjusted so that no current flows through the amplifier. This means the voltage at points A and B is the same and the bridge is said to be balanced or nulled. Any change in impedance of Z2, the test probe impedance, will result in a current change through the leg of the bridge and consequently a change in the voltage at point B. A current will then flow through the amplifier, since a voltage or potential difference exists between points A and B. The bridge is now said to be unbalanced. The bridge can again be balanced by adjustment of Z3 and the change in the test probe impedance, Z2, may be determined by measuring the change in Z3 required to rebalance the bridge. The bridge circuit in an eddy current test instrument is termed an impedance bridge since the circuit contains both resistive and reactive elements. Impedance Z2 in Figure 4-28 would consist of the eddy current test coil. Other reactive elements, inductors, and capacitors may be included in the impedance bridge depending upon the specific design and function. However, the basic principle is that a change in impedance of the test coil results in an imbalance of the bridge circuit. The output (imbalance) from the bridge circuit can be amplified, processed and displayed.

4.4.3.6 Amplification Circuits. The imbalance in the bridge circuit is due to an impedance change at the test probe. It results in a change in signal amplitude, signal phase or both. These signal changes must be amplified, detected or demodulated, and processed for presentation on the output device (meter, scope, or recorder, etc.). The flaw signal may be only several micro volts in amplitude and may require amplification of one thousand to one million times for further processing and display. The frequency content of the flaw signal can range from very low (essentially DC) to the maximum operating frequency of the eddy current instrument. This defines the distortion-free frequency response of the amplifier. The amplifier must also be very stable with very little drift in order to maintain the required sensitivity and calibration throughout the duration of the test.

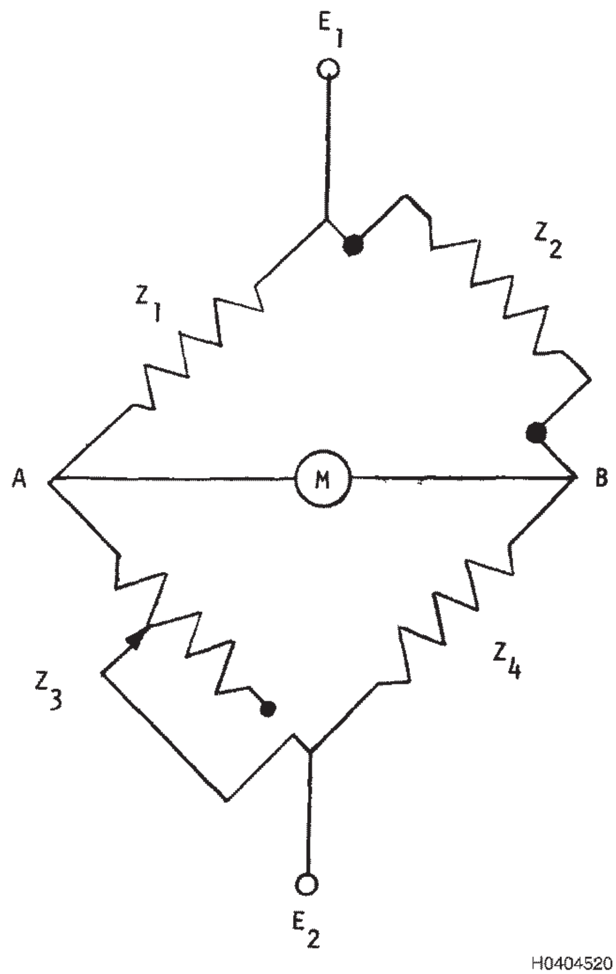


Figure 4-28. Basic Bridge Circuit

4.4.3.7 Presentations and Displays. The output from an eddy current instrument may be read on a meter, impedance plane display, or recorder depending on the type of information required from the test. An analog (pointer) type meter is the simplest type of output indicator. An output consisting of amplitude and phase is called an impedance plane display, and can be displayed on a Cathode Ray Tube (CRT), Liquid Crystal Display (LCD), or an Electroluminescent (EL) Digital Display. LCD/EL display's show the eddy current signal, menu sidebar, status bar, other indicators, and full screen text.

4.4.3.7.1 Meters. Older portable metal flaw and conductivity detectors used a meter that essentially indicated the degree of bridge imbalance in terms of amplitude. Depending upon the instrument circuitry, phase differences could also be displayed on a meter. These eddy current instruments contain built-in output meters specifically designed or selected for use with the particular circuitry involved. If used, these meters SHALL have a speed of response sufficient to detect the discontinuities of interest at the highest expected scan speed. However, the meter should be sufficiently damped so “noise” indications do not confuse the inspector, but not damped to the point information of interest may be suppressed. Optimum meter response is a balance between speed of response and damping.

4.4.3.7.2 Cathode Ray Tube (CRT) Display. The CRT was the device first used for the displays on impedance plane display instruments. They have been replaced with lighter, more compact digital displays. The CRT is a device for display and measurement of electrical phenomena. The CRT consists of four basic parts:

- A glass envelope
- An electron gun
- A means of deflecting, or controlling the electrons produced by the gun
- A screen, which transforms the electrical energy of the electrons from the electron gun into light

The screen consists of a phosphor coating on the inside face of the glass envelope (tube). When electrons strike the screen, light is generated. The relative length of time that the screen continues to glow or give off light after the electrons have impacted the tube is termed "persistence or persistency." Generally, CRT persistence is on the order of 0.1 to 1-second. Storage oscilloscopes have CRTs with long persistency on the order of many minutes. Storage oscilloscopes are used in most CRT type eddy current equipment. A CRT output is used on eddy current instruments where impedance plane analysis techniques are required in order to separate test variables.

4.4.3.7.3 Digital Display. Most eddy current units provide waveform output on a two-dimensional display of small, square spots called pixels. Light is generated on such a screen by applying a small voltage to the individual pixels. A wave form is created by energizing the pixels needed to shape the appropriate waveform. Since the persistency of a digital display is controlled by an applied voltage rather than by electron impact with a phosphor coating, the persistence can be controlled by the operator. In general, the lighted pixel will remain lighted until the operator ‘erases‘ them by turning off the voltage to the pixels.

4.4.3.7.3.1 Linear Time Base Display (Sweep). Eddy current test equipment often has the ability to use a linear time base display. The display’s vertical signal, is received from the test coil and the display’s horizontal signal (e.g., time), is received from a timing voltage. The timing voltage is adjusted to the frequency or period of the generator and provides a linear horizontal sweep of the vertical input voltage. A change in reactance of the test coil result, in a phase change of the voltage across one of the bridge circuit arms (vertical signal). This phase change is evidenced by a shifting (along the horizontal base-line) of the waveform. During operation, the timing or sweep voltage is used to adjust the display to show the desired number of waveform cycles (usually one). Generally, control is also included to control the horizontal position of the waveform on the screen.

4.4.3.7.3.2 Impedance Plane Eddy Current Test Equipment. The use of impedance plane analysis equipment greatly increases the flaw analysis capability of the eddy current inspection process. Some eddy current equipment uses the vector point display technique of displaying information on a screen. Signal phase and amplitude are directly presented for analysis of the eddy current information. The display consists of a point of light rather than a waveform. Changes in the test article relative to the reference standard will cause the point of light to move. Movements of the point of light can be analyzed to determine which test variable (conductivity permeability or dimension) causes the change.

4.4.4 Digital Equipment. The use of digital test equipment, along with digital computers to process and analyze data, has provided significant reduction in noise levels. This has effectively increased the sensitivity of the flaw detection process.

4.4.5 Recorders. Recorders are used primarily in testing where the test coil or the test parts are moving relative to one another. Many newer applications using a test fixture and a mechanical scanner to move an eddy current probe across a specific area of a part can use a recorder to map the flaw indications. A recorder for eddy current applications may be any of several types. However, the strip chart recorder is probably the most common. Newer eddy current instruments provide means of storing information on digital media. This is particularly useful where down time is important, since testing can be accomplished as rapidly as possible, and the information stored on tape for later analysis. When selecting a recorder for use with a particular eddy current instrument, several factors must be considered:

- Impedance match between recorder and instrument
- Frequency response of recorder
- Recorder sensitivity (voltage range)
- Response time

4.4.6 Mechanical Scanners. Increased use of mechanical scanners to control probe movement has improved the detection capability of many test methods. Repeatability of testing is also enhanced by mechanical scanning. A mechanical scanner can provide testing of difficult to reach areas of parts. Remote video cameras can also be incorporated with a mechanical scanner to provide visual coverage during the testing of inaccessible areas.

4.4.7 Fixtures and Guides. The single most important requirement for detecting a small crack is that the coil pass over the crack. Specially shaped probes, fixtures and guides can help ensure this happens. Probe guides increase eddy current inspection detectability and should be used whenever necessary. The simplest eddy current scanning guide is a section of thin flexible plastic cut to conform to the inspection area with allowance for probe positioning. Such a guide can be easily prepared from used x-ray film. The flexibility permits fitting of the guide to compound curvatures. It is necessary that the edge used to guide the probe be smooth to allow steady movement at a constant distance from the edge of the opening. The guide can either be held in place or taped in the required position. Another type of probe guide which can be used for small openings, including holes with bushings, consists of a circular insert which fits into the hole and has a larger diameter at one end to provide the required offset distance from the edge of the hole. Probe guides SHOULD be constructed to provide the required offset from the edge for a specified type of probe and SHOULD NOT interfere with movement of the probe.

4.4.8 Special Processes. A wide variety of electronic techniques have been developed for particular inspection problems in eddy current testing. The circuits used depend upon the type of output, the type of flaw to be detected, or when a particular test variable (such as lift-off) must be suppressed in order to detect other conditions.

4.4.8.1 Amplitude Detection. The most common type of detection meter on eddy current instruments is one which needs to detect signal amplitude changes without the use of phase information. In this case, amplitude detection with a simple diode type detector can be used. The diode rectifies the bridge output to produce a variable amplitude direct current signal.

4.4.8.2 Multi-Frequency Eddy Current. Multi-frequency eddy current can be used where several material properties are changing at the same time, such as when it is necessary to discriminate a crack from geometric changes in a complex part. To be effective, each condition to be suppressed must produce significant impedance changes for one frequency and less significant changes for the other frequencies used in the inspection. An example would be using a dual frequency inspection for subsurface corrosion while compensating for lift-off. A low frequency would be selected that would allow sufficient penetration to detect the corrosion. Lift-off responses would also be present from this frequency. Using a higher frequency would respond to lift-off but, not have sufficient penetration to respond to the corrosion. The analysis of these signals can become extremely complex. At present, most multi-frequency testing is limited to dual frequency testing.

4.4.8.3 Pulsed Eddy Current Techniques. The pulsed eddy current technique is a non-continuous wave test technique, and also has multi-frequency characteristics. The width of the pulse establishes the lower frequency limit while the sharpness of the pulse corners establishes the upper frequency limit. Conventional multi-frequency systems usually use two or three frequencies. Additional frequencies require very complex multiplex mixing systems to analyze the information from the test. A variety of experimental techniques have used the multi-frequency characteristics of a short electrical pulse to achieve the same type of results as the multi-frequency test technique. In principle, this technique is advantageous in that it requires simpler electronics to process the data. It can potentially generate higher frequencies than fixed frequency systems. This would allow testing of thinner materials and materials with very low electrical conductivity (high resistivity). The eddy current pulse can also be a very short, high voltage pulse that can be used to momentarily produce magnetic saturation in a ferromagnetic part. This will allow detection of subsurface flaws in ferromagnetic materials.

4.4.8.4 Metal Thickness Measurements. A wide range of thicknesses can be measured with low frequency eddy current test equipment.

4.4.8.5 Low Frequency Eddy Current. Low frequency eddy current means the inspection requires frequencies below 50 kHz. Improved equipment and data processing techniques now allow the use of test frequencies as low as 55 Hz. Along with impedance plane equipment to measure signal phase, this has provided a means for testing multilayer thick materials. Detection of deep subsurface cracks, cracking in intermediate layers of material, and corrosion on the backside of a material is possible.

4.4.8.6 Dual Frequency Testing. This is a basic version of multi-frequency testing that can be used to filter out one undesired condition. If only two frequencies are used, one frequency channel can operate in the differential probe mode and the other frequency channel can operate in the absolute mode. With this setup, the differential mode can be used to detect discrete indications such as small cracks and holes. The absolute mode can be used simultaneously to record wall thickness or other dimensional changes in the test part.

4.4.9 Electromagnetic Techniques Closely Related to Eddy Current. Although not part of the ET method as currently defined, the following are more closely related to ET than to any other basic NDT method.

4.4.9.1 Barkhausen Noise Testing of Ferromagnetic Materials. Abnormal stresses induced by shot peening, other cold working processes, and grinding burns affect the structural properties of a material, and can lead to flaw growth and part failure. In ferromagnetic materials, these processes affect the ease with which the magnetic domains in the surface of the material can be moved. In un-magnetized ferromagnetic material, the magnetic domains are randomly oriented. If the material is subjected to a magnetic field, the magnetic domains tend to align themselves in the direction of the magnetic field. When the domains move to align themselves, electrical pulses are generated during the domain movement, this is called Barkhausen noise. This electrical noise can be detected and measured by Hall Effect sensors. If the material is free of abnormal stresses, the domains are relatively free to move and little Barkhausen noise is generated. Areas of tensile stress parallel to the applied magnetic field cause an increase in Barkhausen noise. Examples of applications of this test method are ferromagnetic engine components and landing gear. Barkhausen noise measurements are also used to detect the quality of drilling and reaming of holes in ferromagnetic material

4.4.9.2 Magneto-Optic Imaging (MOI). Magneto-optic imaging depends on the ability of certain materials to rotate the plane of polarization of light in the presence of a magnetic field. This Faraday Effect is used to detect disturbances in the magnetic field produced by passing an alternating current in a thin planar foil of doped yttrium iron garnet. When the foil is placed near the surface of a metallic test object, eddy currents are produced which modify the magnetic field in the foil. When defects or other material discontinuities, such as rivets or holes, divert the otherwise uniform flow of electric current near the surface of the test piece, magnetic fields perpendicular to the surface of the test piece are produced which can be imaged in real time by an appropriately designed optical system. Since the system provides optical information, the results can be videotaped for analysis and permanent documentation.

4.4.10 Application of Advanced Techniques. Several of the advanced techniques and processes discussed above do not have fully developed and recognized test procedures, process controls, and qualification procedures. Specific application of ALL of these processes and techniques SHALL be in accordance with approved procedures and engineering approval.

SECTION V APPLICATION OF ET

4.5 GENERAL.

All inspections for cracks or other in-service flaws SHOULD be considered critical. Each inspection on every aircraft or weapon system should be approached with utmost care and concentration. Always setup your eddy current instrument in accordance with the established procedures. Be sure to check your setup several times during the inspection to ensure your equipment is responding properly. Take time to ensure you have carefully scanned the entire area of inspection, double checking your scans if necessary. The inspection you perform may be the last line of defense against a possible failure due to crack growth. Not finding a defect in an area during a previous inspection, does not discount the odds of it presenting itself in the future. Approach each inspection as if there were a known flaw in the area you are inspecting.

4.5.1 Null Point. The null point is the location on an impedance plane at which the eddy current instrument is nulled or "zeroed." If nulled correctly on a defect-free material, the instrument will place the signal (dot) on a specific point on the display, and any changes in the material, such as a crack, will cause the signal (dot) to reflect an electrical impedance change on the display.

4.5.2 Parameters. There are a large number of parameters that can be set on an eddy current instrument. However, the parameters most often adjusted by technicians are frequency, gain, phase angle, sensitivity and filters.

4.5.2.1 Frequency. The only freely adjustable parameter on modern instruments that affects the eddy currents is frequency. The rest of the parameters are there only to enhance the visibility of the signal response on the instrument. The lower the frequency, the deeper the field goes into the material and therefore the increased depth at which eddy currents flow. However, the field not only goes deeper, but it also spreads out, i.e. it "dilutes", resulting in less sensitivity to small variations (see Figure 4-29).

NOTE

The "spread" of the eddy currents depends on the conductivity of the material and the instrument drive frequency.

4.5.2.1.1 Frequency does not affect the strength of the eddy currents, just the "spread". Some instruments may allow adjustment to the drive voltage going thought the generating coil, which in turn affects the strength of the eddy currents, resulting in higher flaw detection sensitivities. This is separate from frequency adjustment.

4.5.2.2 Gain. Gain can be increased to get a larger signal response (i.e. to make a small signal more visible) or decreased to lower the signal response on the instrument display. However, increases in gain will increase the “noise” on the instrument display. Noise can be caused by a variety of factors: the electronics of the instrument (not as likely in modern instruments), material noise resulting from grain-structure of the material, material noise caused by mechanically altering the surface of the material under test, etc.

4.5.2.2.1 Some instruments feature H-Gain (X-Spread) or V-Gain (Y-Spread) along with regular gain. These two gains allow the operator to independently increase or decrease the signal in the vertical or horizontal direction, and are very useful for helping to distinguish noise signals from flaw responses.

4.5.2.3 Phase Angle. May also be known as "rotation," or "rotation angle." Unrelated to the true phase of the eddy currents, it is a setting that allows the user to rotate the signal responses on the instrument screen. It may be used to orient the signal response from lifting the probe off the material ("lift-off" signal, when using an absolute probe). This aids the user in distinguishing between "lift-off" and a signal likely caused by a flaw.

4.5.2.4 Sensitivity. (not available on all instruments) a parameter that allows for "magnification" of the instrument display. It acts like the zoom-feature of the camera; it does not improve the "image," it only makes it larger or smaller. It is used to set the scale of the grid shown on the display. A common setting is 1 Volt per scale-division. This means that a signal that is 2 scale-divisions long has a voltage of 2 Volts. This measure is used to classify signals as acceptable or rejectable.

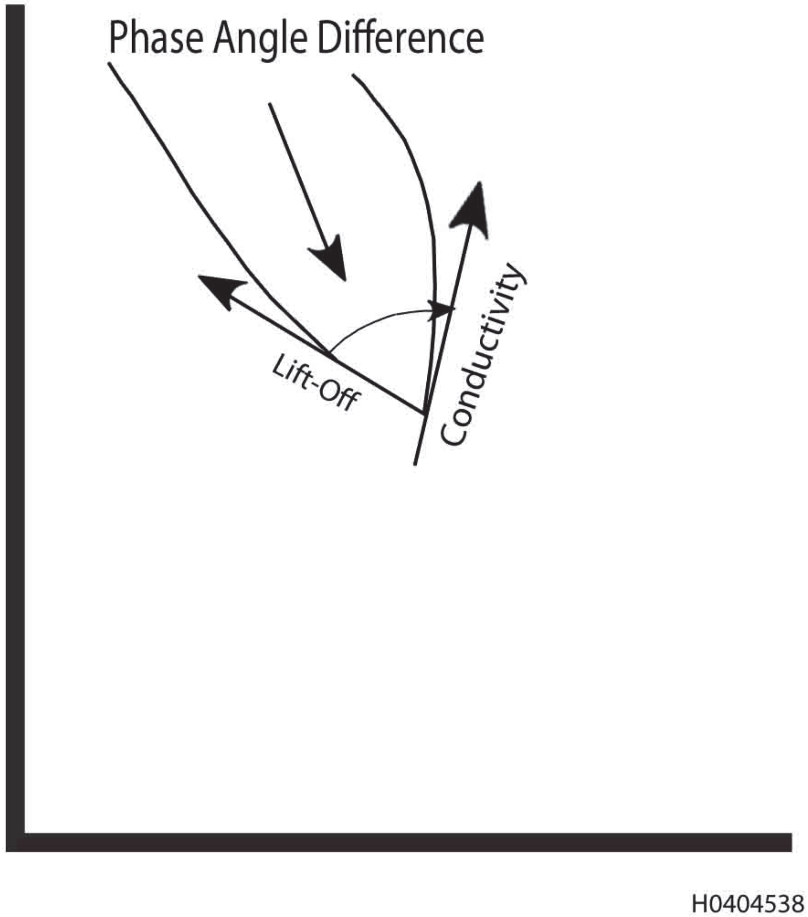


Figure 4-29. Illustration of Frequency and Eddy Current Distribution

4.5.2.5 Filters. Used to filter out unwanted signals and improve the signal-to-noise ratio as illustrated in Figure 4-30. Three types of filters can be used: high-pass, low-pass, and band-pass. A high-pass filter (HPF) removes low frequency signals and lets high frequencies pass, and is useful to eliminate the effect of gradual variations in conductivity or dimensions on the eddy current response. A low-pass filter (LPF) removes high frequency signals and lets low frequency signals pass, and can be used to overcome electronic noise from harmonic frequencies related to variations in magnetic permeability. Band-pass filters combine low and high pass filters to allow a response over a specific range of frequencies and suppress frequencies above and below this range.

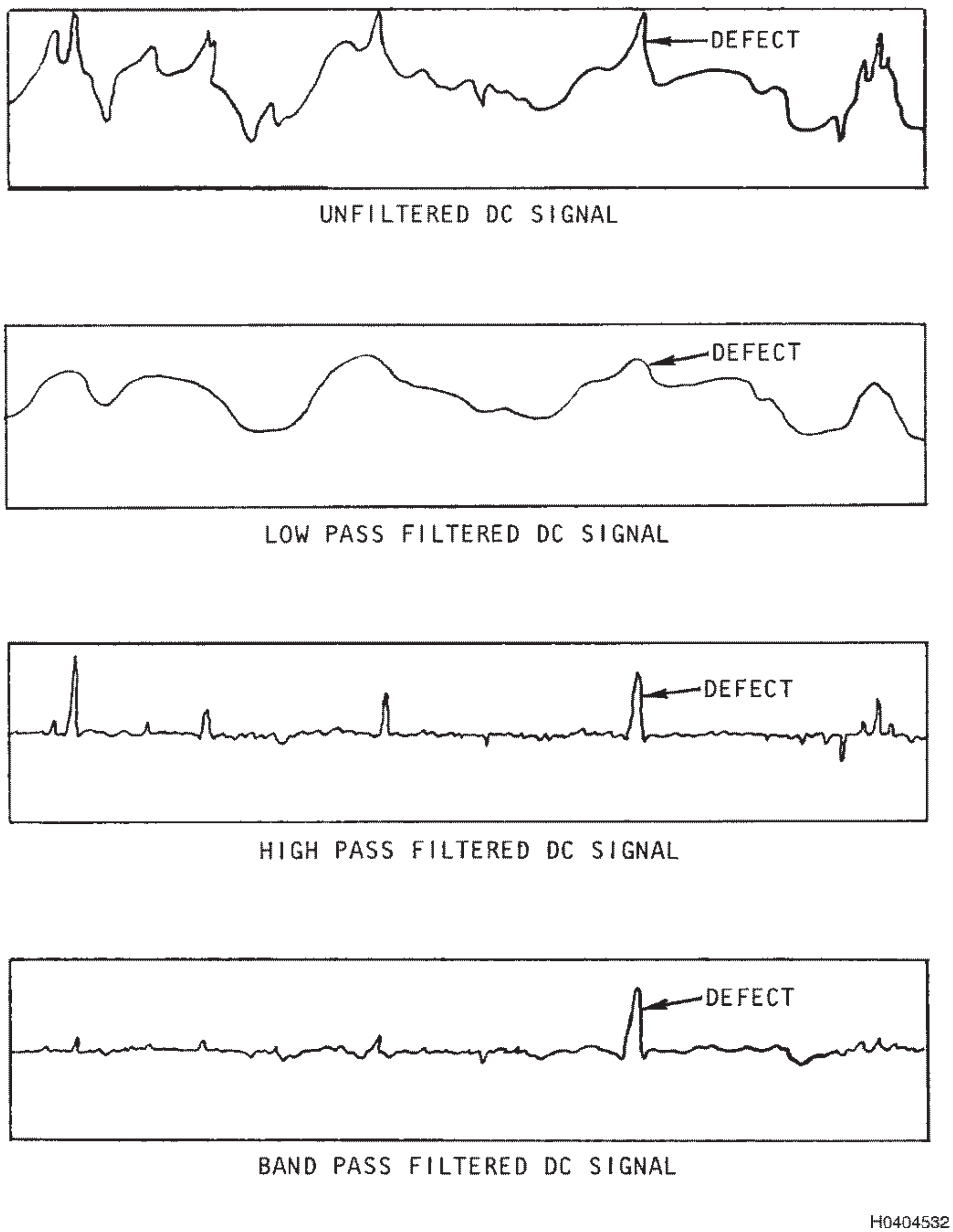


Figure 4-30. Illustration of the Effects of Different Filters on the Eddy Current Signal

4.5.3 Modulation Analysis. A technique useful in separating signals of interest from other signals relies on an analysis of signals as a function of time. A good example of this is using a sweep display or a strip chart where the amplitude of the signal appears on the vertical scale and the times at which the signal appears and disappears is monitored on the horizontal.

4.5.3.1 An example of modulation analysis is when a CRT is used in the sweep mode during a rotating bolt-hole inspection. In this technique, the equipment is typically set so each trace across the sweep represents one rotation in the hole. The clock position of an indication in the hole can be determined by its location across the sweep. Of more importance is the width of the indication or how long it deviates from the baseline. In this example how long the indication is detected (width) is used to identify whether or not it is due to a variable of interest. For example, out of roundness in a bolt hole will produce an indication that lasts a long period, while a crack is very narrow and produces an indication that lasts a short period. Both indications may have the same amplitude, but perhaps only the crack is of interest. An electronic filter can be used to suppress long lasting signals (low frequency) leaving only the crack indication (high frequency) on the display for the inspector to view.

NOTE

Regarding modulation analysis, it is important to understand the terms high and low frequency refer to how long the indication lasts, not the frequency of the alternating current in the coil.

4.5.3.2 The frequency of an indication is the reciprocal of the period that it lasts, or put another way: how many such events (cycles) could occur in 1-second. For example, suppose the indication of the out of round hole discussed in paragraph 4.5.3.1 lasts for 0.1-seconds across the sweep, and the indication of the crack lasts for 0.01-seconds across the sweep. The frequency "f" of the out-of-round signal would be 1/0.1 or 10 cycles/sec (Hz), and that of the crack would be 1/0.01 or 100 cycles/sec (Hz). A high pass filter could be set at 50 Hz to suppress signals under 50 Hz and allow signals over 50Hz to be displayed. Because there can also be signals that have a higher frequency than the variable of interest, a low-pass filter may also be used to suppress high frequency noise. This filter might be set at 200 Hz for the above example. Used together the high and low-pass filters form what is called a band pass filter, meaning only signals having a frequency over a specific range are displayed. In the above example, signals above 200 Hz are suppressed by the low-pass filter, and signals below 50 Hz are suppressed by the high-pass filter. In order to pass through both filters, the signal must be between 50 and 200 Hz, or last from 0.005 to 0.02 seconds.

