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MILITARY HANDBOOK

EDDY CURRENT TESTING

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2.0 SAFETY NOTICE

Eddy current testing uses high-frequency electrical circuits. Therefore, standard safety practices associated with electrically operated devices should be observed. Eddy current testing does not present any other known unique safety hazards to personnel. See Section 2.8 for additional comments on safety.

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2.1 INTRODUCTION

Eddy current testing is one of the standard nondestructive testing methods. It uses electromagnetic fields and is very sensitive to many material and geometric variables. Because it is an electromagnetic test, its signals move with the speed of light, and its measurements can be made very quickly. Being electrical in nature, eddy current testing can easily be automated and its signals can be used to control other electrical devices. Because the sensing devices are coupled to the test specimens through electromagnetic fields, the devices do not have to contact the test specimen. Eddy current testing can even be used in a vacuum. For these and other reasons, eddy current testing is extensively used throughout the industrial world.

This chapter provides the fundamental principles and guides associated with eddy current testing. It includes the theory of operation, the type of equipment, the advantages and disadvantages of the method, various applications and standards, and guides for specific disciplines. The information contained in Chapter 1 should be included with this chapter for general guidelines to the employment of all NDT methods and for a more complete understanding of eddy current testing as it compares with other basic methods.

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2.2 BASIC PRINCIPLES

Eddy current testing is the process of electromagnetically inducing small electrical currents into an electrically conductive specimen and observing the changes in the effects caused by these currents on the electromagnetic fields. Every variable that affects the induction of eddy currents, their flow in the material, and the reactions to their electromagnetic field is capable of being utilized as a test variable.

A knowledge of electricity and magnetism and the electrical properties of materials is required to understand the theoretical operation of eddy current testing. In this chapter these subjects are reviewed as they apply to eddy current testing.

2.2.1 ELECTRICAL CURRENTS

Figure 2.2(1) shows a simple electrical circuit consisting of a voltage source and a conductor of electricity that provides a closed-path circuit through which current will flow. If the voltage source is removed, the current will cease flowing. If the circuit is broken, or otherwise interrupted at any point, the current will not flow.

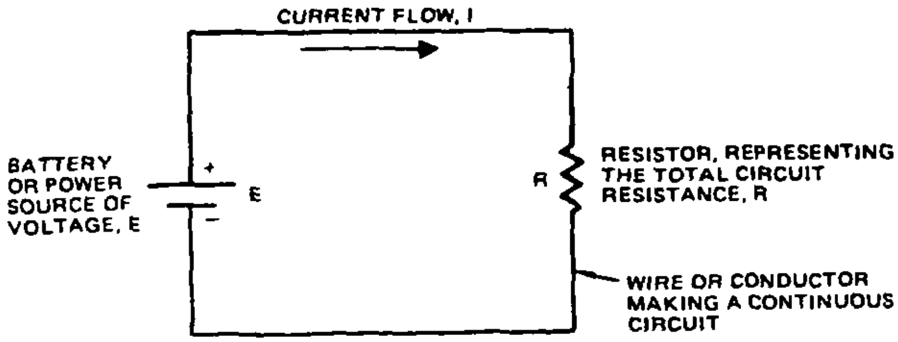

Figure 2.2(1). Simple electrical circuit.

As long as there is a continuous circuit of an electrically conductive material with a voltage applied to the circuit, current will flow. The amount of current flow can be determined from the mathematical expression known as "Ohm's Law." Ohm's law states that the electromotive force (E) in volts across the circuit is equal to the current (I) in amperes flowing through the circuit multiplied by the total resistance (R) of the circuit in ohms. Equation 1 shows this relationship.

$$E = IR \qquad (1)$$

This equation can be transposed to find the current value or the resistance value in terms of the other two parameters: $I = E/R$, $R = E/I$.

2.2.2 ELECTROMAGNETS

When an electrical current flows through a wire a magnetic field exists around the wire. The magnetic field can be represented by magnetic force lines. The direction of the magnetic field or lines of force around the wire depends on the direction of current flow through the wire. This directional relationship may be determined by the "right-hand rule" as illustrated in Figure 2.2(2).