4.5.4 Frequency Response. Frequency response analysis is the most common form of modulation analysis. During eddy current testing, the impedance of the test coil remains constant provided there is no change in inspection conditions or material properties. When variations in impedance do occur, the rates of change in the impedance and resultant eddy current signal are proportional to the rates at which material properties are changing and the scanning speed. Consequently, a small crack would provide a rapid change in impedance during scanning and a corresponding high frequency eddy current signal. These signals can be viewed on a video display or a strip chart recorder as a function of time. The effect on amplitude, while encountering different kinds of material variations, and scanning at a constant speed is shown in Figure 4-31. A fast signal change is often a good indicator of a small flaw or an abrupt change in material characteristics. A slow signal change usually indicates a gradual change in dimensions, lift-off, or some other property.

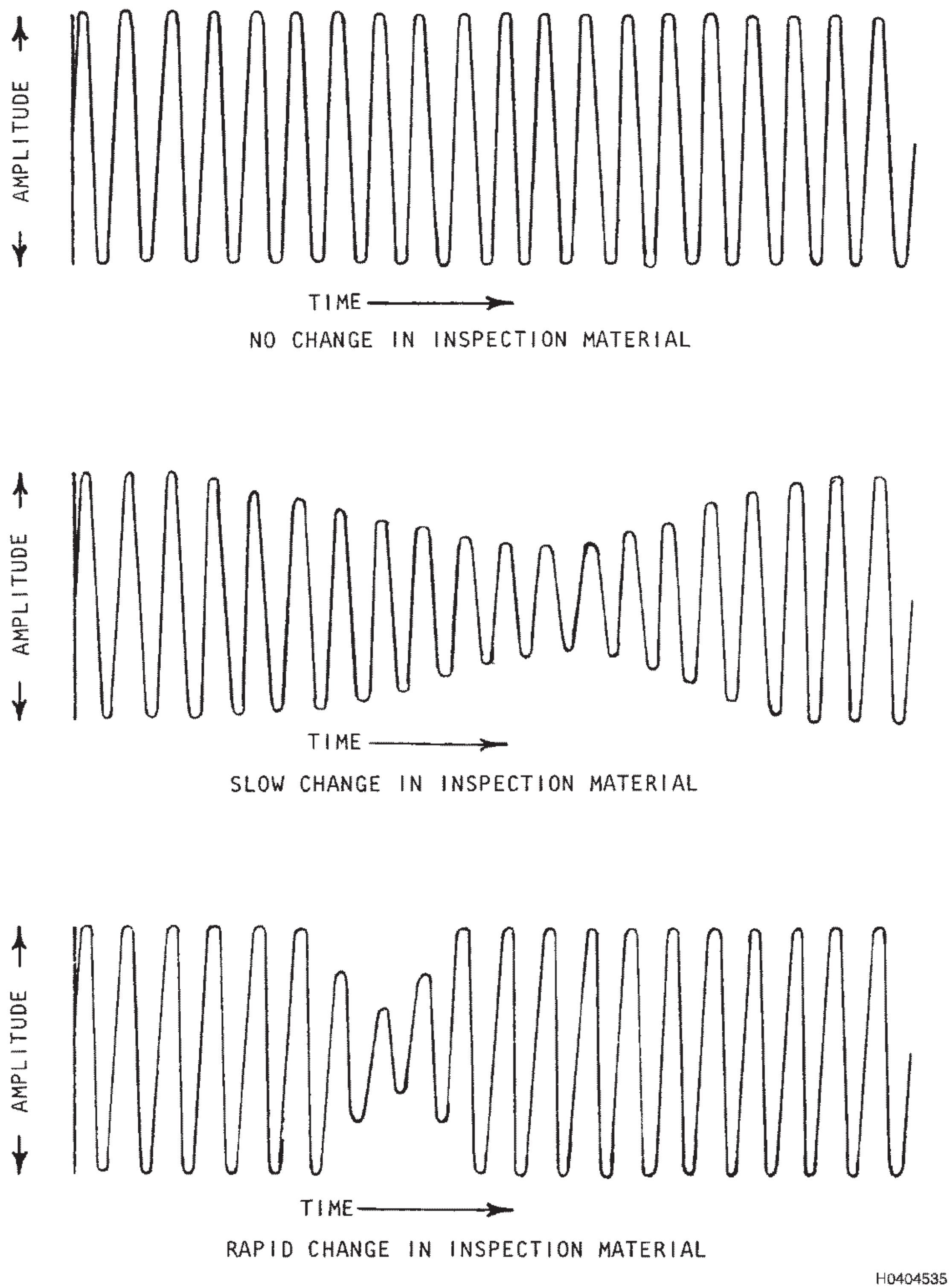


Figure 4-31. Effect of Material Variables on Magnitude of Alternating Current in Test Coil With Constant Scanning Speed

4.5.5 Inspection of Fastener Holes.

4.5.5.1 Cracks in Fastener Hole Walls. A common application of eddy current inspection in aircraft structures is the detection of cracks in fastener holes, or walls. These cracks are usually generated by fatigue, stress corrosion, or a combination of fatigue and corrosion. The progress of these cracks is often slow in the initial stage, where early detection can prevent possible catastrophic failure.

4.5.5.1.1 Fatigue Cracks. Fatigue cracks are usually caused by repeated cyclic loading of a structure at lower stress levels than required for visible deformation. Because stress is concentrated at areas of localized weakness, such as holes, fatigue cracks often initiate at such points. The cracks usually propagate normal to the direction of the maximum applied tensile stress. The following describe two types of fatigue:

a. High Cycle Fatigue (HCF). HCF usually means the stress applied is low compared to the ultimate tensile strength of the material but subjected to a very high number of cycles (examples: Vibration or air turbulence stresses).

b. Low Cycle Fatigue (LCF). LCF usually means the stress applied is high compared to the ultimate tensile strength of the material but subjected to a very low number of cycles (examples: take-off and landing stresses).

4.5.5.1.2 Stress Corrosion Cracks. Stress corrosion cracks occur under the combined influence of a tensile stress and a corrosive environment on a material susceptible to stress corrosion cracking. The tensile stress may result from either an applied stress or a residual stress. Moisture in the air combined with a sufficiently corrosive environment may create stress corrosion cracking in some instances. In addition, a combination of cyclic fatigue in the presence of corrosion cracks can cause rapid growth of cracks.

4.5.5.1.3 Hole Wall Finish and Dimensions. The hole wall finish and dimensions influence both the occurrence and the detectability of cracks in fastener holes. Hole wall damage such as scratches, chatter, and grooves created during manufacturing can create additional stress concentrations at the hole wall and provide preferred sites for crack initiation. Loose fitting bolts caused by oversize or out-of-round holes allow movement in the area of the hole and allow fatigue action. These same conditions can influence the reliability of inspection. During inspection, severe damage to the hole wall results in eddy current indications that may not be separable from crack indications. Excessive lift-off from out-of-round conditions can also mask indications from cracks. All of these conditions can be created during manufacturing processes on the hole or as a result of fatigue action during service and from bolt removal.

4.5.5.1.4 Edge Effects. Many cracks in fastener holes occur at or near the edge of the hole. Adjoining structures, non-uniform countersink and deburring radii, and damage at the hole edges increase the background noise and decrease the signal-to-noise ratio. This leads to a general loss of detection of cracks at the edge of holes. Further effects on crack detectability result from the presence of other metals adjacent to the hole edge. Countersunk surfaces also limit ET by manual techniques adjacent to hole edges.

4.5.5.2 Bolt Hole Preparation. Holes in mating surfaces must be realigned prior to ET or drilled to a larger diameter, which is concentric through the mating parts. Prior to performing bolt-hole inspection, all foreign material must be removed from the hole. Foreign material can include sealant, lubricants, metal slivers, and paint chips. Usually this material can be removed using cotton swabs and a suitable solvent. Holes which are severely damaged during service or during fastener insertion/removal may require reaming prior to ET. If reaming is required, contact appropriate cognizant engineer for component for an approved method.

4.5.6 Fastener Hole Inspection Equipment.

CAUTION

In general, the detection capability of manual bolt hole scanning is significantly less than automatic bolt hole scanning and thus SHALL NOT be substituted for automatic scanning unless specified in part-specific procedures or in specific written authority from the responsible engineering authority.

4.5.6.1 Manual Bolt-Hole Scanning. When used, manual scanning of bolt holes is performed at specified levels throughout the depth of the hole. Inspection is usually initiated with the center of the probe coil positioned immediately within the upper or lower edge of the hole so that the outside edge of the coil is even with the surface of the part. The probe coil position is adjusted to the specified level below the collar of the probe, and the probe is inserted into the hole until the probe collar rests against the surface of the part. Occasionally, intergranular stress corrosion (IGC) can occur along a plane roughly parallel to the part surface. The indication from this type of corrosion appears similar to an elliptical shape hole or a slow change in conductivity. Incorrect application of Band-pass filtering may mask the presence of IGC.

CAUTION

Automatic bolt hole eddy current (BHEC) inspection SHALL be accomplished in accordance with the applicable weapon system TO, and/or the appropriate work package in TO 33B-1-2 for the particular procedure to be performed. Unless otherwise stated, the specific weapon system TO always takes precedence over the manufacturer’s recommendations or any general TO.

4.5.6.2 Automated Bolt-Hole Scanning. Automatic scanning is typically used for bolt hole inspection due to the increased detection capability over manual scanning. This equipment provides a hand held scanning unit which drives a probe in a helical pattern through the length of the hole, or rotates the probe at high revolutions per minute, at a constant speed while the operator indexes the probe through the hole. Equipment that rotates the probe in a helical pattern is referred to as a translational rotation scanner. Oftentimes high speed scanners do not have automated translational movement and they depend on the rate at which the operator pushes and pulls the probe into and out of the hole. Results can be retained on a strip chart recorder or displayed on a digital display.

4.5.6.2.1 The Rotary Scanner. The scanner spins the bolt hole probe at a certain speed, that has been set on the instrument during setup. The probe should be inserted into the fastener hole and indexed down the hole at a slow enough speed where the coil in the probe will scan the entire wall surface of the hole in a tight spiral, thus ensuring 100% surface coverage (see Figure 4-32).

4.5.6.3 Rotary Bolt Hole Probes. The most common bolt hole probe design is shown in Figure 4-33. The probe consists of a probe shell with a 4-pin connector and a main probe body. The shell features two O-rings that hold and center the probe in the connector-receptacle of the scanner. The body consists of shank with an integrated ball at the end, called a “head”. The shaft is split, and one of the two halves of the head contains the sensor coil. The split head provides spring-compliance to ensure that the sensor coil can be as close to the wall of the fastener hole as possible. When choosing a bolt hole probe, the diameter of the ball should be the same diameter or slightly smaller than the fastener hole to be inspected. This provides the "best fit" once the shank is spread and the tape is applied.

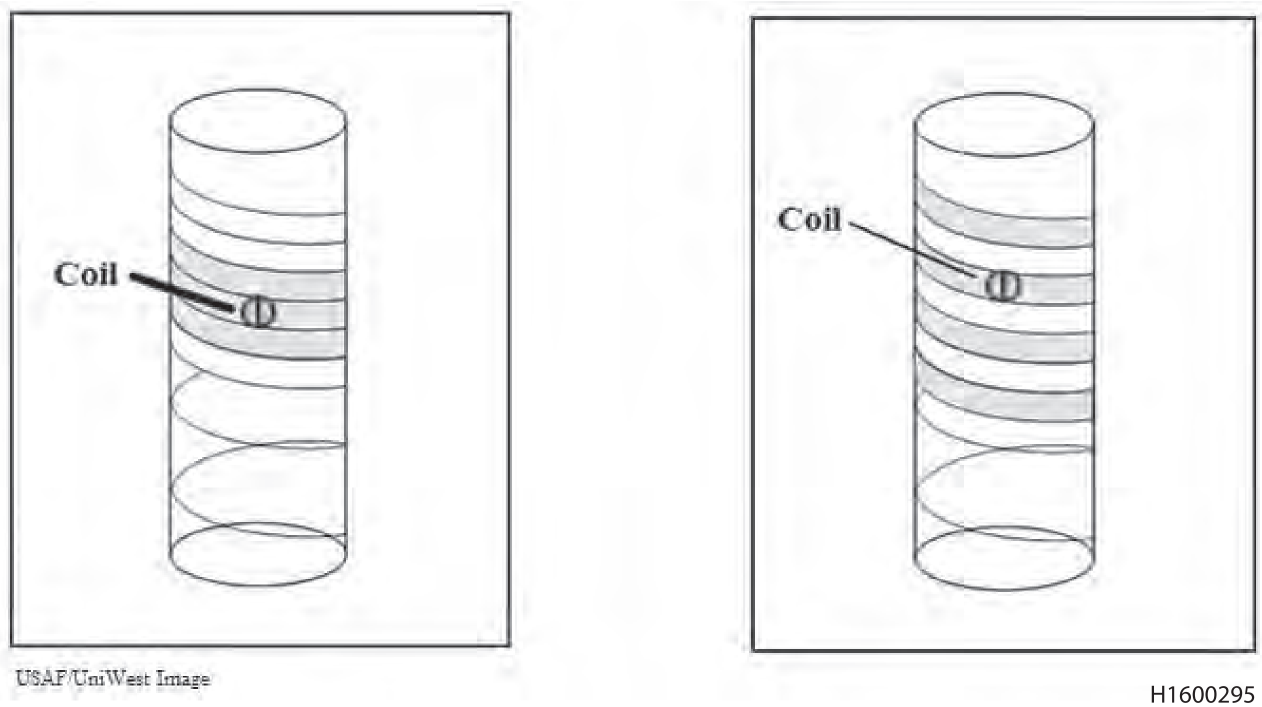


Figure 4-32. Proper Technique to Ensure 100% Coverage (Left), Incomplete Coverage (Right)

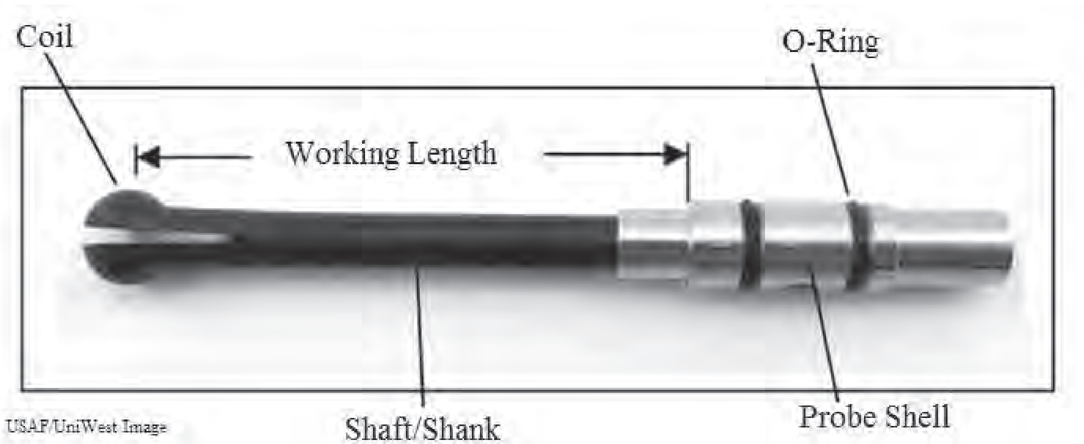


Figure 4-33. Typical Bolt Hole Probe Design

4.5.6.3.1 There are a variety of other designs, such as probes with conical- or cylindrical-shaped heads, or no heads at all. However, studies have shown that the ball-shape probe provides optimum flaw detectability throughout a fastener hole, including at the edge of both open ends. The ball-shape helps to ensure that the coil is in contact with the fastener wall, even if the probe is not quite aligned with the axis of the hole.

4.5.6.3.2 Figure 4-34 shows the typical coil configuration in a bolt hole probe. The coil consists of two receiver coils, each of which is wound on a "D-shaped ferrite. The receiver coils are then placed side-by-side and a driver coil is wound around both. The receivers are connected in difference. This means if Receiver Coil 1 "sees" something it causes an upward signal response. If Receiver Coil 2 "sees" something it causes a downward signal response. This type of coil is called differential-reflection".

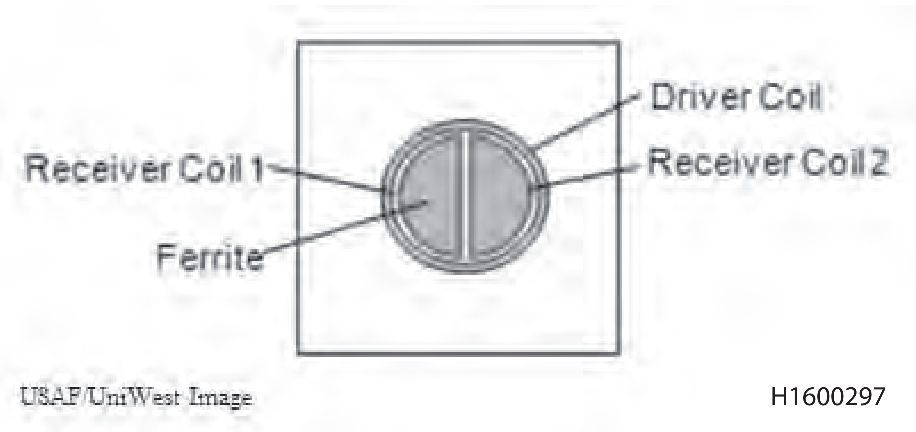


Figure 4-34. Coil Configuration in a Bolt Hole Probe

4.5.6.3.3 Figure 4-35 (A) shows a typical bolt hole probe with a standard “D50” differential-reflection coil. The driver coil is the outer-most coil. The driver coil generates an alternating magnetic field that penetrates the conductive material. The material reacts by generating eddy-currents whose field opposes the primary electromagnetic field. Since the incoming magnetic field is spread-out, i.e. the effective field has a much larger effective area than just the coil diameter, the eddy currents are spread out.

4.5.6.3.4 Figure 4-35 (B) shows the eddy current distribution for the probe shown in Figure 4-35 (A). The eddy currents flow in the same circular pattern as the driver coil-windings, are strongest close to the coil-windings and slowly dissipate in the conductive material. The figure shows the outward extend and depth of the currents to the point where their strength has reached 37% of the strength at the surface ("standard depth-of-penetration"). In this example, the result is that in an aluminum component at 200 kHz, a probe with a 0.070" diameter driver coil will generate an eddy current field about 0.008" deep into the material, and will have a sensing area extending approximately 0.086" in diameter.

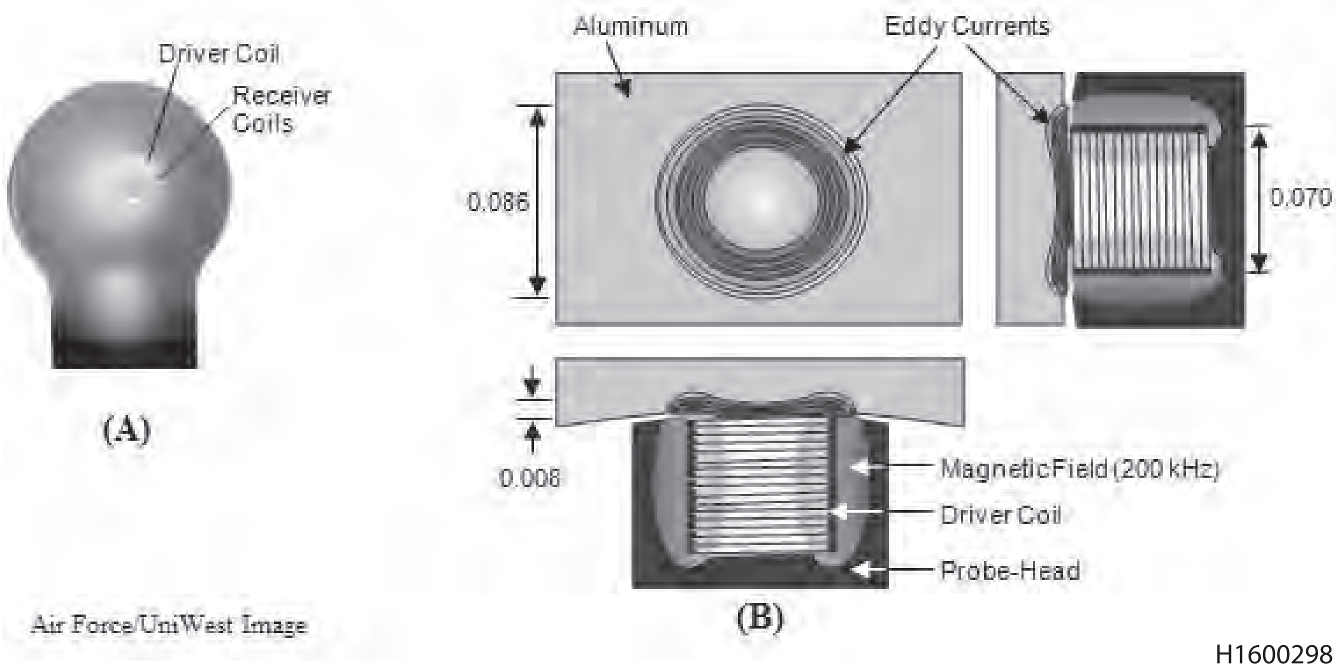


Figure 4-35. Example of (A) Bolt Hole Probe and (B) Drive Coil Field and Generated Eddy Currents

4.5.7 Probe Fit. A probe that fits properly within the hole is critical to inspection performance. A poorly fitting probe will chatter in the hole, resulting in excessive lift-off and signal noise.

CAUTION

Only probes of the correct size SHALL be used to perform eddy current bolt hole inspection. Inspecting with a poorly fitting probe may result in missed crack indications.

4.5.7.1 The following is a simple procedure to ensure a good probe fit:

a. Measure the bolt hole diameter if you do not know it;

b. Select a probe with a size-range that fits the bolt hole;

c. Tape the probe; do not insert it in the scanner;

d. Insert it into the hole;

e. If the probe can almost stand in the hole (if the hole is vertical and down), or hang inside the hole (if the hole is vertical and up), or not slip out or the hole (if the hole is horizontal) and if you can still smoothly spin it by hand, the probe fit is correct (Figure 4-36).

f. If the fit is not correct shim some non-conductive foam or rubbery material into the split in the shank of the probe and try again.

Figure 4-36. Checking Probe Fit

4.5.8 Probe Taping. Bolt hole probes are manufactured using several types of materials depending on the probe type and manufacturer. Some probes are more durable than others. Probes made of soft plastics can wear and expose the coil windings in only a few uses, therefore it is always wise to carry a spare probe. One way to protect the coil is to use Teflon tape to cover the coil. Part of how long a probe lasts and what responses you observe during an inspection is how you tape the probe. Tape that is between 2.5 and 3.5 mils (0.0025-0.0035 inches) thick, is slightly "stretchy" and has adhesive backing SHALL be used. The correct way to apply tape is to wrap it completely around the coil half of a split probe. The ends of the tape must be tucked in between the probe-split. The split probe provides a spring-like action to ensure the coil maintains contact with the bore surface when spinning. Therefore the tape SHALL NOT be wrapped completely around both halves of the split as that will prevent the probe from complying to the hole. Figure 4-37 shows an example of an acceptable taped probe. In this example the tape smoothly covers the coil-half of the probe without wrinkles and the ends of the tape are tucked in between the split. Figure 4-38 and Figure 4-39 show examples of unacceptable taping. Figure 4-38 shows tape covering only half the coil, which would allow the edges of the tape to come up during probe rotation in the hole, and Figure 4-39 shows tape that was not smoothly applied and is wrinkled.

USAF/UniWest Image H1600300

Figure 4-37. Examples of Acceptably Taped Bolt Hole Probes

USAF/UniWest Image

H1600301

Figure 4-38. Unacceptable Taping (Incomplete)

Figure 4-39. Unacceptable Taping (Wrinkled)

4.5.9 Lift-Off Compensation for Bolt-Hole Inspection. Lift-off compensation for bolt hole inspection is dependent upon the surface quality and dimensions of the hole. Optimum lift-off compensation is that which just suppresses lift-off variations within the hole, but does not provide excessive compensation. Excessive lift-off compensation can reduce sensitivity and increase noise. When using unshielded probes, specific amounts of lift-off compensation can be obtained by using a shim between the coil of the bolt hole probe and the hole wall. The thickness of the shim must equal the amount of lift-off compensation desired and must be relatively tough to prevent tearing during insertion and removal of the probe. Teflon tape SHALL be used for this purpose. Lift-off compensation is usually performed in the hole at a point away from the edge or at the center if the part thickness is less than 1/2-inch thick. More tolerance in lift-off compensation settings is permissible when using automatic scanning equipment or shielded probes.

4.5.10 Standardization Settings. The settings to standardize the instrument prior to inspection are based on response to a specified reference standard. A wide variety of test standards are used for bolt-hole inspection. They include cracked parts, electrical discharge machined (EDM) notches, notches cut with a jeweler’s saw, differences in conductivity standards, and a multitude of other standards with larger notches and/or cracks. Each individual procedure SHALL specify the standard to be used and the required response in terms of meter deflection or indication size on a recorder, strip chart, or instrument display. When it is necessary to find small flaws and the possibility exists that different types of probes (coil size and frequency) may be used, it is necessary to use a reference with the same approximate dimensions as the flaws to be detected such as EDM notches.

4.5.11 Scan Speed and Pattern. Scanning speed and pattern must be considered during the setup procedure. This is especially important with manual scanning as probe response with manual scanning will not be the same as that during automated scanning. The distance between scans or the scanning increment is determined by the minimum crack size required to be detected. During manual scanning, the scanning procedure is repeated after setting the probe coil at each scanning position until the entire length of the hole has been inspected. When inspecting multiple layers, inspection should be performed in the materials of each layer adjacent to each interface. When the specific interface position between layers of similar material is not known, its position may be established by running the probe down past the interface and marking the position of maximum signal deflection. Setup and inspection SHALL be performed using the same scanning speed and pattern to ensure the best signal response and maximum scan coverage.

4.5.12 Probe Alignment. When inspecting a hole, the probe must be guided into the hole such that the axis of the probe is aligned with the axis of the hole (see Figure 4-40 and Figure 4-41). This may be difficult to do, especially while monitoring the instrument screen at the same time. If the probe is not properly aligned the coil may not touch the bolt hole surface, preventing an effective inspection. The probe may also wobble or chatter, causing excessive noise.

USAF/UniWest Image

H1600303

Figure 4-40. Correct Probe Alignment

USAF/UniWest Image

H1600304

Figure 4-41. Incorrect Probe Alignment

4.5.13 Probe to Edge Spacing. When inspecting for small cracks initiating from edges, probe-to-edge spacing can become a concern. Some approaches for overcoming these concerns are: increasing the frequency of the eddy current generating source, reducing the physical size of the coil, and adding shielding around the probe coil. Additional shielding will allow inspection closer to the edge because of the reduced volume of material sensed, and will result in greater sensitivity to smaller flaws. Probe-to-edge spacing becomes even more of a concern when the edge of the part is in contact with a ferromagnetic part such as a bearing or bushing. Again, minimizing the volume of material sensed by the probe will alleviate some of these irrelevant concerns and optimize signal response.