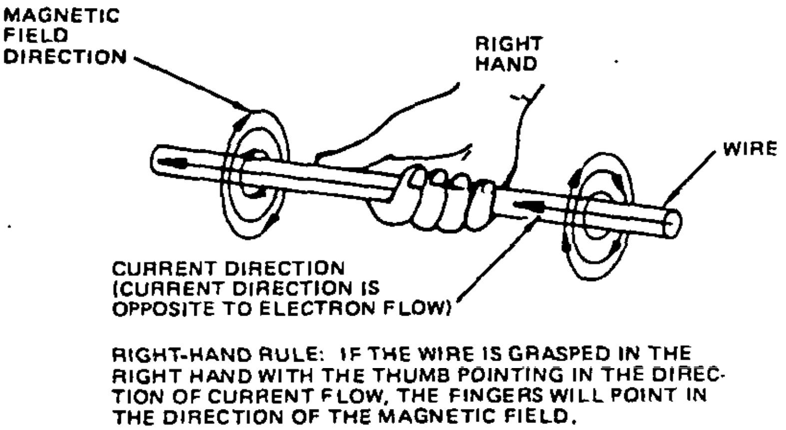

Figure 2.2(2). Magnetic field around a straight conductor.

If the straight wire is wound into a coil (many loops of wire), the magnetic lines of force encircling the wire form a magnetic field inside and outside the loops as illustrated in Figure 2.2(3). The field created is similar to the field of a bar magnet which has opposite magnetic poles at each end. The strength of the magnetic field is dependent upon the number of turns in the coil and the magnitude of the current. Increasing either one increases the strength of the magnetic field. The strength of the magnetic field is also dependent upon geometric factors - mainly the number of turns per unit length or the spacing between the turns of the coil, the coil area and, for each measuring point, its distance and direction from the coil.

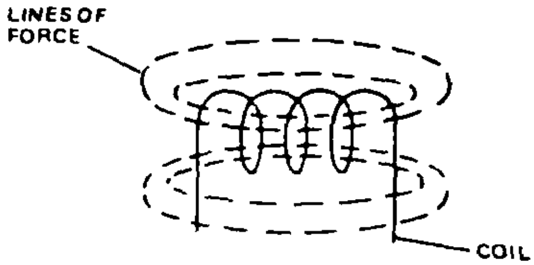

Figure 2.2(3). Magnetic field of a coil.

The direction of the magnetic field depends on the direction of the current flow through the coil as shown on Figure 2.2(4). If the direction of the current through the coil is reversed, the direction of the magnetic field is reversed. The end of a coil can be identified as a North or a South pole depending on whether it is attracted by the North or the South magnetic pole of the earth. By curving and pointing the fingers of the right hand in the direction of the current flow around the coil, the thumb will identify the end of the coil that will be attracted to the earth's North magnetic pole.

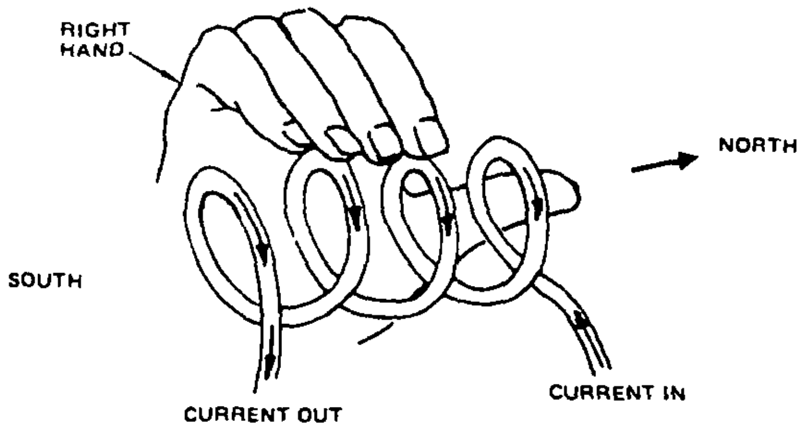

Figure 2.2(4). Direction of a magnetic field in a coil.