4.5.14 Bolt Hole Eddy Current Signal Interpretation. One of the single most important requirements for detecting a small crack is that the coil passes over the crack. Arguably, the technician's ability to interpret eddy current signal responses is just as crucial to a successful inspection. To fully evaluate any indication, technicians should utilize both the impedance plane and sweep displays (Figure 4-42). The impedance plane provides the phase information, allowing the technician to assess whether an indication is lift-off from noise or a crack-like. Figure 4-43 illustrates why passing a differential-reflection probe over a crack results in a "figure-eight" or "double-loop" indication on the instrument display. The sweep display shows how many flaw indications are present and if setup correctly, what clock-position from a reference point each flaw is located in the hole. Used together, the impedance plane and sweep displays allow the technician to determine the orientation of the signal present, how many flaws are present, and their clock-position within the fastener hole.

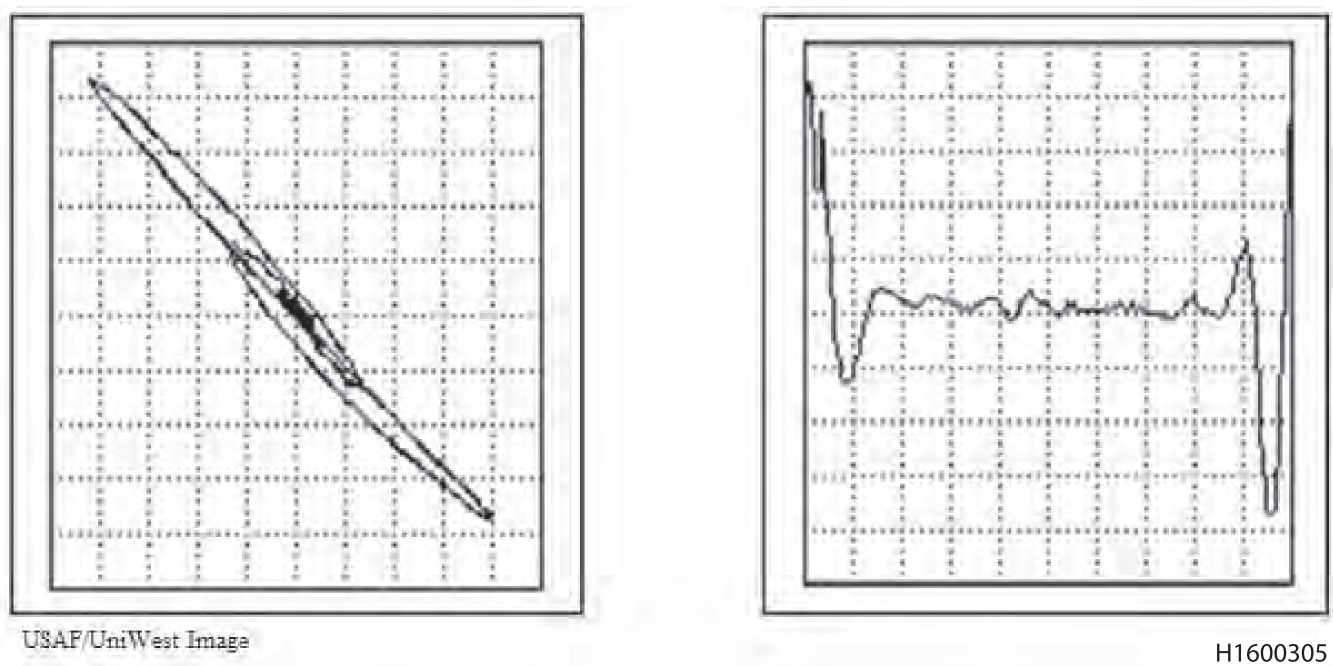


Figure 4-42. Impedance Plane Display (Left) and Sweep Display (Right)

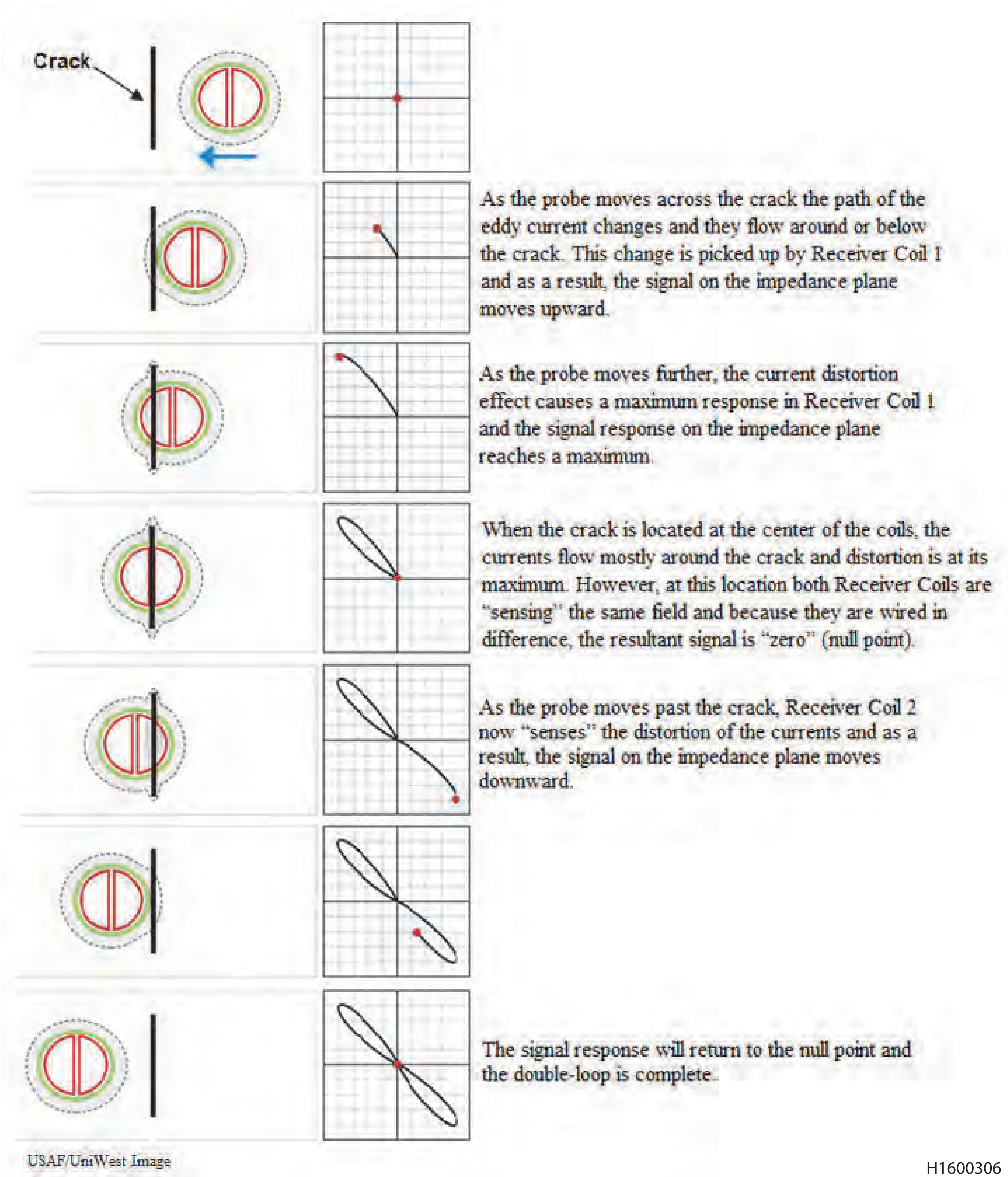
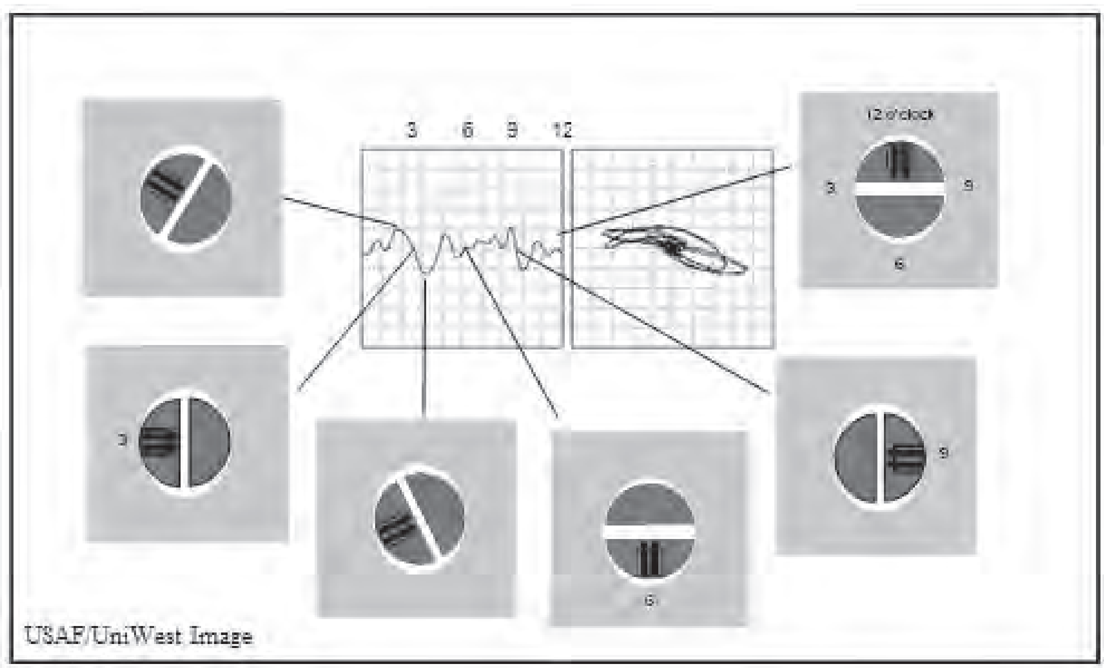


Figure 4-43. Bolt Hole Eddy Current Signal Responses from a Crack

4.5.14.1 Out-of-Round Holes. The effects from out of round holes most often occur in combination, making signal interpretation very difficult and can lead to false calls or missed cracks. It is very important to measure fastener holes prior to inspection if you suspect out-of-round condition. Studies have shown that crack detection is still possible at below 0.006-0.008 inches out-of-round of nominal diameters; however, crack signal response is slightly distorted. Above these values, crack signals are generally distorted, are not distinguishable from noise, and noise levels exceed the reject limits. In field application, out-of-round holes typically exhibit unacceptable levels of signal noise. The following paragraphs describe some of the effects observed on the signal responses from out-of-round holes.

4.5.14.1.1 "Goal Post" Response (no crack). As the probe rotates in the fastener hole it will compress as it enters the narrow section (3-9 o’clock). As it enters the wider section (6-12 o’clock), it will expand, but the coil may no longer touch the surface and thus experiences lift-off. The result is a goal post-like pattern on the sweep-display and an indication on the impedance display similar to a crack indication, but at a different phase-angle (Figure 4-44). This excessive lift-off noise is rejectable.



H1600307

Figure 4-44. "Goal Post" Response in Aluminum

4.5.14.1.2 Excessive Noise Response. If there is a crack at the narrow section of an out-of-round hole, the lift-off effect can mask or distort the signal response from the crack, leading to difficulty in interpreting the crack response (Figure 4-45). Even if a crack-like indication were not present, the hole in Figure 4-45 would still be rejectable, based on excessive lift-off noise.

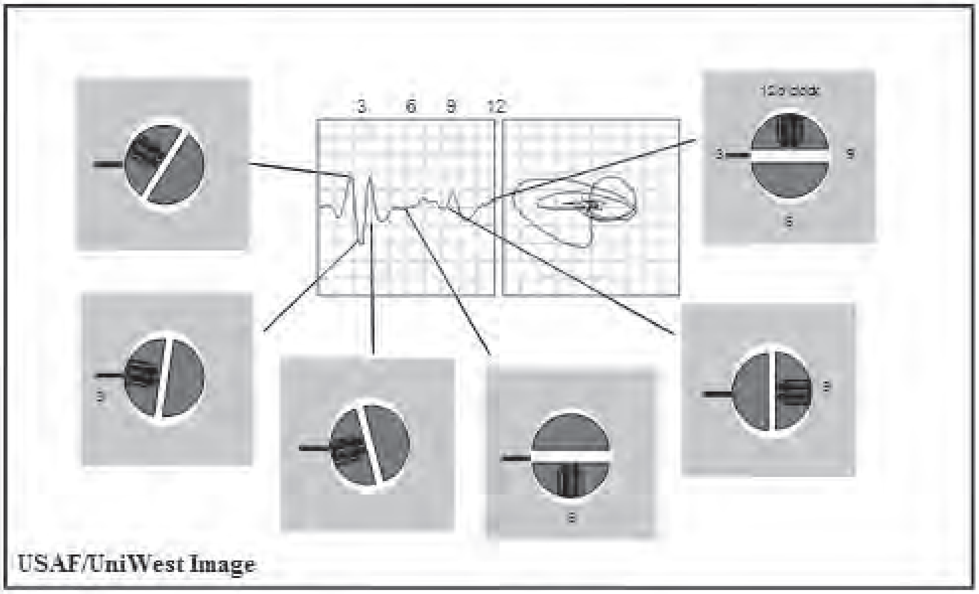


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Figure 4-45. Excessive Noise Response in Aluminum

4.5.14.1.3 Excessive Noise and Crack Response. If there is a crack at the wider section of an out-of-round hole, the lift-off has two effects: it can mask or distort the signal response from the crack, and it reduces the signal amplitude (Figure 4-46). The hole in Figure 4-46 would be rejectable based on the noise, *and* due to a crack-like indication. If the hole is severely out-of-round the lift-off effect can be so great that there is no noticeable response from the crack.

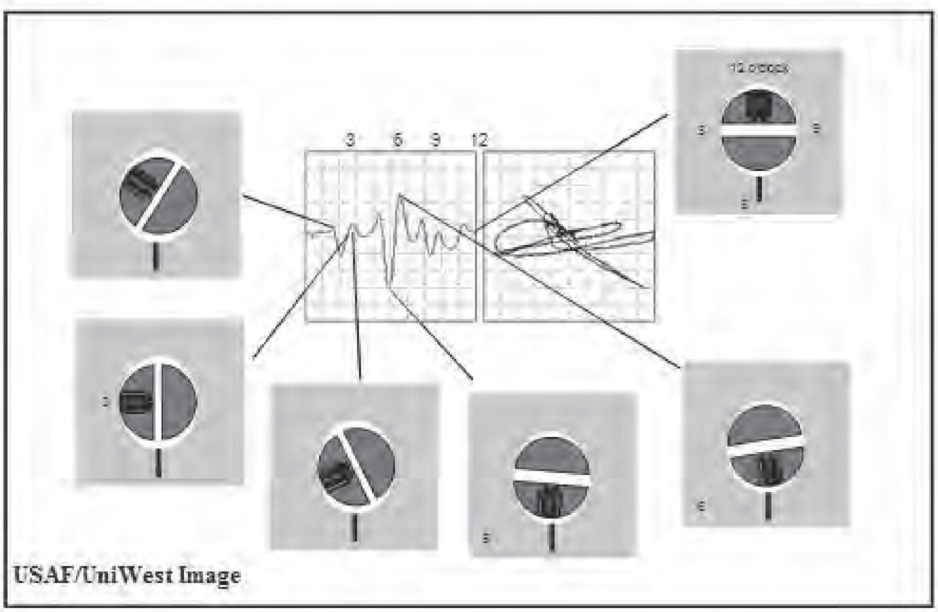

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Figure 4-46. Excessive Noise and Crack Response in Aluminum

4.5.15 Fastener Holes Non-Removable Fasteners.

4.5.15.1 Inspection Application of Fastener Holes. If a fastener cannot be removed from a hole because of fastener type or location, inspection can be performed around the fastener to detect cracks growing from beneath the fastener head or nut. The size of detectable cracks is dependent upon the distance which must be maintained between the probe and the edge of the fastener. In many respects, this application is similar to inspection for cracks at the edge of openings and cutouts. Large low frequency probes and sliding reflectance probes can also be scanned over countersunk fasteners and identify cracks at the 1st, 2nd, and 3rd layers.

4.5.15.2 Probe to Fastener Spacing. If only required to detect relatively large cracks, such as those extending between two fasteners, eddy current inspection can usually be performed at a sufficient distance from the fastener heads to eliminate their effect on eddy current response. When small cracks must be detected, the probe must be positioned closer to the edge of the fastener, and the probe to fastener distance must be held constant during scanning. When fasteners fabricated of magnetic materials such as steel are used in nonmagnetic parts, a relatively large spacing must be used. Also, shielded probes can be used to minimize the distance between the probe and the fastener, allowing inspection near the fastener.

4.5.15.3 Scanning Guides Around Non-Removable Fasteners. For nonferrous (nonmagnetic) fasteners, the head of the fastener may be used as a probe guide. Only those fasteners which protrude from the surface of the part and are concentric with the hole can be used as guides. For fasteners with heads not concentric with the holes, such as hexagonal and serrated heads, a collar fitted to the fastener head can be used as a scanning guide. Most shielded probes can be scanned around steel fasteners without requiring a collar. Templates must be positioned concentric to the fastener head to assure relatively consistent response from defect-free material as the probe is guided around the fastener.

4.5.15.4 Probe Selection. As with many other flaw detection applications, the use of small diameter, radius probes is recommended. These probes permit better visibility of probe coil location and permit more flexibility in establishing spacing between the probe and the fastener. Radius probes are also less susceptible than flat surface probes to lift-off variations with changes in probe to surface angle.

4.5.15.5 Standards for Nonremovable Fastener Holes. Whenever possible, the standards for inspecting around the heads of nonremovable fasteners should duplicate as closely as possible the conditions of the inspection area. If cracked specimens representing the minimum crack size to be detected are not available, EDM slots cut at the edges of holes in the reference standard can be used. Material, geometry, hole size, fastener type, and installation should be the same for the reference part as for the inspection area, unless prior correlation with other available references has been established. Duplication of part geometry in the reference minimizes differences in response between references and cracks in the part.

4.5.16 Fillets and Rounded Corners.

4.5.16.1 Edges (Including Corners and Radii). For most eddy current techniques, the flow is circular and parallel to the surface of the part. If the flow of eddy currents intercepts an edge, corner, or radius of the part, the circular pattern is disrupted and the eddy currents are confined to a smaller volume. This action changes the magnitude and distribution of the eddy currents and is known as edge effect (Figure 4-47). As illustrated, the current density will be slightly greater at the edge of the part than at the interior. This will result in a slight increase in sensitivity to discontinuities located at the edge.

4.5.16.2 Crack Occurrence. Repeated bending loads applied to fillets and radii (rounded corners) of a part can lead to fatigue cracks. Fatigue cracks usually lie parallel to the radius. In formed radii, cracking usually occurs near the center of the radius where there is maximum thinning. In machined fillets or radii of extruded shapes where part thickness is greater at the center of the radius, fatigue cracks are more likely to occur at the tangent point of the radius. Stress corrosion cracking can sometimes occur in the radii and fillets of machined parts where tensile stresses are applied or areas of residual tensile stresses are exposed. Stress corrosion cracking is often promoted by the collection of moisture in these fillets and radii.

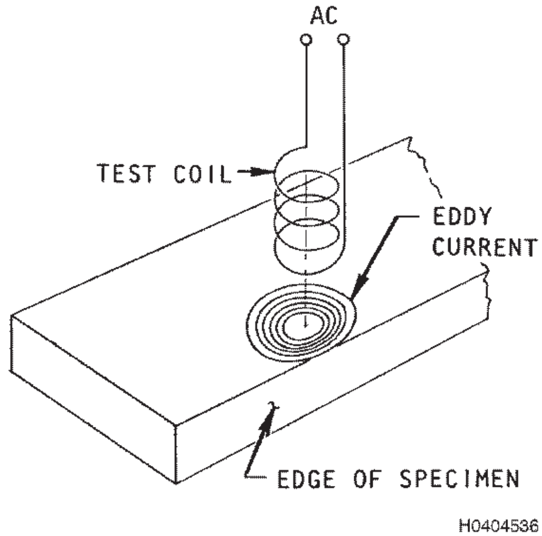

Figure 4-47. Distortion of Eddy Current Flow at the Edge of a Part

4.5.16.3 Equipment Requirements for Fillets and Radii. In general, no special equipment is required for the inspection of fillets and radii. Adequate inspection can be performed using eddy current instruments with a radius tip probe or an equivalent test system. The radius of the probe tip must be less than the radius of the fillet to be inspected to ensure relatively constant contact between probe and part and thereby avoid excessive changes in lift-off. For inspection of the edges of radii or fillets, a thin plastic straight edge is desirable to maintain probe-to-edge spacing in the fillet. Occasionally, a fixture similar to those used for the bead seat radii in wheels can be used for fillets and radii. Fixtures decrease inspection time, improve inspection detectability, and assure complete coverage.

4.5.16.4 Reference Standards for Fillets. The best reference standard is an actual part with an actual flaw. If that can't be obtained then a specimen that represents the configuration of the part to be tested should be used for setup. Therefore, it is preferable to have a standard of the same material, finish, and radius as the fillet to be tested. A flaw or multiple flaws can be placed in the inspection area on the reference standard. The standard should contain at least one flaw equal to or smaller than the required flaw size of the inspection. Flat standards can be used if a standard of the required configuration is not available. Response from flat standards differs very little from response from cracks or slots in fillets or curved surfaces if a radius probe having a diameter substantially smaller than the fillet radius is used. Slots at edges are not interchangeable with slots located away from the edge.

4.5.17 Corrosion.

4.5.17.1 Test System Requirements for Corrosion Detection. The test system requirements for corrosion detection depends on the type and depth of corrosion for which inspection is performed. For uniform etch corrosion and for large pits, thickness measuring systems provide optimum detectability. For small pits and small areas of exfoliation or intergranular attack, the inspection requirements become similar to those for subsurface flaws. Instrumentation and probes with a broad selection of operating frequencies may be needed to cover the wide range of material types and thickness. Battery operated impedance plane analysis equipment can be used for corrosion detection and has many advantages for these applications in most field situations.

4.5.17.2 Types of Corrosion. Corrosion is a deterioration of metals by chemical action. Corrosion occurs where a conductive liquid, like water with ions, allows electrons to move from one piece of metal to another, or from one point to another in the same piece of metal. If salt, or another ion source, is added to water, the conductivity is increased and the rate of corrosion increases. Even condensation from damp air can provide enough water for corrosion to occur. The primary defenses against corrosion on aircraft are insulating dissimilar metals from each other, and protecting metal surfaces from moisture. Although corrosion may be classified in many ways, for purposes of detection, five principal forms are considered: (1) uniform etch, (2) pitting, (3) intergranular attack, (4) exfoliation, and (5) stress corrosion cracking.

NOTE

Further explanation of corrosion theory may be found in Chapter 3 of NAVAIR 01-1A-509-1/TO 1-1-689-1/TM 1-1500-344-23-1.

4.5.17.2.1 Uniform Etch. Uniform etch corrosion is characterized by a general overall reduction in thickness of the metal in which some areas may be corroded more rapidly than others. This form of corrosion is readily detectable by visual means on exposed surfaces. Corrosion of inaccessible surfaces of thin metal structures is detectable with eddy currents if access is available to the non-corroded side. Detection of this type of corrosion then becomes a matter of thickness measurement with some variations expected because of small areas with increased corrosion or the presence of metallic materials at the far surface.

4.5.17.2.2 Pitting. Small localized areas of corrosion are termed pitting. Pitting can vary from pinpoint size to relatively large areas. The detection and measurement of corrosion pits must take these possible variations into account.

4.5.17.2.3 Intergranular Attack. In some materials, including many structural aluminum alloys, corrosion occurs preferentially along grain boundaries. Although slight amounts of corrosion pitting may be observed at the surface, the extent of damage is not readily observable by visual means because of the small crack-like penetrations. This type of attack is particularly applicable to aluminum alloys.

4.5.17.2.4 Exfoliation. Exfoliation corrosion initiates along grain boundaries parallel to the surface and propagates from these initiation sites. The corrosion products force the metal upward resulting in blistering and flaking of the metal. This corrosion form is most prevalent in structural aluminum alloys such as 7075-T6.

4.5.17.2.5 Stress Corrosion Cracking. The combination of a constantly applied residual or service stress and a corrosive environment can lead to stress corrosion cracking in many high strength metals. Residual stress can result from heat treating, machining, forming, shrink fits, welding, and assembly mismatch. Depending on the type of metal and the corrosive environment, stress corrosion cracking may or may not be associated with other forms of corrosion. This form of corrosion is primarily a crack and its detection has been covered under applications related to crack detection.

4.5.17.3 Frequency Selection. The choice of frequency depends on the type of corrosion to be detected and the thickness of the material through which inspection is being performed. Higher frequencies favor resolution of small pits or small areas of intergranular corrosion or exfoliation. Lower frequencies increase the depth of penetration.

4.5.17.4 Probe Selection. The probe must match the frequency at which the inspection for corrosion is performed. When more than one model of probe is operable at the inspection frequency, part and probe geometry are the determining factors in probe selection. For narrow contact areas, a smaller diameter probe may be advantageous. Larger diameter probes provide for greater averaging of thickness and provide somewhat better sensitivity in thicker areas.

4.5.17.5 Corrosion Reference Standards. Because of the unique action of each type of corrosion and its effect upon conductivity, reference standards must be fabricated from the same alloy, temper, and thickness as the material being inspected. When faying surfaces are involved in corrosion detection, the standard should be built up to simulate the joint including nonconductive shims for gap, paint, and primer thickness. Standards for pitting may also be used for exfoliation and intergranular attack. Standards should also have approximately the same geometry as the part.

4.5.17.6 Inspection Procedure-Corrosion Detection. Detection of corrosion with eddy current techniques is applied to aircraft skins when corrosion may occur on inaccessible interior surfaces. Corrosion usually results in areas where moisture is entrapped. If relatively uniform thinning is expected, corrosion detection may be simply a matter of thickness measurement. In most instances, corrosion is confined to smaller localized areas of relatively small diameter. As skin thickness increases, sensitivity to small areas and shallow depths of corrosion is reduced.

4.5.17.7 Part Preparation. Prior to inspection, all foreign material should be removed from the area to be inspected. Any roughness, sharp edges, or protrusions that could damage the probe or cause errors in readings should be removed by light sanding within the limits of the applicable TO. The locations of all fasteners, edges, and changes in structure on the far side of the inspection surface should be established and marked with an approved removable marker to aid in the interpretation of inspection results. Paint removal is not required if it is relatively uniform and not loose or flaking. Because of the wide variety of corrosion attack, inspection SHALL be performed in accordance with the applicable TO

4.5.18 Field Measurement of Conductivity. Eddy current instrumentation is used for determination of electrical conductivity under production and field conditions. The eddy current instruments are calibrated against standards of known conductivity. When available, instruments designed specifically for measurement of conductivity are used. These instruments measure conductivity directly in % IACS.

4.5.18.1 Conductivity of Aluminum Alloys. Conductivity measurement is applied most often to aluminum alloys. This application results from the extensive use of aluminum alloys in the aerospace industry and the wide variation in the electrical conductivity and mechanical properties between different alloys and heat treatment. For most aluminum alloys in common usage, specific conductivity ranges have been established for each alloy and temper. The conductivity ranges for most of the aluminum alloys commonly used in aircraft structural applications are listed in (Table 4-4 in paragraph 4.8). These values represent a collection of values obtained from various airframe manufacturers and Government agencies. The ranges include all values obtained for standard heat treatments except for extreme values obtained from one or two sources which were clearly outside the ranges of all other lists. If a measured conductivity value for an aluminum alloy and temper is outside of the applicable range, its mechanical properties SHOULD be considered suspect. Measurement of conductivity values SHOULD be in accordance with SAE-AMS-H-6088, ASTM E 1004 or another suitable standard.

4.5.18.2 Heat Treatment Effects on Aluminum Conductivity. An aluminum alloy has the highest conductivity and lowest strength when it is in the fully annealed temper. After quenching from the solution heat treating temperature, the strength is increased and the conductivity decreased. Many aluminum alloys are unstable for a considerable period of time after solution heat treatment, even if held at room temperature during this time. A certain amount of atom migration takes place to initiate the formation of submicroscopic particles. This process, sometimes called natural aging, increases the strength of the alloy but has either no effect on conductivity or a slight decrease in the conductivity value. Some aluminum alloys remain unstable for such long periods after quenching they are never used in the solution heat treated condition (e.g., 7075). If a solution heat treated alloy is precipitation hardened by heating at relatively low temperature (generally 200-450°F), alloying atoms form small particles. At a critical size and distribution of particles, the strength of the aluminum alloy reaches a maximum. Conductivity increases during the precipitation hardening or artificial aging process. If aging is carried on beyond the point where optimum strength is obtained, strength will decrease, but conductivity will continue to increase.

4.5.18.3 Discrepancies in Aluminum Alloy Heat Treatment. Variations from specified heat treating practice can result in aluminum alloys with strengths below required levels. Heat treat discrepancies include changes or misapplication of the following processes:

- Solution heat treating temperature
- Solution heat treating time
- Quenching practice
- Aging temperature
- Aging time
- Annealing temperature and time
- Uncontrolled temperature application

4.5.18.4 Applications of Conductivity Measurement.

NOTE

The Tables in Section VIII provide conductive values and ranges for reference. However, when determining the serviceability of an aircraft component or structure based on conductivity, the appropriate conductivity range should be identified or confirmed by cognizant engineering.

4.5.18.5 Separation of Alloys and Tempers. Conductivity measurement can be used to separate mixtures of two or more alloys and/or tempers. Separation is possible when the electrical conductivity of each grouping is clearly different. The process of separation may be accomplished with an instrument calibrated in % IACS.

4.5.18.6 Conductivity Measurement and Magnetic Materials. Use of general purpose instruments may be extended to the separation of magnetic materials where the product of permeability and conductivity of each of the alloys is clearly different. Conductivity meters will not measure the conductivity of magnetic materials.

4.5.18.7 Typical Application. Eddy current techniques are used to separate metal parts or raw materials of similar geometry which have lost alloy and/or temper identification and have become mixed in manufacture or storage. Such procedures can be applied at any stage in the processing, storage, or service of the material.

4.5.18.8 Control of Heat Treatment. The relationship between electrical conductivity and heat treat condition has permitted the use of eddy current techniques for checking the adequacy of heat treatment in aluminum alloys. In this application, conductivity measurements by eddy current techniques are used to supplement a minimum amount of tensile testing and/or hardness testing. Eddy current conductivity measurements are particularly valuable for determining the uniformity of heat treatment of large and complex aluminum alloy structures when tensile specimens are not obtainable and part geometry limits accessibility for hardness testing. Adequacy of heat treatment of aluminum alloys is determined by conformance of the material to the pre-established conductivity ranges. This method of heat treat control has been applied extensively to aluminum alloys. Eddy current techniques are used for evaluation of heat treatment of steels. Generally, more sophisticated instrumentation is used for steels, but general purpose instruments can be used for many applications. Acceptance standards are usually used for eddy current inspection of steel. Conductivity measurement is applied to a lesser degree for heat treat control of copper and magnesium alloys. Eddy current techniques can be used for heat treat control in any alloy system where consistent but different conductivity ranges or permeability values occur with the various heat treating conditions. Conductivity measurement has not been established as a method of determining heat treat response in titanium alloys. Differences in conductivity between various heat treat conditions for most titanium alloys are insufficient to permit determination of temper.

4.5.18.9 Determination of Heat and Fire Damage. A common application of conductivity measurement in field applications is the determination of heat and/or fire damage to aircraft structures. Because of the extensive use of aluminum alloys for aircraft structures and their sensitivity to mechanical property losses at relatively low temperatures, greatest experience and data have been generated for these materials. Heat and fire damage to other metals can be detected if temperatures become high enough to affect conductivity, permeability, and mechanical properties. Damage is detected in aluminum alloys as changes in conductivity from the specified range for the alloy and temper being inspected. Heat and fire damage usually vary over a part because of non-uniform application of heat. Non-uniform heat application, in turn, results in variations in electrical conductivity. Unless the temperature and time of heat application is known, or testing is performed on a number of parts with the same history of heat application, quantitative values of mechanical properties cannot be established from the electrical conductivity values. Hardness testing and conductivity measurement give a good indication of heat and fire damage. Both test methods must be performed to get an idea of the amount of damage.

4.5.18.10 Conductivity Measurement. To determine conductivity directly, eddy current instruments are available which provide a value of conductivity in % IACS. Percent IACS measuring instruments usually require only two standards of known conductivity for calibration. If direct conductivity measuring equipment is not available, general purpose eddy current equipment may be adapted for measuring conductivity. Use of general purpose equipment requires a larger number of standards to establish a calibration curve. The number of standards necessary for a conductivity measuring application is determined by the range of conductivity to be covered and the accuracy required. General purpose equipment can also be used in a go no-go function to separate metals above and below a specified conductivity value. A standard representing the minimum acceptable or disallowable conductivity must be available.

4.5.18.11 Equipment for Magnetic Materials. Impedance plane analysis instruments can be used to measure the conductivity of ferromagnetic materials because the permeability and conductivity can be separated in phase. The combination of conductivity and permeability, in many cases, can be related to variations in alloy, temper, and strength. General purpose meter type instruments can then be used to separate or grade various levels of properties. The number of standards required depends on the number of categories of materials to be established.

4.5.19 Effects of Variations in Material Properties.

4.5.19.1 Conductivity. Conductivity variations can occur in metals as a result of improper heat treatment or as a result of exposure to excessive temperatures during service and cold working. These are the conditions for which eddy current inspection is usually performed. Conductivity variations can stem from other sources. Separation of elements during solidification of metals can lead to either localized or uniform differences in conductivity. For instance, a variation in conductivity can exist with increasing depths beneath the part surface particularly in heavier sections which have not been worked extensively. Slight differences in heat treating time, temperature, or quenching rates imposed by limitations in heat-treating facilities or changes in part configuration also lead to variations in conductivity of a part. Localized cold working of metals, when not followed by heat treatment to relieve residual stress, can reduce electrical conductivity. Many of the variations are considered normal to the processing of the parts and the conductivity lies within the acceptable range for the alloy specification and temper. Conductivity outside the specified range for a given alloy and temper should be considered unacceptable and further investigation should be performed using hardness testing techniques.

4.5.19.2 Edge Effects. If the electromagnetic field of the probe is affected by the geometry of the edge of the part, an error will occur in the measurement of the conductivity. The probe should be located several probe diameters away from the nearest edge or transition boundary.

4.5.19.3 Curvature. Lift-off effects caused by the probe-to-curve surface fit-up will cause an error in the conductivity measurement. On curved surfaces, the smallest practical probe should be used to minimize lift-off effects.

4.5.19.4 Clad Materials. Cladding will affect the measured conductivity of the base metal. The degree to which the cladding will affect the value obtained depends on the conductivity of the cladding, the thickness of the cladding, and the operating frequency. Present applications are usually limited to “Alclad” aluminum alloys in the range of 0.050 to 0.080-inch thick using conductivity meters with operating frequencies of 60 kHz. Special conductivity ranges are required for clad aluminum alloys. The thicknesses of cladding, which are usually based on a percentage range of the overall thicknesses, can vary slightly because of normal tolerances. At 60 kHz, conductivity readings from aluminum alloys less the 0.050-inch in thickness are affected by both cladding and part thickness. Eddy current testing of complex cladding systems is still in an experimental stage for the most part.

4.5.19.5 Magnetic Permeability. Direct meter measurement of electrical conductivity is applicable to nonmagnetic materials with a relative magnetic permeability of one or nearly one. If magnetic permeability exceeds one, it will produce a bridge unbalance in the meter system which cannot be separated from the conductivity measurement and erroneous readings will be obtained. For this reason, conductivity of steels, nickel, and other magnetic materials cannot be determined with conventional eddy current conductivity meters. Some stainless steels (e.g., 300 series) are essentially nonmagnetic in the annealed condition, but slight amounts of cold working or exposure to extremely low temperature can cause transformation to a magnetic structure. Impedance plane analysis equipment can readily separate magnetic permeability and conductivity, allowing an accurate measurement of conductivity of ferromagnetic materials.

4.5.19.6 Geometry. Any change in part configuration that affects distribution or penetration of eddy currents will result in erroneous electrical conductivity readings. The following sources of error are included in these categories:

- Proximity to part edges or adjoining structure
- Metal thickness less than the effective depth of penetration in the metal
- Excessive curvature of part surface

4.5.19.7 Metal Thickness. If metal thickness is less than the effective penetration of the eddy currents, the measured conductivity will differ from the true value. Notice the effective penetration depth is approximately three times the standard depth of penetration. With meter equipment it is important to determine the operating frequency of the instrument. The operating frequency must not exceed the effective penetration depth of the material being tested. Impedance plane analysis equipment has a very wide range of operating frequencies, and the frequency can be adjusted to limit penetration to less than the effective depth. The standard depth can be determined by using the equation in paragraph 4.8.7. Special slide rules are available for calculating depth of penetration. Effective depth is approximately three times greater than the standard depth calculated by this equation. The material thickness must be greater than the effective depth or errors in conductivity measurement will occur.

4.5.20 Effects of Variations in Test Conditions.

4.5.20.1 Frequency. Because frequency affects distribution of eddy currents within the test part, it affects the minimum thickness which can be measured without special adjustments. Higher frequencies permit measurement of thinner metals without compensation for thickness. Select a frequency such that the effective depth of penetration (2.6δ) is contained within metal being tested to reasonably accurate conductivity measurement. However, the higher frequencies are more strongly affected by localized variations in conductivity or by conductive coatings and cladding on metals. Excessive high frequencies SHOULD NOT be used for conductivity measurements.

4.5.20.2 Probes for Conductivity Measurements. With instruments designed for conductivity measurement, probes are carefully matched to the instruments and are usually obtained from the instrument manufacturer. Probes for conductivity measuring instruments are larger than those normally used for defect detection. This design provides for averaging of conductivity over a relatively large area. Probes are designed with plastic or ceramic shoes to prevent damage to the coil. With continued use, wear on the face of the probe reduces the coil-to-surface distance, and calibration cannot be obtained. As wear occurs, the probe shoe must be changed and the instrument recalibrated.

4.5.20.3 Lift-Off Effects on Conductivity. Meter type conductivity measuring eddy current instruments often have a pre-set lift-off adjustment. The lift-off adjustment is usually set during calibration of the instruments. Applicable maintenance manuals describe the procedures that can be performed by trained NDI personnel. With probe wear and changes in instrument electrical components over a period of time, lift-off adjustment can change. Therefore, when conductivity measurements are to be performed on rough surfaces or through thin nonconductive coatings, lift-off adjustment SHOULD be checked prior to performing the measurements. After calibrating an instrument against the conductivity standards, lift-off adjustment SHOULD be checked against a specimen with conductivity representative of the test part. Lift-off, greater than the amount of preset lift-off adjustment (if any), results in errors in conductivity readings.

4.5.20.4 Temperature Effects on Conductivity Measurements. Higher temperature increases the thermal activity, of the atoms in a metal lattice. The thermal activity causes the atoms to vibrate at high amplitude about their position in the lattice. This thermal vibration of the atoms increases the chances of a collision with electrons in the material. This increases the resistance to electron flow, thereby lowering the conductivity of the metal. Lower temperatures reduce thermal oscillation of the atoms resulting in an increased electrical conductivity. The conductivity of standards is usually determined at a specific temperature; 68°F (20C) is most commonly used. Typical conductivity values and allowable conductivity ranges are also established at approximately this temperature. If all instrument calibration and conductivity measurements could be performed at this temperature, errors in conductivity measurement related to temperature variation would not occur and/or temperature compensation would not be required. In field applications, testing temperatures can conceivably be anywhere in the range of 0°F to 120°F. Unless precautions are taken in selection of standards, calibration of the instrument, and testing, errors will occur in the measured conductivity values. Two ways in which erroneous readings may be obtained are:

- Difference in temperature between standards and test part
- Difference in temperature at which conductivity of the standard was originally established and the temperature at which instrument calibration and conductivity measurements are performed

4.5.20.5 To prevent errors from differences in temperature between the standard and test part, the instrument and standards SHOULD be allowed to stabilize at the test part temperature before calibration and conductivity measurements are performed. Measurements SHALL NOT be taken if part and standards temperature differ by more than 10°F. Even though the standard and test part are at the same temperature, errors in determining conductivity values occur when the measuring temperature differs from the temperature at which the conductivity of the standards was originally established. The magnitude of the error becomes larger as this difference in temperature increases.

4.5.21 Flaw Detection. Service-induced cracks in aircraft structures are generally caused by fatigue or stress corrosion. Both types of cracks initiate at the surface of a part. If this surface is accessible, either by direct surface contact or by penetration of the eddy current field through the material, ET can be performed with a minimum of part preparation and a high degree of sensitivity. When establishing an eddy current technique for crack detection, the following factors must be considered:

- Test system capabilities
- Type of material to be inspected
- Accessibility of inspection area
- Location and size of cracks to be detected

4.5.21.1 Capabilities of Test System. The test system for crack detection includes the probe(s), the eddy current instrument, any additional recording or measuring instruments, and reference standards. A wide variety of eddy current units are fabricated for general purpose ET. General purpose eddy current inspection instruments are used for flaw detection. In the aerospace industry, very few general purpose eddy current instruments use meter displays. For the most part, two-dimensional displays of the impedance plane that display the detailed phase and amplitude analysis are used.

4.5.21.1.1 Probe Selection. The primary consideration in selecting an eddy current probe is the type of inspection being performed. To detect small cracks, a shielded probe coil of small diameter with a ferrite core is desirable to concentrate the induced field into a small volume. A small crack has a proportionately greater effect on a small probe field than on a large probe field. In the event encircling coils or inside coils are used, short or narrow coils are preferred for inspection of small localized conditions. Spacing of the coils must be considered when determining the resolution required. The coil or probe must match the frequency range and output impedance of the instrument being used. In general, cracks whose lengths are less than half the diameter of the coil are difficult to detect.

4.5.21.1.1.1 Probe Housings. The housing for most general purpose surface probes is cylindrical in configuration and from 1/8 to 3/8-inch in diameter. Probes can be shielded with either non-permeable (mu) metal or ferrite to concentrate the field. When defect detection around fasteners, in radii, or adjacent to edges is required, it is often advantageous to have a pointed or small rounded tip at the end of the probe. The pointed end allows the probe to be inserted closer to the inspection surface, or edge, and permits better visibility of probe coil position. The advantages of a pointed probe for these applications are illustrated in (Figure 4-48). For inspection of bolt holes, special probes are manufactured that permit contact with the side of the hole at any desired level in the hole. For inspection areas where accessibility is a problem, or where probe positioning is critical, it is often desirable to fabricate special probe housings as an aid in performing the inspection. The use of special housings can greatly decrease the loss of sensitivity associated with probe wobble and lift-off during scanning. When large quantities of parts are to be inspected, special probes present a distinct advantage if they enable per unit inspection time to be reduced. Test procedures and technical orders for the ET of specific aircraft components SHOULD specify the probe and special fixtures and may specify the design also. Probability-of-Detection studies have indicated that probe guides and special fixtures increase inspection reliability and SHOULD be used instead of freehand scanning.

4.5.21.1.1.2 Probe Types. The four different probe types are absolute, differential, reflectance, and remote field probes. Each type of probe is discussed in paragraph 4.4.2.1.

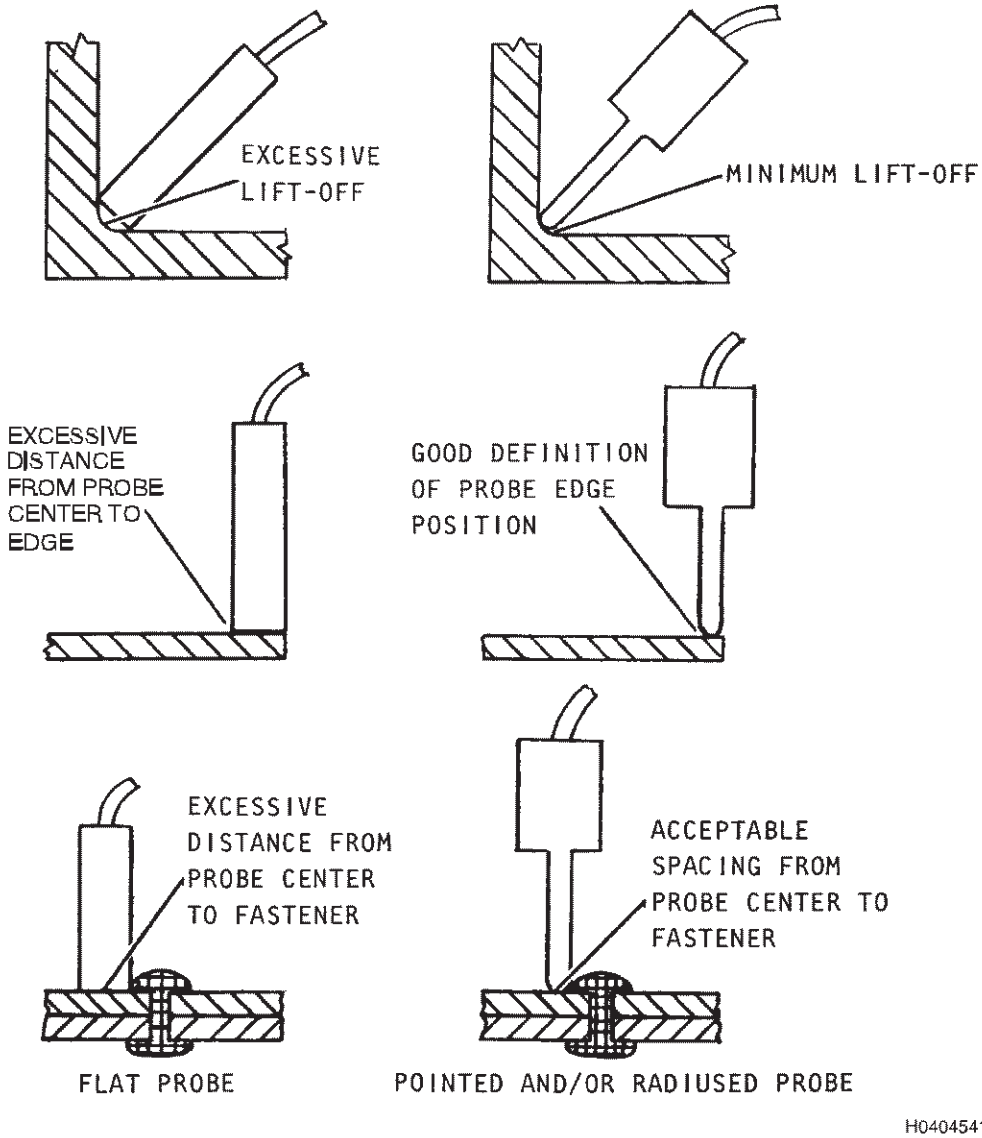

Figure 4-48. Advantages of Pointed and Radius Probes for ET

4.5.21.2 Inspection Material. The material from which the inspection part is fabricated is of primary importance when determining if eddy current inspection should be used and the limitations involved with this method. Conductivity and magnetic permeability influence frequency requirements, instrument choice, signal-to-noise ratio, filtering needs, resulting sensitivity, and reliability of inspection. If surface cracking is to be detected in ferromagnetic material, a high frequency can be used to limit penetration or a high pass filter can be used to minimize permeability problems.

4.5.21.3 Accessibility. Most of the eddy current equipment presently available for use in the field is small, portable, and battery powered. This permits its operation in relatively tight quarters. However, eddy current inspection is only feasible for surface or near surface conditions because of its limited depth of penetration. For this reason, direct access to the surface to be inspected is usually preferred. Sufficient freedom of movement must be available in the area to be inspected to allow positioning and movement of the probe to detect or measure the specified variable. The inspection area must be visible to enable the inspector to determine the position of the probe. Alternatively, a special probe, a fixture, or a guide can be used to position and hold probes in the required location. The extent of disassembly required for inspection should be defined in applicable written procedures.

4.5.21.4 Frequency Requirements. As the eddy current test frequency is increased for a specific eddy current application, the eddy currents are confined to a smaller volume adjacent to the inspection probe coil. This concentration increases the proportion of generated eddy currents intercepted by a small crack or other defect. Higher frequencies should then provide better response to the smallest defects. This statement holds in general, but other conditions may limit the sensitivity when using higher frequencies. In some instruments, high induction losses limit instrument output at these higher frequencies. Lower frequencies may be required for increased penetration to detect subsurface or far surface flaws. Optimum sensitivity to cracks or other flaws generally occurs in specific frequency ranges for each combination of metal, flaw size and flaw depth. Operating frequency ranges can be established for each application by using the calculated depth of penetration using the conductivity and permeability of the material. These calculations SHOULD be confirmed with the use of reference standards which simulate the anticipated flaws to be detected.

4.5.21.5 Signal-to-Noise Ratio. As the gain of a test system is increased, a background of electrical noise will be observed. This may be represented by erratic meter movement, excessive background signals on a waveform display, or excessive, random patterns on a recorder. This “noise” can be the result of random variations in the electrical system of the test instrument, normal variations in material properties, or stray electrical signals from other electrical devices. Signal-to-noise ratio is not a function of the instrument alone, but is also dependent upon lift-off, surface finish, conductivity, and permeability variations within the inspection part. For an eddy current test instrument or any other electrical test instrument to be useful, it must provide flaw signal information greater than the background noise of the test system. Otherwise the inspector could not see the difference between the flaw signal and the background noise. For maximum reliability in ET, a high signal-to-noise ratio is desired. No specific signal-to-noise ratio is mandatory, but a minimum of 3-to-1 is desirable for flaw detection.

4.5.21.6 Signal-to-Noise Ratio and Sensitivity. As the required crack size to be detected is decreased, the gain or sensitivity of the eddy current instrumentation must be increased to provide readable indications from small cracks. The higher gain results in greater indications from small cracks. The higher gain also results in greater response from variables other than cracks and the noise level increases. This decreases the signal-to-noise ratio, making it more difficult to observe the small flaw indication. The decrease in signal-to-noise ratio lowers the reliability of the inspection. Therefore, an increase in gain will increase the amplitude of the flaw signal as well as increase the level of noise. Thus, useful sensitivity must be measured in relation to the noise of the test system.

4.5.21.7 Influence of Frequency on Noise. Increasing the operating frequency for ET improves the sensitivity to near-surface defects, but also tends to increase noise from surface related factors such as lift-off scratches, rough surface, and probe wobble.

4.5.21.8 Suppression Techniques. Suppression techniques are used to eliminate or reduce instrument response to one or more inspection variables to permit better identification of changes in the parameters of interest during eddy current inspection. When the display is rotated as previously indicated, lift-off variations produce little or no signals in the vertical direction. Even though the crack signal is predominately horizontal, it has a significant vertical component. This vertical component can be amplified independently and monitored visually or electronically. A box gate (alarm) can be used to electronically monitor the vertical component of indications and set off visible and audible alarms on the equipment to draw inspector attention. The typical box alarm is a rectangle whose position, height and width can be adjusted to selectively monitor a portion of the impedance plane. Box alarms can be set to trigger when the crack indication signal enters the box (Positive) or when the signal leaves a box (Negative). Where liftoff is horizontal and crack indications are vertical, a “positive” triggered box alarm can be set slightly above the path of the lift-off lines and low enough to be crossed by crack indications. In the example described, defect indications will enter the box alarm over a fairly large area of lift-off conditions while the slight vertical component of these lift-off responses remains outside.

4.5.22 Lift-Off Effects.

4.5.22.1 Sources of Lift-Off Variations. During eddy current inspection, changes in spacing between the probe coil and the inspection surface will cause variations in test coil impedance. These changes in lift-off result from surface roughness, slight contour changes, probe wobble, probe bounce, and inconsistent thickness of nonmetallic coatings, such as paint, primer, and anodic coatings. The magnitude of impedance changes resulting from small amounts of lift-off variations can exceed the response from a crack. Consequently, some means of eliminating or separating this effect must be provided.

4.5.22.2 Lift-Off Suppression. One option for minimizing lift-off effects from the variable to be measured is the use of impedance plane analysis, where the phase direction of the response from the desired variable is separated from the phase direction of signals caused by lift-off variations. This type of analysis can be performed using any of the waveform display instruments that provide amplitude and phase of the signal. The small, meter readout type battery-powered instruments provide only a total amplitude measurement and require some means of lift-off suppression. For these instruments, lift-off compensation is obtained by selection of an off null operating point. The off null operating point is selected to provide equal current flow (meter reading) with the probe on bare metal and at a designated amount of liftoff. ET using small amounts of lift-off compensation or adjustment is also termed intermediate layer technique. The amount of lift-off adjustment is selected to minimize any surface roughness or variation in coating thickness on the part.

4.5.23 Lift-Off Compensation Methods.

4.5.23.1 Impedance Plane Analysis Instruments. Instruments that present the phase and amplitude of the signal on a CRT have phase rotation controls which allow the eddy current signal to be rotated until the phase is in a particular orientation. For instance, the phase can be rotated until the lift-off signals move in a horizontal motion, with increasing lift-off represented by movement to the left or right on the screen. Flaw signals or loss of conductivity will generally be in a vertical direction. The phase angle and amplitude of an indication will depend upon the depth of the flaw and the frequency of the test.

4.5.23.2 Phase Adjustment. In eddy current instruments with two-dimensional displays, the signals displayed can be rotated to align the direction of changes caused by the variable of no interest with the horizontal (or vertical, if so desired) axis as shown in Figure 4-49. This is also called phase adjustment and its purpose is to position the response associated with lift-off variations in a direction that does not interfere with the interpretation of responses from variables of interest. The effectiveness of this technique increases as the phase difference between lift-off and the variable of interest increases from 0° to 90°.