2.2.3 ELECTROMAGNETIC INDUCTION

Faraday's law states that when the lines of a magnetic field and a conductor are moving in such a way that they cut across each other (moving through each other so they are exchanging sides), an electrical current will flow through the conductor (assuming that the conductor is part of a closed circuit). Therefore, electrical current may be induced in a conductor in two ways: 1) when the magnetic field moves or expands or contracts across an electrical conductor, with a component of the motion perpendicular to the conductor, or 2) when the conductor is moving through the magnetic field, with a component of the motion perpendicular to the direction of the field. It is the first application, the expanding and contracting magnetic field, that is used in eddy current testing.

2.2.4 MUTUAL INDUCTION

In Figure 2.2(5) a transformer with primary and secondary coils is shown. The primary circuit consists of a battery, a switch, and the primary coil of the transformer. Transformers work by electromagnetic induction as follows: When the switch is closed, current begins to flow through the primary circuit, increasing towards a maximum value. As the current and its magnetic field are increasing, the magnetic flux lines of the primary coil expand, cutting across the windings of the secondary coil.

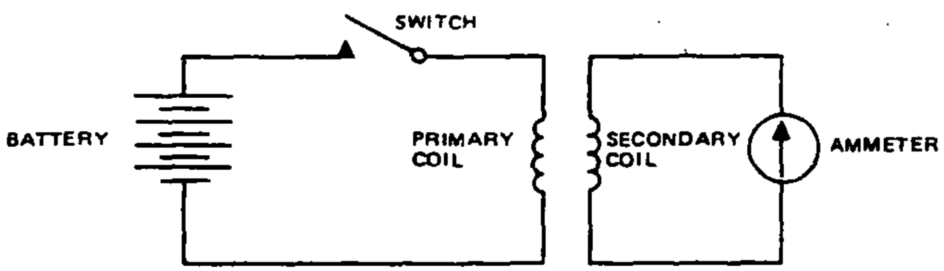

Figure 2.2(5). Electromagnetic induction in a dc circuit.

During this short time, current flows in the secondary circuit as evidenced by a deflection of the needle on the ammeter. In a very short time, the current and its magnetic field in the primary coil reach their maximum values. As long as the switch remains closed and the magnetic field holds constant, there is no further current flow in the secondary circuit; but when the switch is opened, current flow in the primary circuit ceases and the magnetic field around the primary coil collapses. As the magnetic field collapses, flux lines cut across the windings of the secondary coil and the ammeter in the secondary circuit shows a momentary flow of current in the opposite direction as was initially indicated. The current only flows in the secondary circuit when the magnetic flux is moving past the secondary coil. When a change of current in the secondary coil does occur, the changing magnetic field of the secondary coil induces a current in the primary coil that opposes the direction of flow of the original current in the primary circuit. This opposing current is the result of the magnetic field of the secondary coil cutting across the windings of the primary coil. The inducement of current in one coil by the changing magnetic flux of another coil is called mutual induction.

2.2.5 SELF INDUCTION

The magnetic field created by each turn of wire in a coil induces a current in all of the other turns in the same coil. This effect is called self induction and it, too, opposes the original current.

Figure 2.2(6) shows an alternating current source connected to a single coil. The coil shown in this figure represents a real coil, which would have finite resistance as well as inductance. A voltmeter is provided to measure the voltage applied to the coil and an ammeter is provided to measure the current through the coil. If the instantaneous values of voltage and current are plotted on a graph, the current is found to lag in time behind the voltage as shown in the lower portion of the figure. The highest current does not occur at the same time as the highest voltage. Thus, self-inductance affects the phase relationship between the voltage and the current. This electrical property of the coil is called "inductive reactance" and is designated by the letters X_L. It has been determined that in an ac circuit containing only inductive reactance (no measurable resistance), the current will lag behind a sine voltage by exactly 90 degrees. The inductive reactance of a coil is a function of the frequency of the alternating current. Since the higher frequencies cause the magnetic field to change more rapidly, the inductive reactance increases as the frequency increases. The increase in the inductive reactance due to the increase in frequency causes the current through the coil to be reduced, thereby reducing the strength of the magnetic field of the coil.

2.2.6 VECTOR DIAGRAMS

Some resistance is present in all circuits. The total resistance in a circuit includes the resistance of the wiring as well as the resistance of the coil. In an ac circuit containing only resistance, the resistance simply limits the amount of current that flows through the circuit. It does not change the phase relationship between the voltage and the current. The current is exactly "in phase" with the voltage.

Resistance, however, is not the only variable that affects the flow of current. Impedance (designated by the letter Z) is the name given to the combination of all those electrical properties that restrict or limit the flow of current through the circuit. For eddy current testing, this includes resistance (R) and inductive reactance (X_L). (Capacitive reactance is not normally of concern in eddy current testing.) Since these two factors cause results that, for sine waves, occur 90 degrees out of phase with each other, they cannot be simply added together to determine the impedance. The paragraphs that follow show how these factors are related in value and phase.

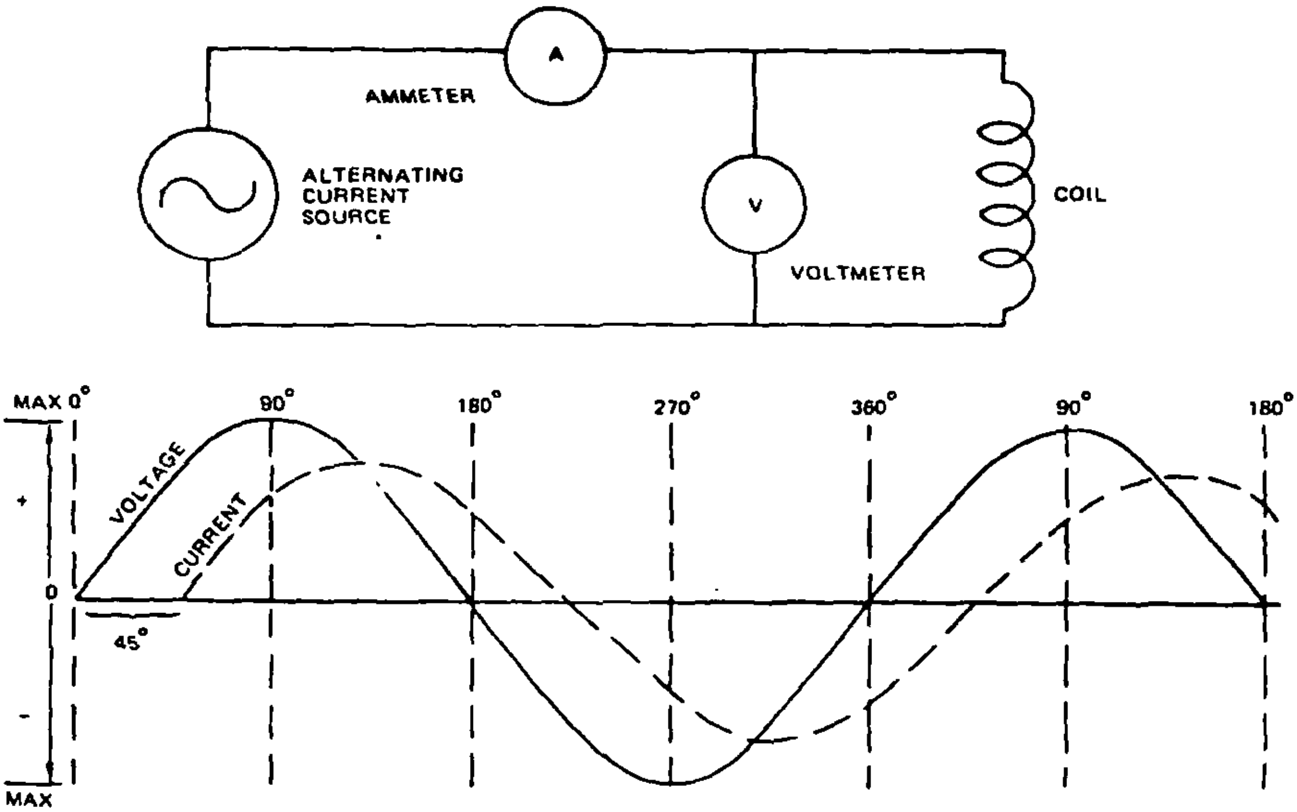

Figure 2.2(6). ac voltage and current plot.