4.5.23.3 Lift-Off Effects on Sensitivity. As lift-off increases, sensitivity of the eddy current system decreases. The magnitude of the response from a crack or other defect decreases continuously as the distance between the cracked metal and the probe increases. The typical effect of increasing lift-off on crack response is shown in Figure 4-50. The magnitude of the total response obtained from two cracks is plotted against the controlled thickness of an intermediate layer between the probe and the part.

4.5.23.4 Lift-Off Compensation Effects on Sensitivity. Lift-off must be minimized or compensated for to maintain a known level of sensitivity during an ET. A meter type of eddy current instrument requires some form of lift-off adjustment. Otherwise, slight variations in lift-off would provide strong signals which would completely mask the response from cracks. The magnitude of crack response is considerably reduced by lift-off compensation. The reduction in sensitivity depends upon the particular eddy current system in use. Each system must be set up for the particular application.

4.5.23.5 Phase Response from Cracks. Difference in phase between lift-off response and crack response is essential for the detection of cracks in most applications of ET. Depending on the crack indication on the impedance diagram, the phase angle between lift-off and crack response can be very small. This makes it very difficult to detect the difference between lift-off and probe motion from crack indications. Referring to Figure 4-50, as lift-off increases and/or the frequency decreases, the impedance of the system approaches the air null point, the phase angle between lift-off and the conductivity line decreases. By maintaining a high fill-factor or low lift-off and operating at a high enough frequency, a crack indication (loss of conductivity) can be easily distinguished from lift-off signals because of the larger phase angle. These relationships, as seen on an impedance plane analysis eddy current instrument, are shown in Figure 4-51 for aluminum, titanium and steel alloys. As crack depth increases, the phase angle approaches more closely the phase angle for conductivity changes.

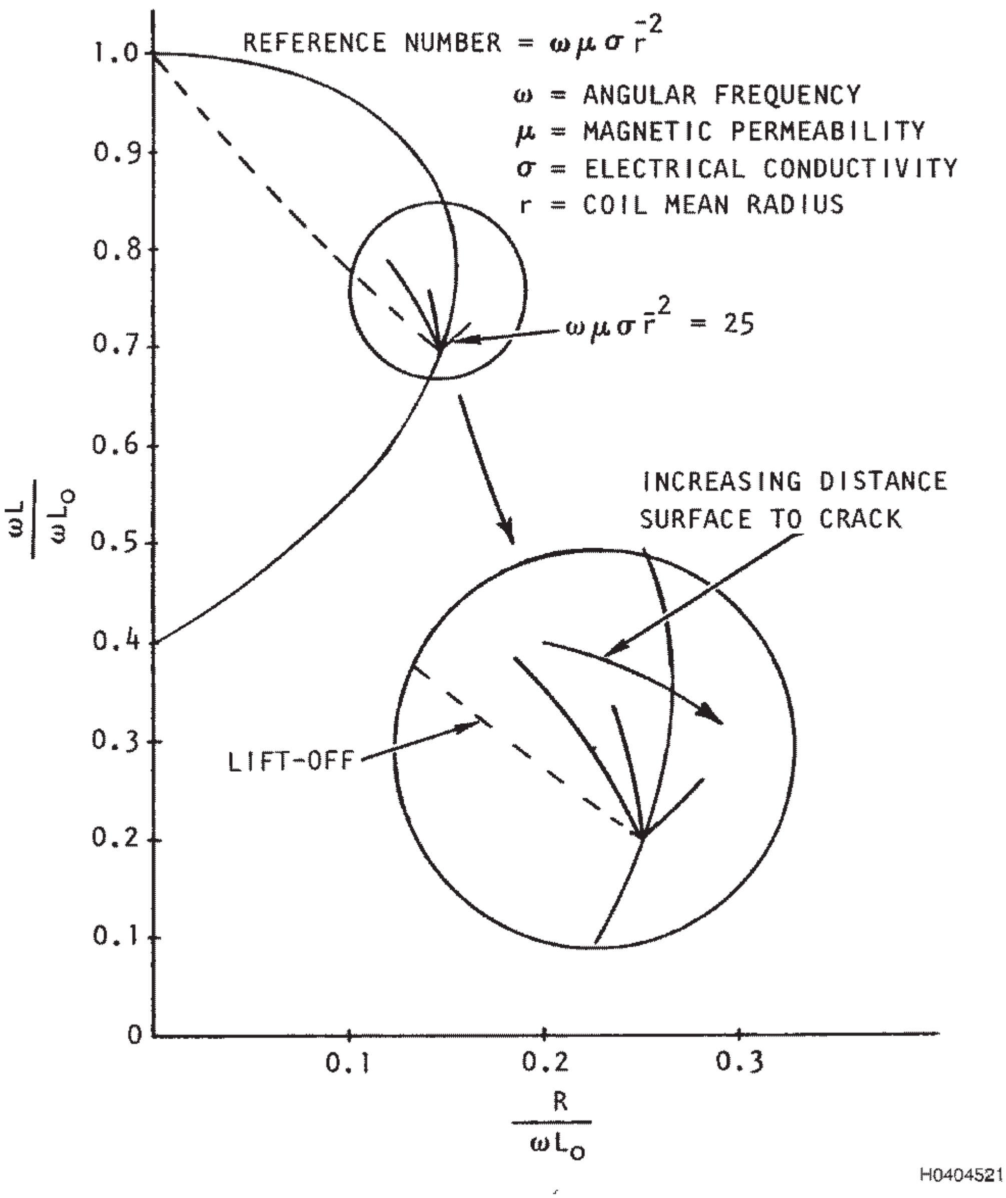

Figure 4-49. Impedance Diagram Showing the Effect of a Crack

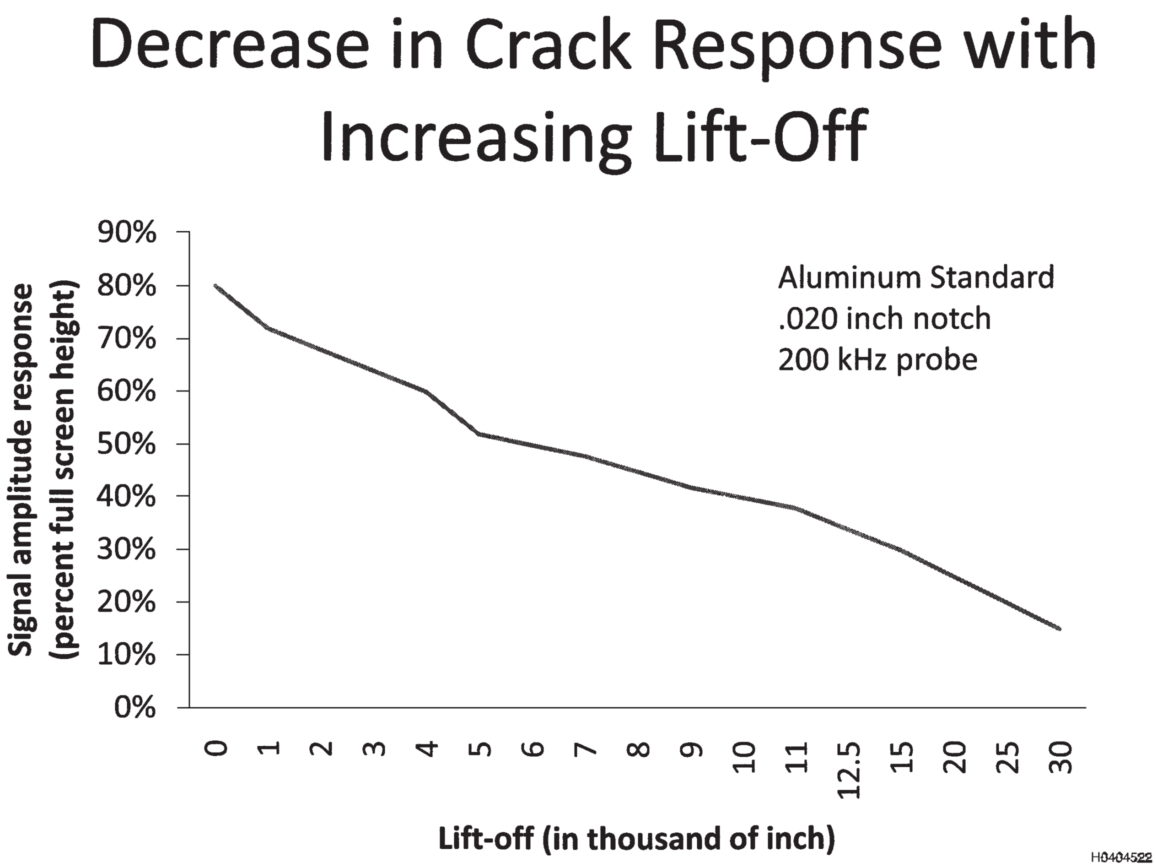

Figure 4-50. Decrease in Crack Response With Increasing Lift-Off

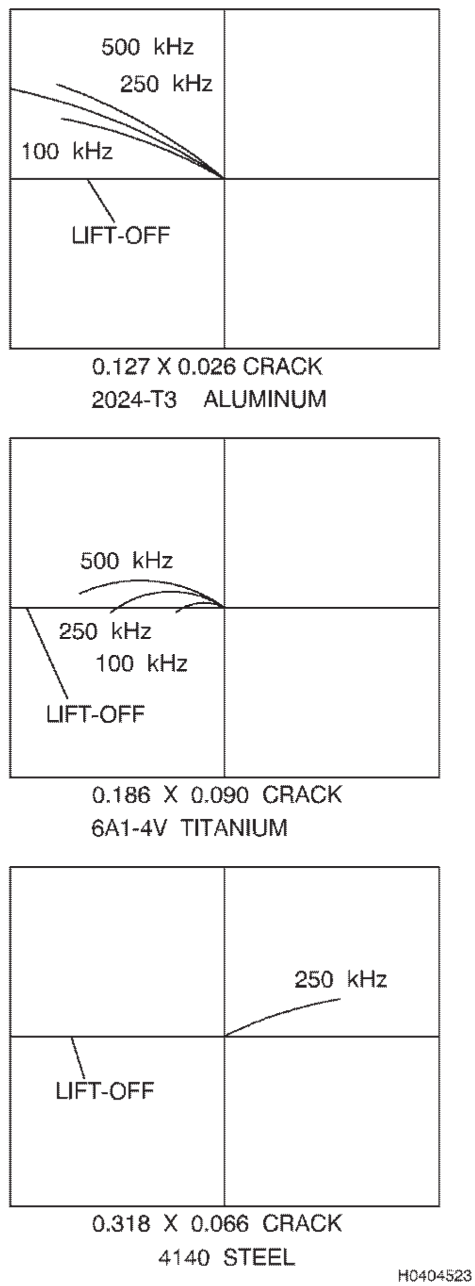

Figure 4-51. Phase Relationship Between Lift-Off and Crack Response for Various Materials and Frequencies

4.5.23.6 Ferromagnetic Materials. Variability in permeability can make eddy current inspection of ferromagnetic materials difficult. Permeability and lift-off have approximately the same direction of impedance change in unmagnetized ferromagnetic materials, but there can be very large variations in permeability that are very difficult to compensate. Magnetic saturation can be used to overcome the difficulties presented by permeability effects. In this technique, the material is magnetically saturated by a high DC magnetic field. This reduces the permeability to about 1 and makes it a constant. This results in a relatively low conductivity material, essentially non-ferromagnetic, for ET applications.

4.5.23.7 Phase Discrimination. Each of the variables (lift-off, conductivity, thickness, permeability, and flaws) has a characteristic effect on the net impedance of a coil. The display of the impedance curves caused by changes in the inspection variables can be of great assistance in determining the cause of a change.

4.5.23.8 Probe Wobble. In performing manual eddy current inspection with a surface probe or pencil probe, it is usually impossible to maintain the probe at the same angle, with respect to the inspection surface, as position is changed. In some instances, holders may be fabricated to guide the probe and hold the angular relationship with the inspection surface. The angular change between the probe and the inspection surface is termed probe wobble. Probe wobble results in changes in lift-off shown in Figure 4-52. The amount of lift-off obtained because of changes in probe angle depends on the diameter and shape of the probe tip. Rounded tips of small diameter probes result in less lift-off than flat tipped probes with larger diameters. On impedance display instruments, lift-off effect can be lessened by changing the vertical to horizontal gain ratio.

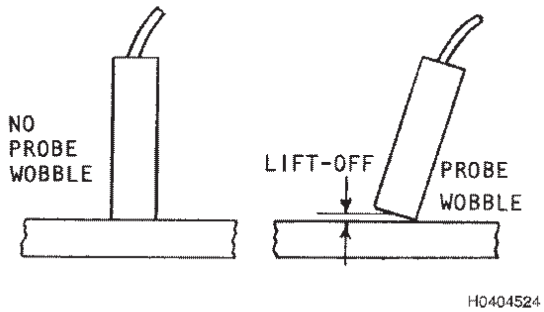

Figure 4-52. Lift-Off Resulting From Probe Wobble

4.5.24 Effects of Crack Location on Detectability.

4.5.24.1 Crack Location and Orientation. Information on the history of cracks in specific inspection sites is very important. Time Compliance Technical Orders (TCTO) are often issued based on problems that have occurred on one or more aircraft systems. This means there is a known problem and inspections are necessary. Precise location of suspect cracks and their orientation produces more reliable inspections. Often, this information is provided from previous history of cracks in the designated locations. In other cases, such information may be determined from knowledge of stress distribution during service. Increasing definition of crack location and orientation permits the inspector to reduce his inspection time. For manual eddy current inspection, reduction in scanning time provides less operator fatigue and consequent improvement in inspection reliability.

4.5.24.2 Cracks at Part Edges. The edge of a part can be represented as an infinitely large crack and, consequently, produces a strong signal during eddy current inspection. The problem in inspecting part edges for cracks is separation of crack response from the strong edge response (edge effect). By fixing the distance of the probe from an edge, edge effect is minimized. Probe guides improve crack detection capabilities on edges.

4.5.24.3 Inspection at Part Edges. Two approaches can be used to inspect for cracks at part edges. The first method is to null the instrument with the probe at the edge of the part. Then, usually with a non-conductive fixture or some other method, the probe is maintained at the edge as it is scanned along the edge. If this position can be maintained, the inspection can be done with greater sensitivity than is possible with the same instrument and probe away from the edge. The second approach is to use a shielded probe, thus minimizing response from edges.

4.5.24.4 Fixtures and Holders for Edge Inspection. One of the simplest methods for eddy current inspection adjacent to a linear edge of a part is to tape or hold a straight edge at a predetermined distance from the edge. Nonmetallic straight edges SHOULD be used for this purpose. A simple fixture which can assist in positioning the probe adjacent to an edge is shown in Figure 4-53. This fixture maintains the probe center 1/8-inch from the edge, but closer edge inspection can be obtained by varying the position of the drilled hole.

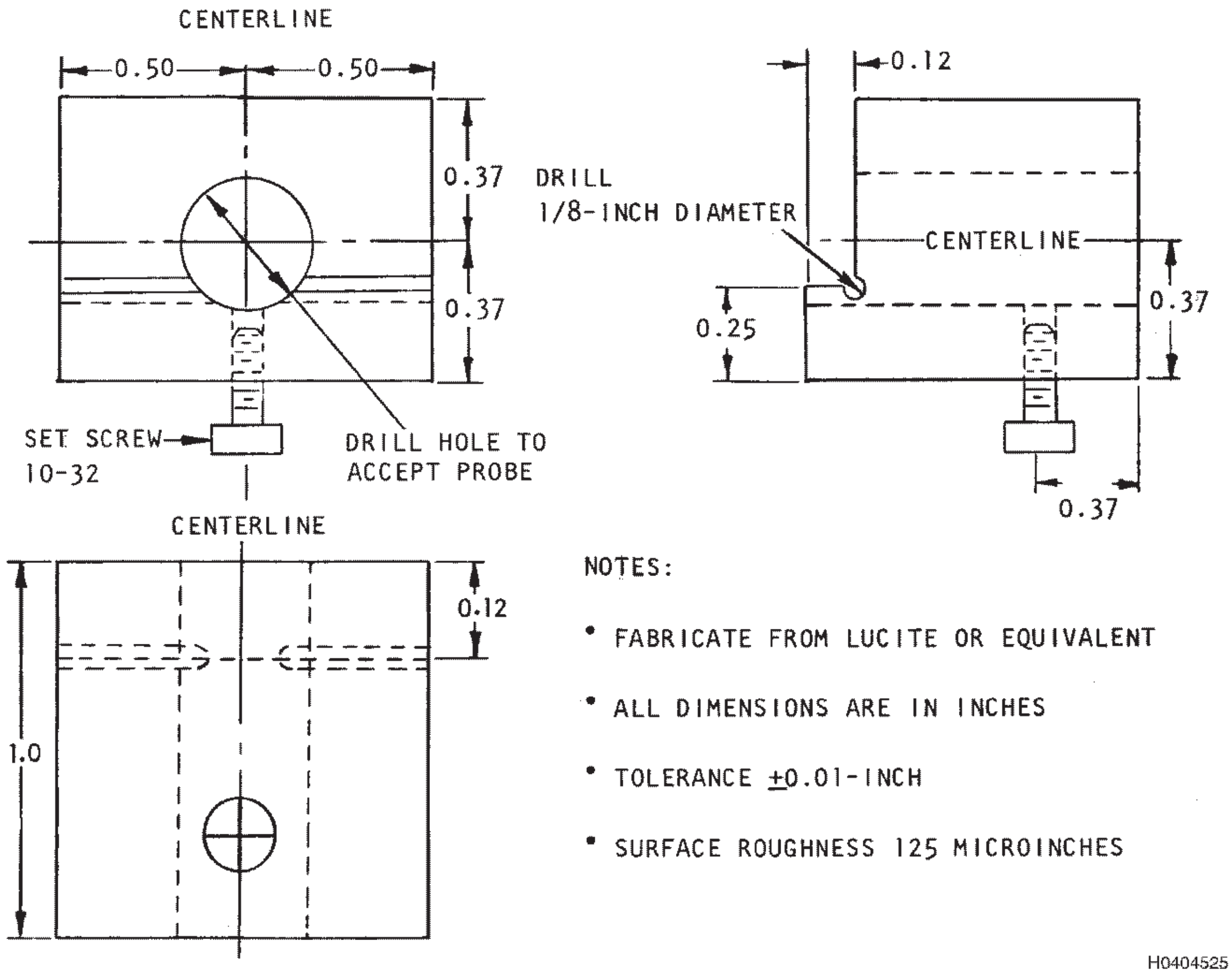

Figure 4-53. Edge Probe Guide

4.5.24.5 Curvature. When small diameter pencil probes are employed, curvature has minimal effect on crack response. This is due to the minimal lift-off effect of the small size of the probe tip. For most applications involving inspection of curved surfaces with small diameter pencil probes, flat standards can be satisfactorily used for curved surfaces in establishing sensitivity requirements.

4.5.24.6 Subsurface Flaw Detection. Increasingly, applications arise where it is desired to inspect for cracks initiating beneath an accessible surface. This could be a crack initiating on the opposite side of the accessible surface, in the structure contacting the opposite surface of an accessible surface, or beneath a conductive coating or plating. ET can be a powerful tool for the detection of subsurface flaws.

4.5.24.7 Impedance Plane Analysis of Subsurface Flaws. If the required frequency is used with impedance plane analysis instrumentation, eddy current penetration to the flaw area can be obtained. The phase and amplitude information received from the flaw can be directly related to the flaw depth.

4.5.24.8 Detection of Cracks under Metallic Coatings. The detection of cracks under metallic plating and coating is similar to detection of subsurface flaws. The magnitude of the total response consistently decreases with increasing coating thickness. With meter type instrumentation with a constant frequency test system, the thickness of plating or coating through which cracks can be detected decreases with increasing plating conductivity and magnetic permeability. In general, decreasing frequency permits detection of larger cracks under thicker coatings because of the increased depth of penetration. Detection of cracks under metallic coatings with phase analysis instrumentation using the impedance plane diagram can be performed with more accuracy and sensitivity than with meter instruments because phase information can be measured. Recent research has shown that multi-frequency eddy current systems may find application for detecting and measuring cracks under metallic coatings.

4.5.25 Effects of Scanning Techniques on Detection.

4.5.25.1 Inspection Technique. Consistent positioning of the probe in relation to edges and interfaces during setup and scanning should be established to ensure maximum response from flaws with minimum interference from other sources of indications. If conditions are known to exist which may result in false indications or which could mask true indications from flaws, these conditions SHOULD be noted in the procedure and a means of interpreting or evaluating the false indications provided. In performing eddy current inspection of an area, the distance between scans or between measurements must be selected to ensure complete coverage for the minimum size flaw or variation in properties to be detected. In determining maximum distance between scans, consideration must be given to the change in magnitude of flaw response as the probe coil center position increases in distance from the center of the crack.

4.5.25.2 Scanning Speed. The scanning speed used in ET for cracks is related to the type of equipment and the inspection technique used. Slower scanning speeds are necessary when the inspector is required to interpret the readout while manually directing the probe in the specified scanning pattern. However, if the high pass filter (HPF) is used during the inspection process, consistent scanning speed is critical to ensure that the signal response received for a flaw is accurate. The HPF may diminish the signal response if the scanning speed is reduced during the evaluation process from the speed used during the initial standardization. The higher the HPF, the more dramatic the change in signal response when scan speed is reduced (Figure 4-54).

4.5.25.3 Scanning Pattern. The scanning pattern required for ET is based on the possible initiation site of the crack, the orientation of the cracks, and the size of the cracks which must be detected. If cracks initiate from an edge in thin material (0.050-inch or so), eddy current inspection is usually limited to a single scan of the edge. For thicker materials, scans might be required on both surfaces adjacent to the edge and one or more scans of the material between the edges. When cracks initiate beneath the heads of non-removable fasteners, the pattern usually consists of a single scan around the protruding head of the fastener to detect cracks growing outward from the hole. If cracks can occur at a variety of positions and orientations, as is possible on flat surfaces, in radii, and on cylindrical surfaces, scanning must be performed in a manner which will assure detection of the smallest cracks required to be found. For these types of inspection areas, the direction of scanning, the number of scans, and the distance between scans SHOULD be specified.

4.5.25.4 Automatic or Semi-Automatic Equipment. Automatic eddy current equipment in conjunction with high speed recorders is capable of operation at extremely high speeds. The upper limits of scanning speed are based on the operating frequency and the sampling rates of the recorder or readout. The principal use for automated eddy current equipment by the military is for the inspection of bolt holes. In this application, rotational speeds of 40-3000 rpm can be obtained by the inspection system.

4.5.25.5 Use of Recorders or Oscilloscopes. The use of recorders or oscilloscopes (CRT type eddy current instruments) permits increasing the speed of manual scanning to the limits imposed by the reaction time of these instruments. Generally, other restrictions related to guiding the probe in the prescribed scanning pattern become the controlling factor when recorders or oscilloscopes are used.

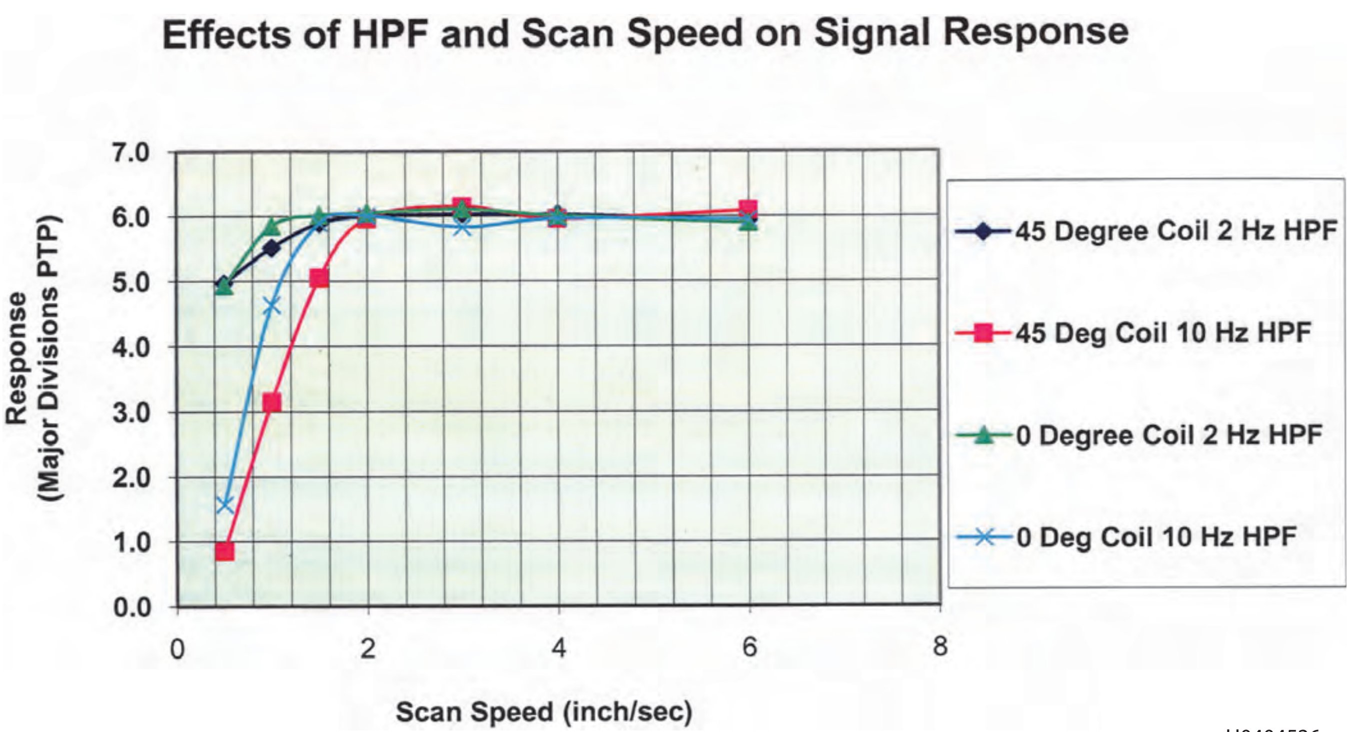

Figure 4-54. Effect of Scanning Speed on Response from a Crack Using Ribbon Coils

4.5.26 Reference Standards for Cracks. There are several different materials undergoing inspection within the Department of Defense. An inspector will find two primary general purpose eddy current standards for aluminum in the field: the Air Force standard, NSN 6635-01-092-5129, P/N 7947479-10 (aluminum) and the Navy standard, PN NRK-3A (aluminum). The aluminum Navy standard has a higher conductivity bottom plate. The Navy also has a kit consisting of three standards of the same geometric configuration, each of a different material (kit PN NRK-3AST, NSN 5280-01-352-1336). This kit consists of:

- One aluminum standard, P/N: NRK-3A, is made of 7075-T651 top & middle layers and a 7075-T73 bottom layer
- One steel standard, P/N: NRK-3S, is made of 4340 alloy on all three layers
- One titanium standard, P/N: 6AL4V, is alloy on all three layers

NOTE

Unless otherwise specified by the weapon system engineering authority, the Air Force general purpose eddy current standard (Figure 4-55, Sheet 1 through Figure 4-55, Sheet 3) SHALL be the common standard used to perform ET's on aluminum components within the Air Force. The standard made to the Navy configuration (Figure 4-56) may be used as a substitute for the Air Force general purpose eddy current standard. When using the Navy standard, calibrate on the long EDM notches for surface inspections and the corner notches in the upper layers for bolt hole inspections unless otherwise directed by a part specific procedure.

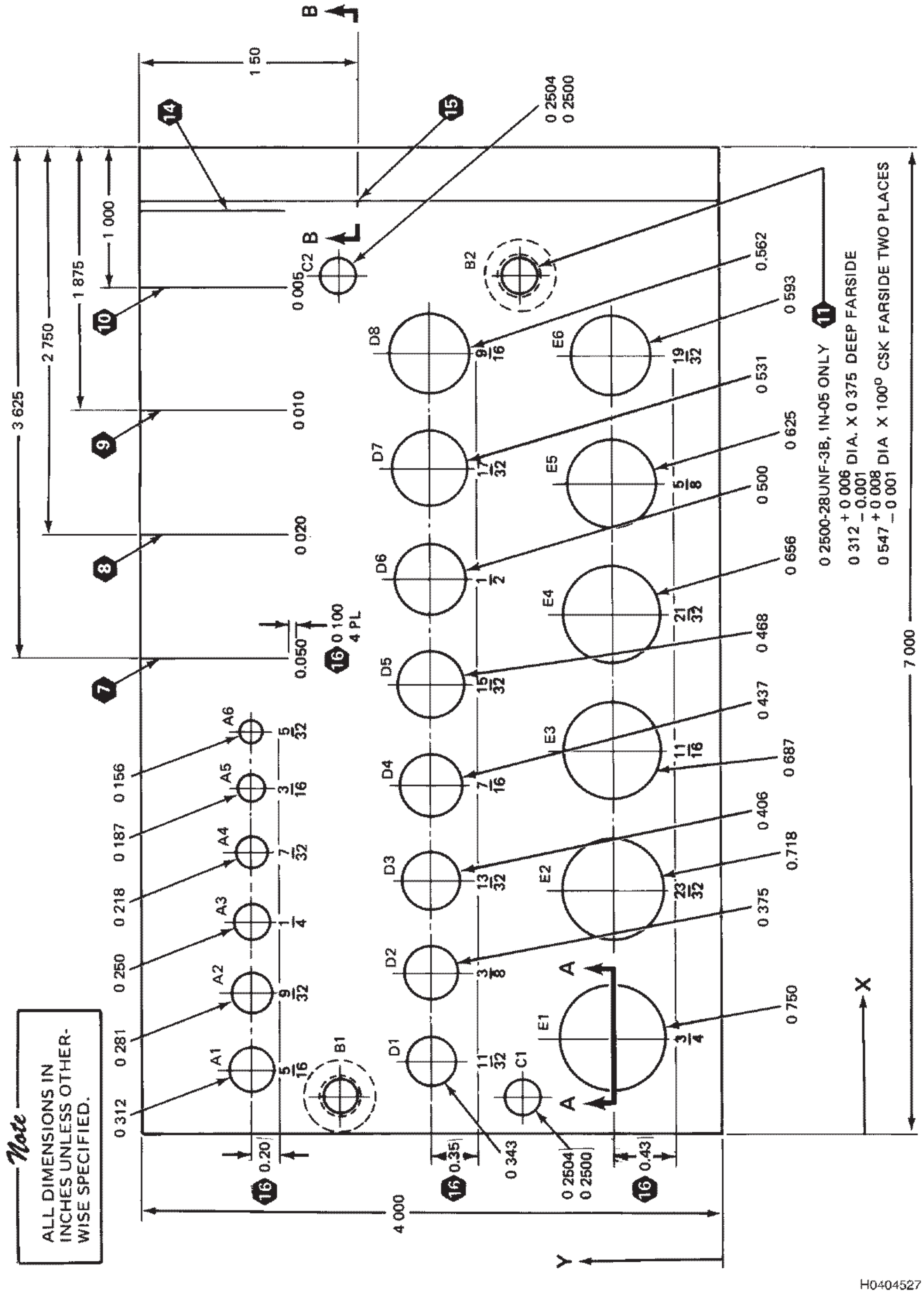

Figure 4-55. Air Force General Purpose Eddy Current Standard (Sheet 1 of 3)

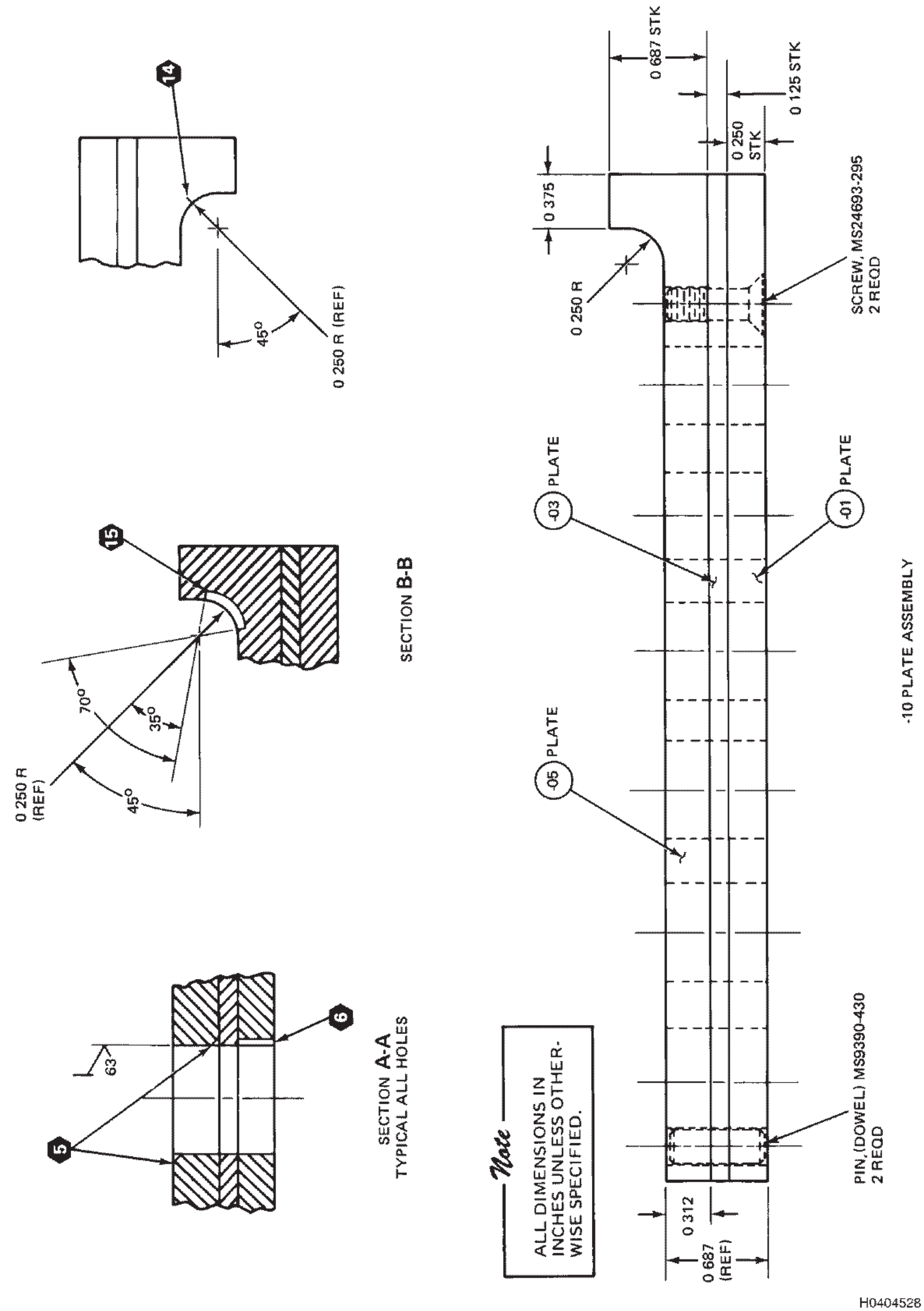

Figure 4-55. Air Force General Purpose Eddy Current Standard (Sheet 2)

Note

1 INTERPRET THIS DRAWING PER MIL-STD-100

2. IDENTIFY PART PER MIL-STD-130

3. BREAK SHARP EDGES EXCEPT AT HOLES AND REMOVE BURRS

(4) FINISH ANODIZE AL ALY PARTS PER MIL-A-8625, TYPE II, CLASS I

(5) ELOX SLOT, 0 030 X 0 030 X 0 004 ± 0 001.

(6) ELOX SLOT, 0 020 X 0 250 X 0 004 ± 0 001

(7) ELOX SLOT, 0 050 X 1 000 X 0 004 ± 0 001

(8) ELOX SLOT, 0 020 X 1 000 X 0 004 ± 0 001

(9) ELOX SLOT, 0 010 X 1 000 X 0 004 ± 0 001

(10) ELOX SLOT, 0 005 X 1 000 X 0 004 ± 0 001

(11) THREADS PER MIL-S-7742

12. SURFACE ROUGHNESS 63√ MAX ALL OVER PER ANSI B46 1-1978

(13) THE EDDY CURRENT METHOD IS USED TO DETECT CRITICAL CRACKS ORIGINATING IN HOLES OF LOWER WING SKIN OF ALL AIRCRAFT

(14) ELOX SLOT, TAPERED 0 200 AT EDGE CORNER TO 0 000 X 1 000 X 0.004 ± 0.001

(15) ELOX SLOT, 0 050 DEEP X 0 004 ± 0 001 AND PERPENDICULAR TO THE RADIUS

(16) MECHANICAL ETCH NUMBERS 0.093 HIGH AS SHOWN.

17 ALL DIMENSIONS IN INCHES UNLESS OTHERWISE SPECIFIED

DRILLING LEGEND

QUANTITY REQUIRED		6	2	2	8	6			
HOLE DIAMETER		~	~	~	~	~			
POSITION		HOLE SYMBOL							
X →	Y ↑	A	B	C	D	E	F	G	H
0 437	3 250	A1							
0 983	3.250	A2							
1 498	3 250	A3							
1 982	3 250	A4							
2 435	3 250	A5							
2 856	3.250	A6							
0.250	2.625		B1						
6.094	1 375		B2						
0 250	1 375			C1					
6.094	2 625			C2					
0 500	2 000				D1				
1 125	2 000				D2				
1 781	2 000				D3				
2.468	2 000				D4				
3 186	2.000				D5				
3 936	2.000				D6				
4.717	2 000				D7				
5 529	2 000				D8				
0 687	0 750					E1			
1 718	0.750					E2			
2 718	0 750					E3			
3.686	0 750					E4			
4 623	0 750					E5			
5 529	0 750					E6			

PARTS LIST

QTY	NOMENCLATURE	PART NO.	MATERIAL/SPECIFICATION
2	SCREW	MS24693-295	
2	PIN	MS9390-430	
1	PLATE	-05	AL ALY PL 0 687 THK QQ-A-250/12. CMPSN 7075, CONDTN T6
1	PLATE	-03	AL ALY SH 0 125 THK QQ-A-250/12 CMPSN 7075, CONDTN T6
1	PLATE	-01	AL ALY PL 0 250 THK QQ-A-250/12 CMPSN 7075, CONDTN T6
	PLATE ASSY	-10	

H0404530

Figure 4-55. Air Force General Purpose Eddy Current Standard (Sheet 3)

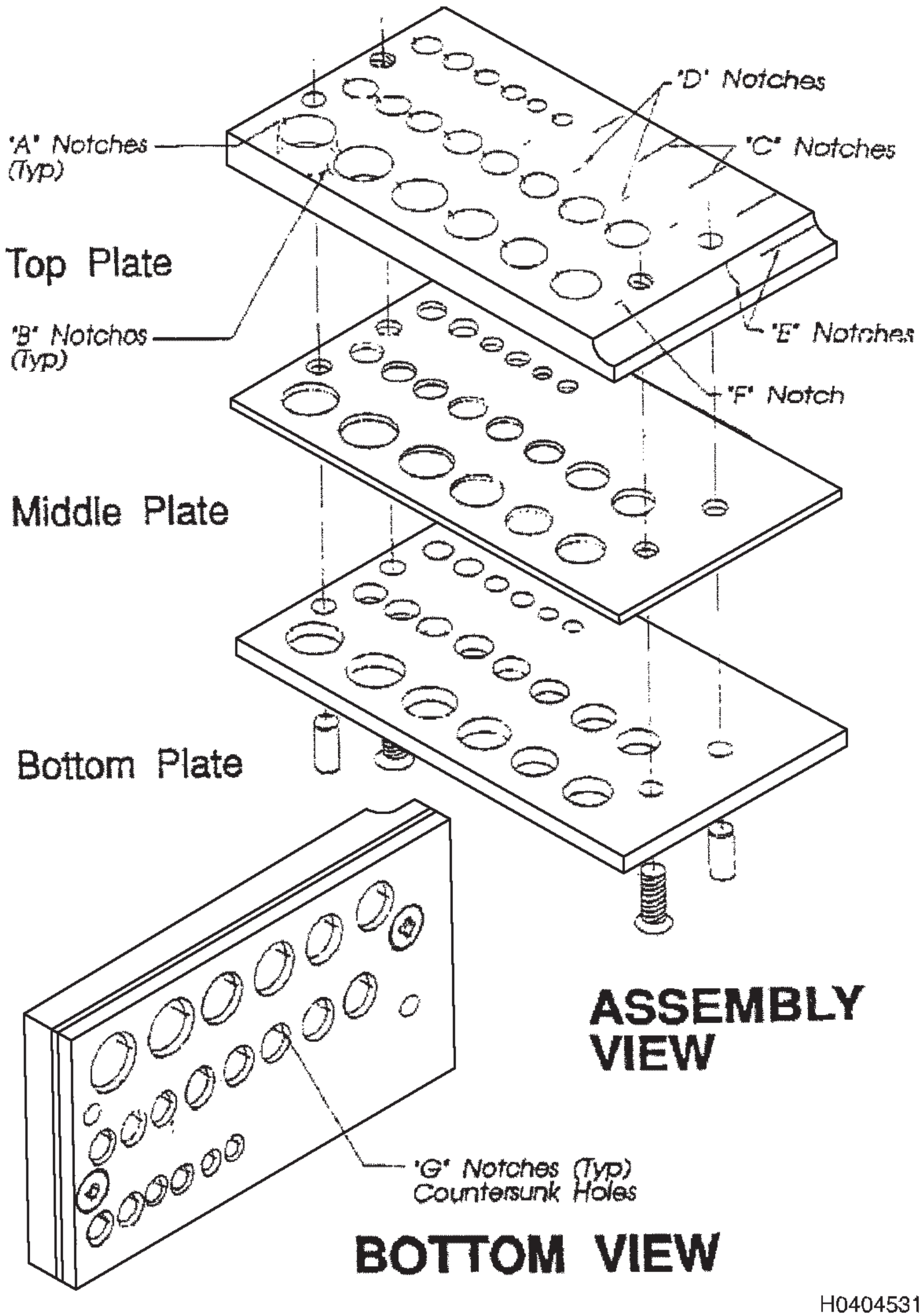

Figure 4-56. Navy Eddy Current Reference Standard (Sheet 1 of 2)

P/N NRK-3AST

Contents:

(1) 7075-T651 top and middle layers, 7075-T73 bottom layer P/N NRK-3A
(1) 4340 Steel P/N NRK-3S
(1) 6AL4V Titanium P/N NRK-3T

Mounted In a Hi-Impact, Waterproof Plastic Case

EDM Notch Location & Size

"A" Notches: .030" x .030" corner notch in each of 20 holes on surface of top plate.

"B" Notches: .030" x .030" corner notch in each of 20 holes on bottom surface of top plate.

"C" Notches: .750" long surface notches; .005", .020", .050" deep.

"D" Notches: .100" long surface notches; .005", .020", .050" deep.

"E" Notches: 1 each transverse radius notch .050" deep & 1 each longitudinal radius notch one inch long and tapered from .050" deep at edge to .000" at inboard edge of notch.

"F" Notches: .030" long notch, .010" deep.

"G" Notches: .250" long notch, .020" deep in 20 countersink holes.

All notches are certified at .004" +/- .001" width.

H1211408

Figure 4-56. Navy Eddy Current Reference Standard (Sheet 2)

4.5.26.1 Cracks as Reference Standards. When an eddy current instrument is setup for detection of cracks, some means must be provided to assure that the sensitivity of the test system is sufficient to detect the smallest required crack size. Ideally, the best standard would be a section of the same material containing a crack of this minimum size. Cracks of specified sizes are difficult to obtain. With few specimens to choose from, such situations are rare. Fatigue cracks of specified size can be grown under laboratory conditions, but this method is extremely expensive. The length of the crack along the surface and its width at the surface is easily measurable. The depth of the crack is generally unknown and must be approximated from other data. Because of difficulty in obtaining actual cracks for reference standards, a number of other standards may be used. These standards are discussed below.

4.5.26.2 Requirements for Reference Standards. The primary requirement for eddy current reference standards is they provide uniformity of response which can be correlated to the condition or material property to be detected or measured. Two fundamental ideas are assumed by uniformity of response. First, this means all tests can be done with the same sensitivity or that different levels of sensitivity can be compared on a quantitative basis. Second, standards fabricated to a specific design should be stable devices able to provide a repeatable response within certain specified limits. To be useful for flaw size and type evaluation, the reference standard must relate to the flaw to be detected. By means of correlation data, prior history or investigation, the response from the reference standard must relate to the response from the condition or material property of the part. To permit fabrication of standards at a number of locations, material, alloy, temper and dimensional tolerances which will provide the required response should be defined in the applicable technical order for the test being performed. Methods of fabrication which use simple tools SHOULD be specified when adequate uniformity and sensitivity can be obtained. Ideally, when an instrument has been adjusted for a specified response from the standard, a signal of approximately the same amplitude and phase (where applicable) should be obtained from the condition or material property with an eddy current instrument and probe of the same general type.

4.5.26.3 Standards for Specific Tests. Standards must be designed for the specific material property or condition being tested. Specific standards are required for each type of test being performed. Calibration standards used to sort alloys must meet very specific conductivity requirements. Calibration standards for measuring coating thickness of conductive coatings would not be suitable for measuring coating thickness of paint or other nonconductive coatings or for detecting cracks around rivet holes. Drilled holes or EDM (electro-discharge-machining) notches in an aluminum block should not be used to test for material thickness or alloy composition of titanium or stainless steel parts.

4.5.26.4 Artificial Defects for Standards. Due to the difficulty of obtaining the types and sizes of real flaws in parts for use as reference standards; a variety of artificial flaws have been developed to simulate the real flaws. Fatigue cracks have been grown under laboratory conditions, but reproducible sizes in sufficient quantity for standards are impractical. Artificial flaws, such as drilled holes, EDM notches, saw cuts, two surfaces clamped together to simulate a crack, or chemically produced conditions to simulate pits or corrosion, can be produced in a variety of ways. Ideally an artificial flaw will produce an eddy current response identical to the response from a real flaw of the same size, orientation, and location. This ideal is seldom achieved with artificial flaws. Estimation of flaw size from the response to artificial flaws must be based upon correlating previous known flaw sizes with the response from the artificial flaws. To maintain the quality of this correlation, it is necessary to carefully specify the material properties and fabrication process of the artificial defect standard.

4.5.26.5 Simulated Conditions for Standards. When using eddy current techniques to measure conductivity, coating thickness, permeability, alloy sorting, and hardness, standards can usually be obtained which represent the materials and conditions being tested. These calibration standards are used for direct comparison to the response seen on the part being tested. Great care must be exercised in handling these types of calibration standards. Scratches, dents, distortion, oxidation, or other conditions can alter the calibration standards making them useless for comparison and calibration purposes. The primary standards are usually maintained under laboratory storage conditions, and may be traceable to the National Institute for Standards and Technology (NIST). The secondary standard, is compared to the primary standard for response; the secondary standards are said to be traceable to the primary standard. The actual testing in the field environment use the secondary (or tertiary) standards and the standards are periodically compared to the primary standard to assure integrity.

4.5.26.6 EDM Notches. Electrically discharge machined (EDM) notches, in a variety of sizes, shapes and locations, can be placed in almost all metals. The width of the notch can be held to as small as 0.003-inch, and although far greater in width than most cracks, this method provides a narrower slot, or notch, than all other fabricating techniques such as saw cuts. Similar responses are obtained on real cracks.

4.5.26.7 EDM Notches in Ferromagnetic Steel. The eddy current signal does not penetrate well in ferromagnetic materials because of the shielding effect of the high magnetic permeability. EDM notches are useful as examples of flaws open to the surface of a part. Surface breaking cracks are best detected by using a very high frequency (500 kHz and greater) which is not meant to penetrate deeply into the part. Under these conditions the test provides very high sensitivity to surface flaws in ferromagnetic materials. Likewise the test provides little if any information on flaw depth.

4.5.26.8 Saw Notches. Probably the simplest method of preparing eddy current standards is by means of a jeweler's saw. With a 7/0 blade, notches as narrow as 0.007 to 0.008-inch can be made in the edge of a standard. Circular jeweler's slotting saws are also available for other notch locations. Phase response is similar to that obtained from cracks. However, as notch width increases, the similarity to a crack decreases.

4.5.26.9 Machined Notches. Standards with machined notches can be used under some test conditions. However, the response of a particular probe size and frequency to the notch must be evaluated for its applicability to a test situation.

4.5.26.10 Choosing Reference Standards for Cracks. As previously discussed, the primary requirement for eddy current reference standards is they provide uniformity of response that can be related to the minimum size crack to be detected. To various degrees, several types of reference standards may meet this criterion. Consequently, such factors as cost, ease of fabrication, availability, and field application become prime considerations.

4.5.27 Thickness Measurement.

4.5.27.1 Criteria for Application.

4.5.27.2 Types of Measurements. In general, three types of thickness measurements may be performed by eddy current techniques. The total thickness of thin metallic products, such as foil, strips and sheets, may be determined when the thickness dimension is less than the effective depth of penetration of eddy currents in the material. A second category of thickness measurement includes the measurement of metallic plating or coating on a conductive or magnetic base. Subcategories of plating and coating measurements can be established on the basis of the relative conductivity or permeability of the plating and the base metal on which it is plated. Typical subcategories of plating measurements include the following:

- Low conductivity plating on high conductivity base
- High conductivity plating on low conductivity base
- Low permeability plating on a high permeability base
- High permeability plating on a low permeability base

4.5.27.3 The terms high and low are relative and are not meant to indicate specific values. The third category of measurement is the determination of nonconductive coating thickness on a metallic base. This application can also be extended to measure the total thickness of thin nonconductive materials that are accessible from both sides, by holding a block of metal against the surface opposite the probe.

4.5.27.4 General Limitations of Plating Thickness Measurement. The use of eddy current techniques for thickness measurement is confined to thin materials. This limitation results from the inability of the eddy current field to penetrate deeply into conductive materials. The effective depth of penetration, and therefore the thickness that can be measured, decreases as the conductivity and/or permeability of the metal increases. To determine the thickness of plating or coatings on metallic substrates, a difference must exist in conductivity or permeability between the surface material and base material. Increased sensitivity is obtained, as the differences between plating and substrate conductivity or permeability become larger. For nonconductive coatings, the sensitivity improves with increasing frequency. Larger probe diameters provide greater sensitivity for measurement of thicker plating. A summary of the effects of an increase in material properties and inspection variables on the sensitivity and range of thickness measurements is presented in (Table 4-8 in paragraph 4.8).

4.5.27.5 Test Systems. A wide variety of specialized equipment is manufactured for thickness measurement. Many such instruments are optimized for one or two types of applications. Examples include instruments designed to measure nonconductive coatings on nonmagnetic metals or instruments for measuring nonmagnetic plating on a magnetic substrate. Because of limited requirements, such specialized equipment is usually not available for use in the field. In most cases, general purpose instruments may be adapted for thickness measurement. Many of the meter type instruments can be used for a wide variety of thickness measurement operations. Impedance plane analysis equipment is very useful for thickness measurement. Phase change is nearly linear with increasing depth of penetration, thereby providing more consistent sensitivity and accuracy over the entire range of measurement.

4.5.27.6 Thickness Measuring Procedures. Before thickness measurement can be performed, the eddy current measurement procedures SHALL be carefully established and proven to ensure accuracy and reliability. Curves SHOULD be prepared to relate instrument readings to known thickness standards. A sufficient number of samples within the thickness range to be measured must be used in preparing the curves to ensure that a smoothly increasing or decreasing curve will be obtained. The type and number of standards necessary for instrument standardization SHALL be defined. The limitations of the procedures in terms of material and dimension applicability SHALL be established and noted in the procedures.

4.5.28 Measurement of Total Metal Thickness.

4.5.28.1 Applications of Total Thickness Measurement. The primary use of eddy current techniques for measuring the total thickness of metal parts is to detect corrosion on the far sides, or between layers of structure. However, this technique can also be used to establish the thickness of a thin sheet, to determine wear or thinning of sheet materials, and to measure thickness, erosion, or corrosion of tubing walls. Thickness measurement with ET is generally used when:

- calipers or other mechanical measurement is impractical
- ultrasonic equipment is not available
- if very thin materials are to be measured

4.5.28.2 Total Thickness Limitations. The accuracy and range of metal thickness measured with ET are dependent upon the electromagnetic properties of the material and the test system. Increasing conductivity and magnetic permeability increase accuracy in measuring very thin specimens, but decrease the effective range of measurement and the accuracy at greater depths. Therefore, at a specified frequency, you can measure thicker metals that have low conductivity and/or low magnetic permeability compared to metals that have high conductivity and/or high permeability.

4.5.28.3 Frequency Effects in Total Thickness Measurement. Just as decreasing frequency increases the depth of penetration of eddy currents in a conductor, decreasing frequency also increases the thickness of a metal that can be measured by ET techniques. Higher sensitivity is obtained for the thinnest specimens with a higher frequency. For thicknesses (over 0.050-inch), the lower frequency provides greater sensitivity and greater overall penetration. Sensitivity in any thickness range can be determined by slope of the plotted thickness line: the greater the slope (ordinate over the abscissa) the better the sensitivity. Optimum frequency can be estimated by using the formula for one standard depth of penetration.

4.5.28.4 Effects of Probe Construction. Probes designed specifically for thickness measurement have air cores, and are generally larger in diameter than the ferrite core probes used for flaw detection. Larger diameter probes average thickness measurements over a larger area. Smaller diameter probes, and probes with ferrite cores, reduce the area of measurement, and therefore can be used in smaller areas and closer to edges. The larger air core probes can provide greater sensitivity for thickness measurements than the ferrite core pencil probes.

4.5.28.5 Operating Procedures for Total Thickness Measurement. All thickness measuring SHOULD be performed in accordance with pre-established procedures. In general, these procedures will include the following steps:

a. Prepare part for thickness measurement.

b. Establish the presence of geometrical factors, which will limit or restrict thickness measurement.

c. Select appropriate test system, probe, and operating frequency.

d. Develop or verify a calibration curve by using either NIST traceable calibration standards or using known thickness reference standards to setup the test system.

e. Perform thickness measurements at designated points.

f. Record thickness and report all rejectable values as required by the written procedure.

NOTE

When measuring thickness using ET, ensure the probe and the part being measured are kept far enough away from any other metal that the eddy currents are not affected. Metal standards on metallic table tops should be avoided because of conductive interference.

4.5.28.6 Prepare Part for Thickness Measurement. Many thickness measurements must be performed through nonconductive coatings such as paint or anodic coatings. Lift-off compensation must be used during the calibration. Any loose foreign material SHOULD be removed from the surface where thickness is being determined. Any sharp edges, protrusions, or chemicals that are potentially damaging to the probe SHOULD be removed.

4.5.28.7 Presence of Geometrical Limitations. Prior to measuring thickness by eddy current techniques, the presence and position of any structural features that could restrict accessibility or reduce accuracy of measurement must be established. Thickness measurement must be performed sufficiently far away from fastener and other conductive objects to prevent its influencing the meter reading. Limited access may restrict the type of probe to be used. In most cases, written inspection procedures will define geometrical limitations.

4.5.28.8 Selection of Test System. The test system selected for thickness measuring must be based on thickness measuring requirements, frequency of the eddy current instrument, and the types of probes available.

4.5.28.9 Selection of Test Frequency for Thickness Measurement. For each thickness measurement task to be performed by eddy current techniques there is an optimum frequency or range of frequencies that will provide optimum sensitivity at the depth to be measured. The product of the material conductivity in percent IACS and the relative magnetic permeability is plotted along the vertical axis, and frequency in kilohertz is plotted along the horizontal axis. Lines representing optimum thicknesses are plotted on the graph. To determine the recommended frequency, the product of material conductivity and relative permeability of the material to be measured is found on the vertical axis. Follow this point horizontally to the diagonal line representing the thickness to be measured. The recommended frequency is found on the horizontal axis by extending a line vertically downward from the established point. Considerable variation from this frequency value will still provide sufficient sensitivity for most applications. When in doubt, the adequacy of a frequency may be determined by establishing a trial calibration curve.

4.5.28.10 Instrument Setup. Because the general-purpose instruments are not specifically designed for thickness measuring, correlation must be established between instrument readings and thickness dimensions. Therefore, the thickness ranges over which measurements are to be performed SHOULD be defined as closely as possible to minimize the number of data points to be established. Where applicable, lift-off compensation should be used to minimize the effects of variations in surface finish on thickness readings.

4.5.28.11 Record Thickness and Report Rejectable Values. Most written procedures provide acceptance limits for the thickness dimension. When a rejectable value is obtained, it is advisable to recheck the instrument using the reference or calibration standards. The written procedure usually provides methods for reporting rejectable values.

4.5.28.12 Standards for Total Thickness Measurement. The standards used for setup for thickness measurement must have the same electrical conductivity, magnetic permeability, and geometry as the material being measured. The same electrical conductivity is usually obtained by requiring the standards to be fabricated from the same alloy and temper as the inspection material. In magnetic materials, permeability can vary to such a degree within a single alloy and temper that selection of representative standards can be difficult. The high permeability of iron and ferromagnetic steel restricts the use of eddy current thickness measurement to very thin metals. The curvature of the standards SHOULD be the same as the part being inspected. All standards SHOULD be uniform in thickness and the accuracy of the standard thickness SHOULD be at least 10 times that required for the accuracy of the thickness measurement. For example if thickness measurement is required to the nearest 0.001-inch, the standards SHOULD be accurate to the nearest 0.0001-inch. All standards SHOULD be clearly identified with alloy, temper and thickness.

4.5.28.13 Accuracy of Thickness Measurement. The accuracy obtained in metal thickness measurement varies widely depending on material properties, thickness, frequencies used, and system noise level. With higher frequencies (500 kHz and up) on thin materials (0-010-inch and less), thicknesses may be measured to the nearest 0.0001-inch. As frequencies are lowered and thicknesses increase, accuracy decreases. For maximum accuracy, variations in lift-off, conductivity, geometry and magnetic permeability must be reduced to the lowest possible level.

4.5.29 Application of Conductive Coating Measurement. ET techniques are commonly used to measure the thickness of conductive plating on metallic materials. These measurements may be used as a process control to determine the proper thickness of plating or conductive coatings has been applied to a substrate. The thinning of such plating and coatings, because of erosion or corrosion, can also be established. ET is sometimes used to determine the presence and thickness of surface layers which have been altered in composition from the metal deeper within the part. This application includes the measurement of carburized cases in steel and the depth of oxygen or hydrogen contamination of the surface layers of titanium alloys. The absorption of carbon into the surface layers of steel effectively lowers the magnetic permeability. The solution of hydrogen and oxygen in the surface of the titanium alloy lowers the conductivity of the surface. The amount of surface contamination can be measured by measuring the changes in permeability and conductivity.

4.5.29.1 Effect of Material Properties on Plating Thickness Measurements. Although the depth of penetration of eddy currents in metals decreases with increasing electrical conductivity, lack of penetration for measuring plating thickness is seldom a problem. Plating and coating thicknesses rarely exceed 0.005-0.010-inch and in many instances are less than 0.003-inch thick. The sensitivity of inspection is controlled to a large measure by the difference in conductivity and/or magnetic permeability between the base metal and the plating. Coating or plating thickness measurement is considered feasible if the product of conductivity and permeability for the base metal and the coating have a ratio of 1.5 or greater or 0.67 or less. Sensitivity increases as the difference in the conductivity or permeability value between coating and substrate increases. Therefore, a rough determination of sensitivity can be obtained from an impedance curve, which shows the positions of substrates and coating at the frequency and probe size used for inspection.

4.5.29.2 Effect of Test Conditions on Plating Thickness Measurement. Normally, the frequencies used for plating thickness measurement are relatively high, 100 kHz and greater in specialized equipment; frequencies as high as 6 MHz are available. These frequencies provide high sensitivities for very thin coatings. As the conductivity differences between plating and base metal decrease, the frequency may be either increased or decreased as necessary to obtain equivalent sensitivity for the thickness to be measured. Considerable latitude from these approximate values may be exercised in choosing the actual operating frequency. If doubt exists, a trial calibration curve should be prepared. To reduce the effects of surface roughness and variations in nonconductive coatings, lift-off compensation (intermediate layer technique) SHOULD be used. Generally, 0.002 to 0.003-inch lift-off compensation is sufficient unless very rough surfaces are present in the test area. An increase in probe diameter and the use of air cores rather than ferrite cores has the effect of increasing measuring sensitivity and extending the depth to which accurate plating thickness measurement can be performed.

4.5.29.3 Procedures for Plating Thickness Measurement. An approved written procedure is required for each application of ET techniques for plating thickness measurement. Each procedure SHOULD include the following steps:

a. Define the objective of the plating or coating thickness measurement. The type of base metal and plating SHOULD be included in the procedure.

b. Clean any foreign material from the inspection area. Even though lift-off compensation is used, excessive build-up of foreign material in excess of lift-off adjustment could lead to significant errors.

c. Select the test system, instrumentation, and probe that will perform the thickness measurement to the required accuracy.

d. Develop or verify calibration curve, and standardize the test system using the specified standards. A calibration curve must be available for each combination of instrument and probe.

e. Perform plating thickness measurements at the designated points. At least three readings SHOULD be taken at each measurement position to ensure accurate and repeatable values. The probe should be held against the part with constant pressure (when available, spring loaded probes can be used to aid in maintaining constant pressure). For curved surfaces, a fixture may be used to maintain the probe normal to the surface. Plating thickness measurements SHOULD be made in areas where the readings are not affected by adjoining structures, edges, or variations in total plating plus substrate thickness that are within the effective limit of penetration.

f. The calibration of the instrument SHOULD be periodically checked against the standards to guard against instrument drift.

g. Check all measured values against the tolerances specified by the written procedure. All abnormal values SHOULD be reported as required by the procedure.

4.5.29.4 Plating Thickness Reference Standards. Reference standards for plating thickness measurements must have the same electrical conductivity, magnetic permeability, and geometry as the part. These requirements apply to both the base material and the plating. Electrical conductivity and magnetic permeability for the base material are usually obtained by using the same alloy and temper for the standards as used in the part. Particular care SHOULD be taken in processing the materials to ensure that similar properties are obtained. The surface finishes of the part and standard SHOULD also be alike. To obtain the same electrical conductivity, magnetic properties, and surface finish for plating on the parts and reference standards, the plating must be performed in baths of similar composition and subject to similar controls. If the plating on the part is stress-relieved prior to thickness measurement, the references SHOULD receive the same treatment. Several methods of determining plating thickness on reference standards can be used. One of these is to carefully measure the thickness prior to plating and again after plating. The difference represents the thickness of the plating which is applied to one side only. A second method is to measure the plating on an adjacent area by sectioning a metallographic specimen. The total thickness of the plating plus substrate must exceed the effective depth of penetration in the part. A total thickness of 2.5 to 3 combined standard depth of penetration is usually considered sufficiently thick. This thickness may be determined by adding the standard depth of penetration in the plating and the substrate at the frequency used. For example, if approximately 0.003-inch thick silver plating on aluminum is to be measured at 200 kHz, the minimum total thickness can be determined as follows:

- The standard depth of penetration of silver at a frequency of 200 kHz is 0.007-inch. Therefore, the 0.003-inch of silver in the plating represents 0.4 standard depth of penetration
- The 2024-T3 aluminum base material must be at least 2.5 - 0.4 = 2.1 standard depth of penetration
- If the conductivity and magnetic permeability of a metal are known, the standard depth of penetration can be determined

4.5.30 Measurement of Nonconductive Coatings.

4.5.30.1 Nonconductive Coatings. A wide variety of nonconductive coatings are applied to military hardware. Primers, paints, and plastics and sealants are widely used to protect metals from corrosion. Anodic coatings are used on metals, particularly aluminum, to prevent surface deterioration. Other oxide coatings provide protection against heat or wear. Boron epoxy laminates increase stiffness and strength. To control the thickness of such nonconductive coatings or to measure their loss during service, ET techniques have been used with a high degree of accuracy.

4.5.30.2 Basis for Measurement of Nonconductive Coatings. The determination of thickness of nonconductive layers or materials is a relative measure of the magnetic coupling between the probe and the underlying conductive material. In other terms, the thickness of a nonconductor is a direct measurement of lift-off or the spacing between the probe and the conductor. Because the properties (electrical conductivity, magnetic permeability, and geometry) of the underlying materials affect the signal detected by the probe, they must be constant or their variation minimized by instrument adjustment. Three requirements for measurement of nonconductive coatings by eddy current techniques are:

- The nonconductive coating must be in intimate contact with a conductive material
- The thickness of the coating must be less than the effective range of the varying magnetic field generated by the probe
- The thickness of the substrate must be at least 2.5 times the standard depth of penetration at the test frequency

NOTE

(NAVY Only) Follow PD-214 instructions for nonconductive coating thickness measurement.

4.5.30.3 Impedance Effects of Nonconductive Coatings. When an eddy current probe is placed on bare metal, the impedance of the coil is changed by an amount that is dependent on the frequency of the oscillating current, the conductivity, magnetic permeability, and geometry of the test part, and the geometry and construction of the test coil. When impedance measuring eddy current instruments are used, the measurement of nonconductive coating thickness is determined from variation in current or voltage across the coil as the coil impedance changes due to increase or decrease in lift-off.

4.5.30.3.1 Influence of Material Properties and Frequency. An increase in the conductivity or magnetic permeability of the base metal or in the operating frequency improves the sensitivity of the thickness measurement of nonconductive coatings.

4.5.30.3.2 Test Systems for Nonconductive Coating Measurement. Nonconductive coating thickness can be measured with almost any ET system. Sensitivity is limited by the frequency attainable with available test instruments. Accuracy and range of measurement are increased with increasing frequency. The size and construction of available probes, and instrument circuit design affect the accuracy of measurement. Accuracy decreases with increases in coating thickness. Sometimes probes are spring-loaded to prevent variations in readings caused by inconsistent pressures.

4.5.30.3.3 Procedures for Measuring Nonconductive Coatings. The following steps SHOULD be followed to perform thickness measurements on nonconductive coatings:

- Establish the range of thickness to be measured and the accuracy required
- Select test system capable of performing required thickness measurement to specified tolerances
- Prepare the part or area for thickness measurement
- Prepare calibration curve or verify calibration curve with existing calibration standards. A calibration curve is required for each combination of instrument and probe and for each base metal
- Perform thickness measurement checking the calibration occasionally with the known calibration standard

4.5.30.4 Standards for Measurement of Nonconductive Coatings. If calibration standards are unavailable, standards for measurement of nonconductive coatings MAY be obtained from a number of sources. Layers of paper, plastic, and tape are three of the most available standards. Standards SHOULD be uniform in thickness and conform to the surface of the bare metal representing the part to be measured. When standards are stacked layers of material, no gaps or pockets should exist between the layers. Standards can also be actual sections of parts with known thicknesses of the nonconductive coating applied. These standards usually require more effort and expense to prepare. When possible, standards SHOULD be measured to an accuracy of 10 times greater than the accuracy required for the measurement of the nonconductive coating. This may not always be possible under field conditions. However, accuracy measuring the standard SHALL be at least 3 times better than the required measurement (e.g., If measurement to ±0.003 is required, the standard must be measured to ± 0.001). Materials soft enough to compress under the pressure of a firmly applied probe should not be used.

SECTION VI INTERPRETING EDDY CURRENT SIGNALS

4.6 ET INTERPRETATION.

4.6.1 Flaw Detection. When eddy currents are induced in a metal in the region of a crack or other flaw, the eddy current flow is distorted. The distortion results in a localized decrease in electrical conductivity. In this manner an ET is able to detect flaws

4.6.1.1 Evaluation of Crack Indications.

4.6.1.1.1 Acceptance Rejection Criteria. In most cases, the depth of flaws detected by ET cannot be directly measured. In almost all cases, the eddy current signal of the flaw must be compared to the eddy current signal produced by the reference standard. The relationship between response to the standard and the corresponding response to the defect size must be established prior to the test and should be considered an essential part of the setup process. Prior to the start of any test, the instrument setup process SHOULD confirm that the test can be conducted with the required sensitivity.

4.6.1.1.2 Conditions Affecting Flaw Evaluation. Inspection for cracks, measurement of conductivity, or hardness can often be complicated by the surface damage, and manufacturing processes. Included in this category are scratches, gouges, pitting, and metal smearing. Severe damage may require refinishing of the area prior to inspection, inspection at a lower sensitivity, or selection of another test method.

4.6.1.1.3 Discontinuities. Discontinuities in an electrically conductive material can also change the circular eddy current flow pattern as shown in (Figure 4-57). Discontinuities include cracks, inclusions, voids, seams, pits, laps, and numerous other material variables related to the production, fabrication and use of metallic parts. The change in the magnitude and distribution of the eddy currents is roughly proportional to the size of the discontinuity intercepted by the eddy currents. Because of the weaker eddy currents at increasing depths beneath the surface, the eddy current response to flaws at or near the surface is greater than the reaction from same size flaws at greater depths.

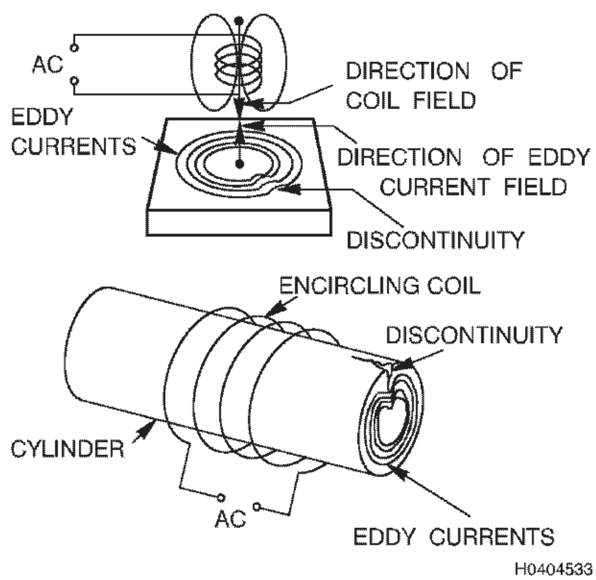

Figure 4-57. Effect of Discontinuities on Distribution of Eddy Currents

4.6.1.1.4 Metal Smearing. Flowing of surface metal may result from machining operations, abrasion during service, or by deformation during assembly or disassembly of an aircraft or component. The depth of smearing in nonmagnetic materials and its metallurgical effects will rarely exceed 0.002 to 0.003-inch. At normal crack detection frequencies, the metallurgical changes created by smeared metal may not affect eddy current response. However, metal build-up and depressions associated with the smearing create changes in lift-off. Because the phase angle is displayed, impedance plane analysis instruments will detect flaws even with changes in lift-off. In ferromagnetic steel, eddy current penetration is very shallow and any blemish of the surface increases the difficulty of inspection.

4.6.1.1.5 Metal Spacing. The spacing of metal sheets separated by a nonconductive adhesive layer can be successfully measured by using an eddy current frequency for which the thickness of both metal sheets is less than, or equal to three times the corresponding standard depth of penetration.

4.6.1.1.6 Scratches, Gouges, and Pitting. Scratches, gouges, and pits may result in eddy current signals similar in magnitude to those from cracks. As test frequencies increase, the sensitivity to scratches tends to increase, because the eddy current field is more concentrated at the surface.

4.6.1.1.7 Rate of Deflection. Rapidity of response with an impedance plane display instrument is also a means of evaluating indications. When traversing a crack, a quick rapid deflection is obtained. Variations in conductivity, gradual thickness changes, out-of-round holes, and variations in edge-to-probe spacing provide a slow, gradual change in measured response. The inspector SHOULD be aware of the rate of change in response from cracks, as contrasted to the rate of signal change from slow changing material properties or test conditions.

4.6.1.1.8 Estimation of Crack Size. Cracks have the three dimensions of length, width, and depth. All three of these dimensions have an effect on the eddy current response from the flaw. In general, the length of the flaw can be related to the distance over which a signal above a specified level is obtained. When the crack is perpendicular to the surface and is less than 2 standard depths of penetration deep, the approximate depth of the crack can be estimated from the eddy current indication. With impedance plane analysis instruments the depth can be determined by the phase angle and amplitude of the indication. The width of the crack also influences the magnitude of the indication. With impedance plane analysis instruments, the signal shape, phase, and amplitude can be used to estimate the depth and area of the crack. In general, a crack will be as deep or deeper than indicated by comparing its ET response to the response from the reference EDM notches.

4.6.2 Effect of Scan Rate and Pattern.

4.6.2.1 Signal Response of Impedance Plane Analysis Instruments. The speed of manual scanning with impedance plane analysis instrumentation does not affect signal response because the system response time is not limited by the response of a meter movement

4.6.2.2 Indications on Storage Oscilloscope or Strip Chart Recorder. The use of a strip chart recorder or storage oscilloscope for recording indications during manual scanning of fastener holes makes evaluation less subjective. Comparison of rate of deflection from indications in the hole and the reference can be observed at the same time.

4.6.2.3 Indications with Automatic Bolt-Hole Scanning. Due to the rough surface of many bolt holes, numerous indications are obtained from causes other than cracks. Indications should therefore be examined carefully to establish if indications could be from cracks or if they are attributable to other causes. Evaluation can be made on the basis of direction of deflection and rate of deflection.

4.6.2.4 Indications from Indexing Automatic Scanners. The controlled rate of scanning obtained with the indexing automatic scanning (rotational/translational scanners) unit provides additional improvement in ease of evaluation. Because of the small scanning increment (pitch of scanner screw), usually 0.025-inch (40 threads to the inch), any crack of significant size will be detected during at least three consecutive revolutions of the scanner. This should result in three or more evenly spaced indications on the strip chart recorder or storage oscilloscope. If crack-like indications are observed, inspect the hole visually to determine if the indications are due to obvious deformations such as metal tears or gouges. Gouge indications, while cyclic in nature, are generally recognized due to the fact such indications usually appear 180-degrees opposite in phase (or polarity) to crack or slot indications. Additionally, a gouge indication will usually not be as sharply peaked as an indication from a crack or slot. Careful study must be made of such indications to ensure that they do not mask an indication of a crack at the bottom of the gouge.

4.6.3 Openings, Large Holes, and Cutouts.

4.6.3.1 Location and Orientation of Cracks. An opening or cutout in a stressed aircraft part serves as a stress riser and a potential source of fatigue cracks and/or stress corrosion cracks. Fatigue cracks initiate at the edges of an opening, hole, or cutout and grow away from the edge at right angles to the direction of stress. Stress corrosion cracking usually occurs in sections subject to either an applied or residual tensile stress. The direction of tensile stresses can often be defined by engineering stress analysis or from the history of previous cracking in the part. This application covers openings for doors and accesses in aircraft skins, cutouts at part edges, and attachment holes too large for bolt-hole probes.

4.6.3.2 Inspection Requirements. If inspection is required only for large cracks (greater than approximately 1/4-inch in length) adequate inspection can usually be performed without special equipment or fixtures. For such cracks, inspection can be performed sufficiently far enough from the edge to avoid interference from edge effects. To detect small cracks, a relatively constant probe-to-edge distance must be maintained. For maximum reliability, a fixture or probe guide is used to establish probe positioning.

4.6.4 Conductivity Measurement.

4.6.4.1 Size and Accuracy of Conductivity Standards. For convenience of transportation and storage, conductivity standards are usually kept relatively small. Standards must have sufficient size to prevent edge effects or thickness from having a bearing on conductivity readings. These requirements can be satisfied by requiring length and width to be 1-inch greater than the probe diameter and the thickness greater than 3.5 times the standard depth of penetration at the test instrument frequency. Standards should be flat, have a surface finish of 63 RMS or better, and be free of any coatings. Standards used for calibrating instruments immediately prior to measuring conductivity SHOULD be accurate within ±0.5% IACS of the nominal value. A second set of standards accurate within 0.35% IACS SHOULD be periodically made available for checking the performance of instruments and field calibration standards. Calibration standards shall be traceable to NIST. Standards are available from manufacturers of eddy current conductivity instruments.

4.6.4.2 Conductivity Range. The conductivity range of the standards must be within the range of the instrument and cover the range of conductivity values to be measured. The calibration blocks shall have the same change in resistivity with temperature as the test parts.

4.6.4.3 Stability of Standards. Excessively high temperatures and sudden changes in temperature can have damaging metallurgical effects on standards. Aluminum alloys are particularly susceptible to thermal shock. Surfaces of standards can also corrode if exposed to moisture or other hostile environments. Damage due to rough handling can cause erroneous conductivity readings. For these reasons, standards shall be transported and stored in dry, clean, protected areas not subject to excessive temperatures.

4.6.4.4 Number of Standards Required. A minimum of two calibration blocks with accurately determined conductivity values must be available for calibration of eddy current conductivity meters. When using general purpose instruments, the number of standards may vary from two to several depending on the inspection purpose and the accuracy required.

4.6.4.5 Inspection Procedures.

4.6.4.5.1 Conductivity Procedure Requirements. Procedures for conductivity measurement should take into account the varieties of environments and test part conditions which might be encountered. In preparing for conductivity measurement, the following steps should be considered:

- Background and objectives of the inspection
- Equipment requirements
- Part preparation
- Instrument calibration including calibration standards
- Conductivity measurement procedures
- Acceptance/rejection criteria

4.6.4.6 Background and Objectives. An understanding of the problem that initiates a conductivity measurement requirement enables the inspector to better interpret inspection results and handle unexpected test conditions. The purpose of the test can be separation of mixed or improper alloy, determination of improper heat treatment, and detection of heat or fire damaged material. The types of material involved and the location of the inspection SHOULD be specifically established. Heat and/or fire damage may be confined to a portion of a part and may vary in the degree of damage. These variables must be considered during conductivity measurement.

4.6.4.7 Part Preparation. As with all types of ET, areas on which conductivity measurement is to be performed must be free of any sharp slivers or foreign material that could damage a probe or cause lift-off changes. Such conditions can be removed with fine emery paper or other approved means. Conductivity measurements can be performed through nonconductive coatings that have thicknesses equal to or less than the amount of lift-off adjustment on meter type equipment. Both the thickness and uniformity of the coating thickness and the amount of lift-off adjustment provided should be checked prior to measuring conductivity through nonconductive coatings. If lift-off adjustment cannot be obtained, correction factors can be determined for uniform coatings by establishing the change in conductivity readings caused by the coating and adding this change to each of the measured values. Non-uniform coatings in excess of lift-off adjustment must be removed prior to measuring conductivity. Excessively rough surfaces SHOULD be smoothed with emery paper to provide a surface finish 250 RMS or better before performing conductivity measurements.

4.6.4.8 Calibration for Measuring Conductivity Values.

NOTE

See WP 407 00 of TO 33B-1-2 for a procedure for digital conductivity measurement.

a. Select a sufficient number of standards to obtain a smooth continuous curve over the range of conductivity to be measured. The actual number of samples will depend on the expected range to be measured and the accuracy required.

b. Adjust the instrument for lift-off, if applicable, and a standard representing approximately mid-range of the conductivities to be measured.

c. Determine the meter or scope readings corresponding to each of the intermediate standards and record the conductivity value.

d. Note each of the values on a graph with meter or scope readings on the vertical axis and conductivity values on the horizontal axis.

e. Construct a smooth curve through all the points. The curve should increase or decrease smoothly throughout the range with no minimum or maximum values. This curve is used to measure conductivity with the specific instrument and probe.

4.6.4.9 Calibration for Separation of Mixed Alloys. To calibrate the general purpose instruments for separating two groups of materials with different conductivity, the instrument is set to obtain readings at one end of the scale for one group of material, and the other end of the scale for the second group of material. Lift-off is usually set on a specimen representing the group with the lower value of conductivity or permeability.

4.6.4.10 Calibration Check. Calibration SHOULD be checked approximately every 10-minutes during continual use and whenever abnormal values are obtained. Whenever an instrument is found to be out of calibration, all measurements performed since the previous calibration verification SHOULD be rechecked.

4.6.4.11 Acceptance/Rejection Criteria. Acceptance/rejection criteria can be found in the applicable TO or material specifications. Acceptable conductivity ranges for many aluminum alloys are shown in (Table 4-7 in paragraph 4.8).

SECTION VII EDDY CURRENT PROCESS CONTROL

4.7 ET PROCESS CONTROL.

4.7.1 General. For maximum reliability in ET, a high signal-to-noise ratio is desired. No specific signal-to-noise ratio is mandatory, but a minimum of 3-to-1 is desirable for flaw detection

4.7.2 Specific. Specific procedures are part of the general set up requirements for inspection published in TO 33B-1-2. To catch weak or defective probes before they are needed for an inspection, new probes SHOULD be tested for adequate performance upon receipt.

SECTION VIII EDDY CURRENT EQUATIONS

4.8 EDDY CURRENT EQUATIONS.

Table 4-1. Common Applications of Eddy Current Inspection

Electrical Conductivity	Magnetic Permeability	Geometry	Material Discontinuities	Lift-Off or Fill-Factor
Alloy Sorting	Alloy Sorting	Metal Thickness	Cracks	Insulation Thickness
Heat-Treat Condition	Heat-Treat Condition		Segregation	Nonmetallic Coatings Thickness
Heat Damage	Case Depth		Seams	Proximity Gage
Plating Thickness	Plating Thickness		Inclusions	Diameter (e.g. of bar stock with encircling coil)
Cladding			Corrosion	
Thickness				
			Porosity	
			Carbon Fiber Breakage	
* Ferromagnetic Materials Only				

Table 4-2. Conductivities of Some Commonly Used Engineering Materials

Metal	Conductivity	60 kHz Probe	480 kHz Probe	Resistivity
	% IACS	Minimum Thickness (Inch)	Minimum Thickness (Inch)	μ Ω cm *
Silver	105	0.028	0.010	1.64
Copper, annealed	100	0.028	0.010	1.72
Aluminum Bronze- 5%, annealed	17	0.068	0.024	10.14
70-30 Brass	28	0.053	0.019	6.16
Cartridge Brass	28	0.053	0.019	6.16
Phosphor Bronzes	11	0.085	0.030	15.68
Phosphor Bronze- 5%, annealed	15	0.073	0.026	11.50
Gold	73.4	0.033	0.012	2.35
Magnesium	37	0.046	0.016	4.66
Magnesium, K60A-0	30	0.052	0.018	5.75
Magnesium, AZ31B- T5	18.5	0.066	0.023	9.32
Nickel, 99.4%	18	0.067	0.024	9.58
Nickel, 99.95%	25.2	0.056	0.020	6.84
Inconel 600	1.7	0.217	0.077	101.43
Monel 400	3.6	0.149	0.053	47.90
Monel	3.6	0.149	0.053	47.90
Zirconium	3.4	0.153	0.054	50.72
Zircaloy-2	2.4	0.182	0.064	71.85
Titanium	3.1	0.160	0.057	55.62
Ti-55A	3.1	0.160	0.057	55.62
Ti-8AI-1Mo-1V	0.87	0.303	0.107	198.20
Ti-6AI-4V	1	0.282	0.100	172.43
430 Stainless Steel	2.9	0.166	0.059	59.46
304 Stainless Steel	2.5	0.179	0.063	68.97
Inconel 600	1.7	0.217	0.077	101.43
Hastelloy X	1.5	0.231	0.082	114.95
Waspaloy	1.4	0.239	0.084	123.17
Platinum, 99.85%	16.3	0.070	0.025	10.60
Cobalt	27.6	0.054	0.019	6.24
Lead, 99.73%	8.4	0.098	0.035	20.65
* micro ohm centimeter				

Table 4-3. Conductivity and Effective Depth of Penetration in Various Metals

Metal	Conductivity	60 kHz Probe	480 kHz Probe	Resistivity
	% IACS	Minimum Thickness (Inch)	Minimum Thickness (Inch)	μ Ω cm *
Silver	105	0.028	0.010	1.64
Copper, annealed	100	0.028	0.010	1.72
Aluminum Bronze- 5%, annealed	17	0.068	0.024	10.14
70-30 Brass	28	0.053	0.019	6.16
Cartridge Brass	28	0.053	0.019	6.16
Phosphor Bronzes	11	0.085	0.030	15.68
Phosphor Bronze- 5%, annealed	15	0.073	0.026	11.50
Gold	73.4	0.033	0.012	2.35
Magnesium	37	0.046	0.016	4.66
Magnesium, K60A- 0	30	0.052	0.018	5.75
Magnesium, AZ31B-T5	18.5	0.066	0.023	9.32
Nickel, 99.4%	18	0.067	0.024	9.58
Nickel, 99.95%	25.2	0.056	0.020	6.84
Inconel 600	1.7	0.217	0.077	101.43
Monel 400	3.6	0.149	0.053	47.90
Monel	3.6	0.149	0.053	47.90
Zirconium	3.4	0.153	0.054	50.72
Zircaloy-2	2.4	0.182	0.064	71.85
Titanium	3.1	0.160	0.057	55.62
Ti-55A	3.1	0.160	0.057	55.62
Ti-8AI-1Mo-1V	0.87	0.303	0.107	198.20
Ti-6AI-4V	1	0.282	0.100	172.43
430 Stainless Steel	2.9	0.166	0.059	59.46
304 Stainless Steel	2.5	0.179	0.063	68.97
Inconel 600	1.7	0.217	0.077	101.43
Hastelloy X	1.5	0.231	0.082	114.95
Waspaloy	1.4	0.239	0.084	123.17
Platinum, 99.85%	16.3	0.070	0.025	10.60
Cobalt	27.6	0.054	0.019	6.24
Lead, 99.73%	8.4	0.098	0.035	20.65

* micro ohm centimeter

Table 4-4. Conductivity and Effective Depth of Penetration in Nonclad Aluminum Alloys

Nonclad Aluminum Alloy	Temper	Conductivity (% IACS)	60 kHz Probe Minimum Thickness	480 kHz Probe Minimum Thickness
1100	T0	57-62	0.037	0.013
3003	T0	44.5-50.5	0.042	0.015
5052	T0	34-37	0.048	0.017
2014	T0	43.5-51.5	0.043	0.015
2014	T3	31.5-35	0.050	0.018
2014	T4	31.5-34.5	0.050	0.018
2014	T6	35.5-41.5	0.047	0.017
2024	T0	46-51	0.042	0.015
2024	T3	28.5-32.5	0.053	0.019
2024	T4	28.5-34	0.053	0.019
2024	T6	36.-40.5	0.047	0.017
2024	T8	35-42.5	0.048	0.017
2048	T8	35-42.5	0.048	0.017
2124	T3	28.5-32.5	0.053	0.019
2124	T8	35-42.5	0.048	0.017
2219	T0	44-49	0.043	0.015
2219	T3	26-31	0.055	0.020
2219	T37	27-31	0.054	0.019
2219	T4	28-32	0.053	0.019
2219	T6	32-35	0.050	0.018
2219	T8	31-35	0.051	0.018
2219	T87	31-35	0.051	0.018
6061	T0	42-49	0.044	0.015
6061	T4	35.5-43	0.047	0.017
6061	T6	40-47	0.045	0.016
6063	T0	57-65	0.037	0.013
6063	T1	48-58	0.041	0.014
6063	T4	48-58	0.041	0.014
6063	T5	50-60	0.040	0.014
6063	T6	50-60	0.040	0.014
6066	T0	42-47	0.044	0.015
6066	T4	34-41	0.048	0.017
6066	T6	38-50	0.046	0.016
7049	O	44-50	0.043	0.015
7049	T73	40-44	0.045	0.016
7049	T76	38-44	0.046	0.016
7050	T0	44-50	0.043	0.015

Table 4-4. Conductivity and Effective Depth of Penetration in Nonclad Aluminum Alloys - Continued

Nonclad Aluminum Alloy	Temper	Conductivity (% IACS)	60 kHz Probe Minimum Thickness	480 kHz Probe Minimum Thickness
7050	T73	40-44	0.045	0.016
7050	T736	40-44	0.045	0.016
7050	T76	39-44	0.045	0.016
7075	T0	44-48	0.043	0.015
7075	T6	30.5-36	0.051	0.018
7075	T73	40-43	0.045	0.016
7075	T76	38-42	0.046	0.016
7178	T0	43-47	0.043	0.015
7178	T6	29-34	0.052	0.019
7178	T76	38-42	0.046	0.016

Table 4-5. Standard Depths of Penetration for Metal Alloys at Various Frequencies

Metal	Conductivity	Standard Depth of Penetration (Inches)											
	% IACS	100 Hz	500 Hz	1 kHz	5 kHz	10 kHz	50 kHz	100 kHz	200 kHz	500 kHz	1 MHz	2 MHz	6 MHz
Silver	105	0.254	0.113	0.080	0.036	0.025	0.011	0.008	0.006	0.004	0.003	0.002	0.001
Copper, annealed	100	0.260	0.116	0.082	0.037	0.026	0.012	0.008	0.006	0.004	0.003	0.002	0.001
Aluminum Bronze 5% annealed	17		0.282	0.199	0.089	0.063	0.028	0.020	0.014	0.009	0.006	0.004	0.003
70-30 Brass	28	0.491	0.220	0.155	0.069	0.049	0.022	0.016	0.011	0.007	0.005	0.003	0.002
Cartridge Brass	28	0.491	0.220	0.155	0.069	0.049	0.022	0.016	0.011	0.007	0.005	0.003	0.002
Phosphor Bronzes	11		0.351	0.248	0.111	0.078	0.035	0.025	0.018	0.011	0.008	0.006	0.003
Phosphor Bronze 5% annealed	15		0.300	0.212	0.095	0.067	0.030	0.021	0.015	0.009	0.007	0.005	0.003
Gold	73.4	0.303	0.136	0.096	0.043	0.030	0.014	0.010	0.007	0.004	0.003	0.002	0.001
Magnesi-um	37	0.427	0.191	0.135	0.060	0.043	0.019	0.014	0.010	0.006	0.004	0.003	0.002
Magnesi-um K60A-0	30	0.475	0.212	0.150	0.067	0.047	0.021	0.015	0.011	0.007	0.005	0.003	0.002
Magnesi-um AZ31B-T5	18.5		0.270	0.191	0.085	0.060	0.027	0.019	0.014	0.009	0.006	0.004	0.002
Nickel 99.4%	18		0.274	0.194	0.087	0.061	0.027	0.019	0.014	0.009	0.006	0.004	0.003
Nickel 99.95%	25.2		0.232	0.164	0.073	0.052	0.023	0.016	0.012	0.007	0.005	0.004	0.002
Inconel 600	1.7				0.282	0.199	0.089	0.063	0.045	0.028	0.020	0.014	0.008
Monel 400	3.6			0.433	0.194	0.137	0.061	0.043	0.031	0.019	0.014	0.010	0.006
Monel	3.6			0.433	0.194	0.137	0.061	0.043	0.031	0.019	0.014	0.010	0.006

Table 4-5. Standard Depths of Penetration for Metal Alloys at Various Frequencies - Continued

Metal	Conductivity	Standard Depth of Penetration (Inches)											
	% IACS	100 Hz	500 Hz	1 kHz	5 kHz	10 kHz	50 kHz	100 kHz	200 kHz	500 kHz	1 MHz	2 MHz	6 MHz
Zirconium	3.4			0.446	0.199	0.141	0.063	0.045	0.032	0.020	0.014	0.010	0.006
Zircaloy-2	2.4				0.237	0.168	0.075	0.053	0.038	0.024	0.017	0.012	0.007
Titanium	3.1			0.467	0.209	0.148	0.066	0.047	0.033	0.021	0.015	0.010	0.006
Ti-55A	3.1			0.467	0.209	0.148	0.066	0.047	0.033	0.021	0.015	0.010	0.006
Ti-8AI- 1 Mo- 1V	0.87				0.394	0.279	0.125	0.088	0.062	0.039	0.028	0.020	0.011
Ti-6AI- 4V	1				0.368	0.260	0.116	0.082	0.058	0.037	0.026	0.018	0.011
430 Stain-less Steel	2.9			0.483	0.216	0.153	0.068	0.048	0.034	0.022	0.015	0.011	0.006
304	2.5				0.233	0.164	0.074	0.052	0.037	0.023	0.016	0.012	0.007
Stainless Steel													
Inconel 600	1.7				0.282	0.199	0.089	0.063	0.045	0.028	0.020	0.014	0.008
Hastelloy X	1.5				0.300	0.212	0.095	0.067	0.047	0.030	0.021	0.015	0.009
Waspaloy	1.4				0.311	0.220	0.098	0.069	0.049	0.031	0.022	0.016	0.009
Platinum 99.85%	16.3		0.288	0.204	0.091	0.064	0.029	0.020	0.014	0.009	0.006	0.005	0.003
Cobalt	27.6	0.495	0.221	0.157	0.070	0.049	0.022	0.016	0.011	0.007	0.005	0.003	0.002
Lead 99.73%	8.4		0.402	0.285	0.127	0.090	0.040	0.028	0.020	0.013	0.009	0.006	0.004

Table 4-6. Standard Depths of Penetration for Clad Aluminum Alloys at Various Frequencies

Clad Aluminum Alloy	Temper	Standard Depth of Penetration (Inches)											
		100 Hz	500 Hz	1 kHz	5 kHz	10 kHz	50 kHz	100 kHz	200 kHz	500 kHz	1 MHz	2 MHz	6 MHz
2014	T6	0.436	0.195	0.138	0.062	0.044	0.020	0.014	0.010	0.006	0.004	0.003	0.002
2024	T3	0.487	0.218	0.154	0.069	0.049	0.022	0.015	0.011	0.007	0.005	0.003	0.002
2024	T4	0.487	0.218	0.154	0.069	0.049	0.022	0.015	0.011	0.007	0.005	0.003	0.002
2024	T6	0.439	0.197	0.139	0.062	0.044	0.020	0.014	0.010	0.006	0.004	0.003	0.002
2024	T8	0.439	0.197	0.139	0.0062	0.044	0.020	0.014	0.010	0.006	0.004	0.003	0.002
2219	T6	0.460	0.206	0.145	0.065	0.046	0.021	0.015	0.010	0.007	0.005	0.003	0.002
2219	T8	0.467	0.209	0.148	0.066	0.047	0.021	0.015	0.010	0.007	0.005	0.003	0.002
6061	T6	0.411	0.184	0.130	0.058	0.041	0.018	0.013	0.009	0.006	0.004	0.003	0.002
7075	T6	0.471	0.211	0.149	0.067	0.047	0.021	0.015	0.011	0.007	0.005	0.003	0.002
7075	T76	0.422	0.189	0.133	0.060	0.042	0.019	0.013	0.009	0.006	0.004	0.003	0.002
7178	T6	0.483	0.216	0.153	0.068	0.048	0.022	0.015	0.011	0.007	0.005	0.003	0.002

Table 4-7. Conductivity and Effective Depth of Penetration for Clad Aluminum Alloys

Clad Aluminum Alloy	Temper	Conductivity Range (% IACS)	60 kHz Probe Minimum Thickness (Inch)	480 kHz Probe Minimum Thickness (Inch)
2014	T6	35.5-44	0.047	0.017
2024	T3	28.5-35	0.053	0.019
2024	T4	28.5-35	0.053	0.019
2024	T6	35-45	0.048	0.017
2024	T8	35-45	0.048	0.017
2219	T6	32-37	0.050	0.018
2219	T8	31-37	0.051	0.018
6061	T6	40-53	0.045	0.016
7075	T6	30.5-36	0.051	0.018
7075	T76	38-42	0.046	0.016
7178	T6	29-34	0.052	0.019

Table 4-8. Effects of Material and Inspection Variables on the Sensitivity and Range of Thickness Measurements

Variable Increased	Sensitivity of Measurement	Range of Measurement
Conductivity	Increases for thin metallic parts and plating. Increases throughout affect range for nonconductive coatings.	Decreases for metallic materials. Increases for nonconductive coatings.
Permeability	Increases for thin metallic parts and plating. Decreases for thick metallic parts and plating. Increases throughout for nonconductive coatings	Decreases for metallic materials. Increases for nonconductive coatings.
Frequency	Increases for thin metallic parts and plating. Decreases for thicker metallic parts and plating. Increases throughout the effective range for nonconductive coatings.	Decreases for metallic materials. Increases for nonconductive coatings.
Probe Diameter	Increases for thicker metallic parts and plating and throughout effective range for nonconductive coatings.	Increases for metallic parts, plating, and nonconductive coatings.

NOTE

The following formulas are used by NDI engineers and inspection developers. Technicians should have a working knowledge of the most basic electrical component equations as presented in the classroom.

4.8.1 Resistance. When DC flows through an element of an electric circuit, or AC flows through a circuit element having negligible inductance (e.g., a straight section of wire or a carbon resistor), the impedance is resistance only and is expressed as:

$$R = E / I$$

Where:
R = Resistance (ohms)

E = Voltage drop across the resistor (volts)

I = Current flowing through circuit (amperes)

4.8.1.1 In an AC circuit containing resistance only (i.e., having negligible inductance), the voltage and the current are in phase. The term "in phase", when used to describe the relationship between the voltage and current, indicates that changes in current occur at the same time and in the same manner (direction) as changes in voltage. Examples of two quantities that are in phase are shown in (Figure 4-58).

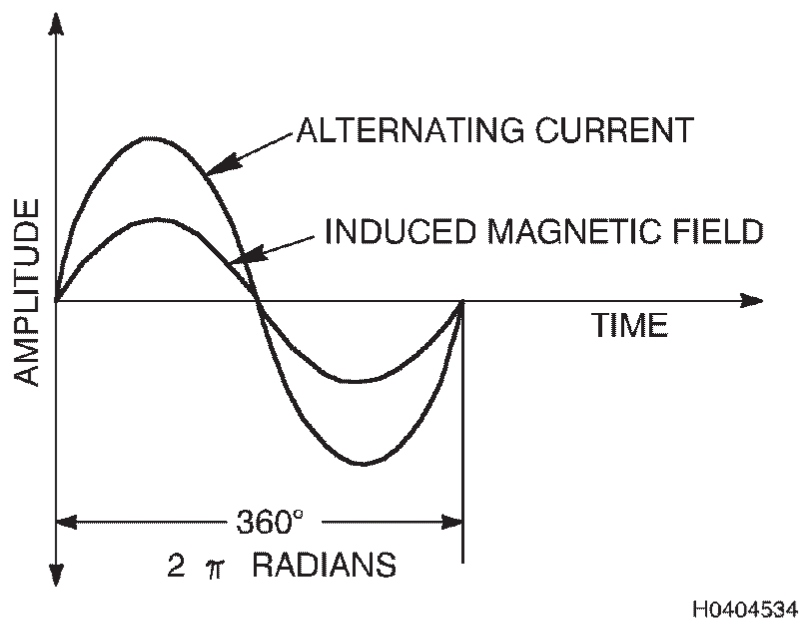

Figure 4-58. Sinusoidal In-Phase Variation of Alternating Current and Induced Magnetic Field

4.8.1.2 Resistance.

$$R = \frac{\ell \rho}{A} ohm$$

Where:

ℓ	=	Length of conductor
ρ	=	Resistivity
A	=	Area (cross sectional) of conductor

4.8.1.3 Resistivity.

$$\rho = \frac{RA}{\ell} ohm\ mm$$

4.8.1.4 Conductivity (inverse of resistivity).

$$\sigma = \frac{\ell}{RA} \quad mho/mm \text{ or } siemen/mm$$

$$1\,mho = \frac{1}{ohm}$$

4.8.2 Inductance. The inductance of an eddy current probe is the result of magnetic field effects of the alternating electric current in the probe. Inductance is a measure of the capability of a circuit to induce current flow in another circuit. It is proportional to the ratio of the magnetic flux linking (encircling) a circuit to the current (I) that produced the flux. When the flux from one inductor is linked to (passes through) another inductor, the inductance is called mutual inductance (M). An electrical transformer is an example of a device where "M" is a significant parameter. For eddy current testing, we consider only the inductance of a single circuit element, specifically, the coil used to sense changes in eddy current flows in test specimens. This inductance is called self-inductance (L).

$$L = \frac{0.8 \times (rN)^2}{6 \times r + 9 \times l + 10 \times b}$$

L	=	in micro-henrys
r	=	mean coil radius
l	=	coil height
b	=	coil wrap thickness
N	=	number of turns

4.8.2.1 Self Inductance. Self-inductance (L) is expressed in "henrys." A "henry" is the inductance by which one volt is produced across a coil when the inducing current is changed at the rate of one ampere per second. A formula for self-inductance expressed in these terms is as follows:

$$L = \frac{E}{(\delta I / T)}$$

Where:

L	=	Inductance (henrys)
E	=	Induced Electromotive Force (volts)
δI	=	Change in Current (amperes)
T	=	Time (seconds)

Because the "henry" is such a large unit, inductance is more commonly expressed in terms of "millihenrys" (1/1000 "henry") or "micro-henrys" (1/1,000,000 "henry"). Typical coils used in ET have self-inductances in the range of 10 to several hundred "micro-henry."

4.8.3 Fill Factor. Is the ratio of the effective cross-sectional area of the primary internal probe coil to the cross-sectional area of the tube interior.

$$\eta = \left(\frac{D_o}{D_i}\right)^2$$

Where:

η	=	Fill factor
D_o	=	Outside diameter of test part
D_i	=	Inside diameter of coil

4.8.3.1 Fill Factor example: if an encircling coil with an internal diameter of 2.25-inches were used to inspect 2.00-inch diameter rod, the fill factor would be:

$$\eta = \left(\frac{D_o}{D_i}\right)^2 = \left(\frac{2.00}{2.25}\right)^2 = (0.889)^2 = 0.79$$

4.8.3.2 For internal coils, electromagnetic (inductive) coupling is determined by the air gap between the external diameter of the coil and the internal diameter being inspected. Fill-factor is calculated using the basic formula, but in this case D_i is the inside diameter of the part and D_o is the outside diameter of the coil placed in the part. For example, if a coil with an external diameter of 1.5-inches is used to inspect tubing with an internal diameter of 1.6-inches, the fill factor is given by:

$$\eta = \left(\frac{D_o}{D_i}\right)^2 = \left(\frac{1.5}{1.6}\right)^2 = (0.9375)^2 = 0.88$$

4.8.4 Inductive Reactance and Capacitive Reactance.

$$X_L = 2\pi f L$$

X_L = Inductive reactance in Ohms
f = frequency in hertz
L = inductance in henrys

$$X_C = \frac{1}{2\pi f C}$$

f = frequency in hertz
C = capacitance in Farads
X_C = capacitive Reactance in Ohms

4.8.5 Impedance. Impedance is the opposition to current flow and is a two-dimensional parameter consisting of resistance and reactance. Resistance is the opposition to the flow of both direct and alternating current. Reactance is the opposition to flow of alternating current only. Reactance can be either capacitive or inductive. Both resistance and reactance are measured in ohms. Of primary interest in ET are resistance and inductive reactance, the latter due to inductance of a coil. Capacitive reactance becomes significant in only a few cases and will be discussed later. The impedance of a test coil is related to the current flow in and voltage drop across the coil as follows:

$$Z = \frac{E}{I}$$

Where:

Z	=	Impedance of coil (ohms)
E	=	Voltage drop across the coil (volts)
I	=	Current through coil (amperes)

4.8.5.1 Impedance formula:

$$Z = \sqrt{R^2 + (X_L - X_c)^2}$$

4.8.6 Permeability.

$$\mu = \frac{B}{H}$$

Where:

μ	=	permeability
H	=	magnetizing force oersteds or amp – turns
B	=	flux density in Gauss or Tesla (10000 G = 1 T)

4.8.6.1 Relative Permeability:

$$\mu_{rel} = \frac{B}{H\mu_o}$$

Where:

μ_o of free space = $4\pi \times 10^{-7}$
Ferromagnetic $\mu_{rel} >> 1$
Paramagnetic $\mu_{rel} \geq 1$ Nonferrous
Diamagnetic $\mu_{rel} < 1$ Au, I

4.8.7 Depth of Penetration (δ).

$$\rho = \frac{172}{IACS}$$, resistivity in micro-ohm cm

$$\delta = 660 \sqrt{\frac{1}{IACS \times \mu \times f}}$$, depth of penetration in mm

$$\delta = 26 \sqrt{\frac{1}{IACS \times \mu \times f}}$$, depth of penetration in inches

$$\delta = 1.98 \sqrt{\frac{\rho}{\mu \times f}}$$, depth of penetration in inches, using resistivity in micro-ohm cm.

4.8.7.1 Frequency necessary for one standard depth:

$$f = \frac{676}{\mu \times IACS \times \delta^2}$$

Where:

f	=	frequency in Hertz, Hz
μ	=	relative permeability
$IACS$	=	conductivity as a percentage of the conductivity of copper
δ	=	the standard depth of penetration in inches

4.8.7.2 Phase Lag at one Standard Depth:

$$\theta = \frac{Depth}{\delta} \times 57^\circ$$

Phase lag on impedance diagram is

2 times θ, signal down and
back at 1δ phase lag is 114°

4.8.8 Limit Frequency, f_g, and the "Similarity" Law.

$$f_g = \frac{5066}{d^2 \mu\sigma}$$

$$\sigma \cdots = conductivity = {}^{m}\!/_{ohm \cdots mm^2}$$

d	=	diameter of test object in cm
f	=	frequency I Hz
μ_{rel}	=	relative permeability

4.8.9 Characteristic Frequency. f_g is lowest frequency where eddy currents are induced in a material. Where frequency and conductivity for one material is known, the frequency for "similar" phase separation can be calculated for another material of known conductivity.

$$f_1 \times \sigma_1 = f_2 \times \sigma_2$$

4.8.10 Coverage of Coil or Effective Coil Diameter.

Unshielded	=	coil diameter + 4δ
Shielded	=	coil diameter
δ	=	Standard depth of penetration

4.8.11 Calculating Flaw Frequency for Setting Filters. Assume flaw is infinitely narrow compared to coil:

- For scanning across a surface, surface speed is how fast the probe is moved across that surface
- For a rotating bolt-hole inspection, surface speed depends on the rotational speed of the scanner and the diameter of the probe. Surface speed may be calculated as follows:

$$\textbf{Flaw Frequency} = \frac{\text{Surface Speed}}{\text{Effective Coil Diameter}}, H_z$$

$$\textbf{Surface Speed} = \textbf{Scanner RPM} \times \Pi \times \textbf{Probe Diameter}$$

4.8.12 Measurement of Conductivity. Formula: σ = L/RA = 1/ρ; therefore, R = ρL/A

Where:

σ	=	electrical conductivity (mhos/unit-length)
L	=	length
R	=	resistance (ohms)
A	=	cross-sectional area
ρ	=	resistivity (ohms–unit-length)

SECTION IX EDDY SAFETY

4.9 EDDY CURRENT SAFETY.

4.9.1 Safety Requirements. Safety requirements SHALL be reviewed by the laboratory supervisor on a continuing basis to ensure compliance with provisions contained in AFI 91-203 or appropriate service directive as well as provisions of this technical order and applicable weapons systems technical orders. Recommendations of the Installation Bioenvironmental Engineering Office and the manufacturer regarding necessary personnel protective equipment SHALL be followed.

NOTE

AFI 91-203 or appropriate service directive, and equipment manuals SHALL be consulted for additional safety requirements.

4.9.2 General Precautions. Precautions to be exercised when performing eddy current inspection include consideration of exposure to electrical current. The following minimum safety requirements SHALL be observed when performing eddy current inspections:

4.9.2.1 Most eddy current units can operate safely in the Class I, Division 2 environment. This environment is identified in NFPA 70, *National Electrical Code*. It is recommended that probe changes be performed outside this environment.

4.9.2.2 Most eddy current instruments are NOT rated as "explosion proof" and not rated for use in the Class I, Division 1 environment.

4.9.2.3 Batteries, power cord, and charger/adaptor are provided with most eddy current instruments. Ensure the correct batteries, charger/adaptor, and power cord are used to avoid damage to instruments or serious injury to the user.