Figure 2.2(6) shows the relationship between the voltage and the current that resulted from the impedance of the circuit. In this case the current is shown to lag behind the applied voltage by 45 degrees, which means that the resistance and inductive reactance were equal. The same relationship can be shown by means of a vector diagram (a vector whose length represents a value and whose direction represents a phase relationship). A vector diagram of the voltage and current shown in Figure 2.2(6) is shown in Figure 2.2(7).

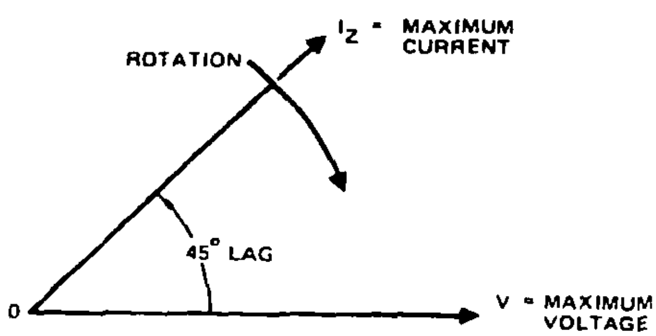

Figure 2.2(7). Vector diagram.

The vector lengths represent the maximum values of voltage and current. The actual or instantaneous values are represented by the magnitude of their horizontal projections, which vary as the vectors rotate. If the vectors are considered to be rotating in a clockwise direction, the maximum current will occur 45 degrees in rotation after the maximum voltage occurs.

2.2.7 CURRENT-PLANE DIAGRAMS

When the current lags the voltage, as shown in Figure 2.2(7), the current vector representation can be broken up into two components, one in phase with the voltage and the other 90 degrees behind the voltage. These two components, shown in Figure 2.2(8), are defined as the resistive current (I_R) and the reactive current (I_{X_L}). The original vector is defined as the impedance current (I_Z). As shown in Figure 2.2(8), a vertical line drawn from the impedance value to the zero degree (in phase) line gives the value of the resistive current (I_R) while a horizontal line drawn from the impedance value to the 90 degree line gives the value of the reactive current (I_{X_L}).

If the values of I_R and I_{X_L} are known, these values can be plotted on the zero and 90-degree lines of a current impedance diagram, a rectangle constructed, and the diagonal drawn will represent the value of I_Z.

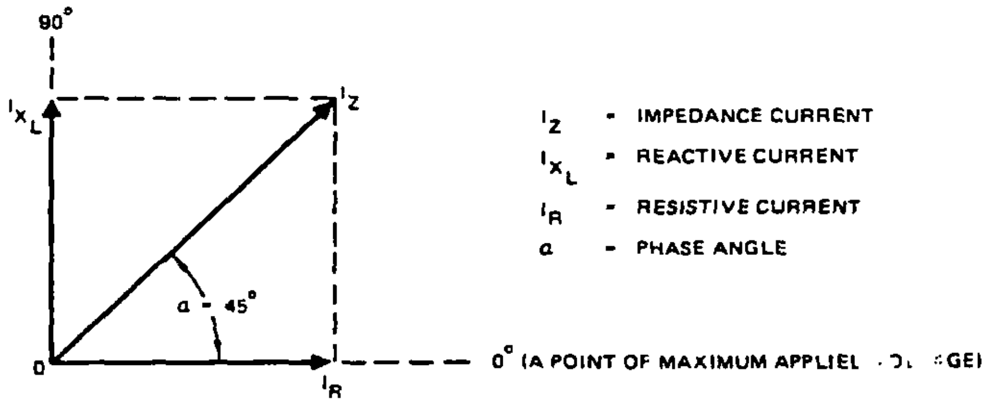

Figure 2.2(8). Vector diagram showing values of I_R and I_{X_L}.

Figure 2.2(9) shows the vector diagrams of two circuits having different currents due to different values for resistance and inductive reactance. In View A, the resistive current is relatively low while the reactive current is relatively high. Note the effect on the phase angle (a) as compared to the phase angle shown on View B where the resistive current is relatively high and the reactive current is relatively low. Varying values of resistance and inductive reactance therefore affects the phase angle as well as the magnitude of the currents.

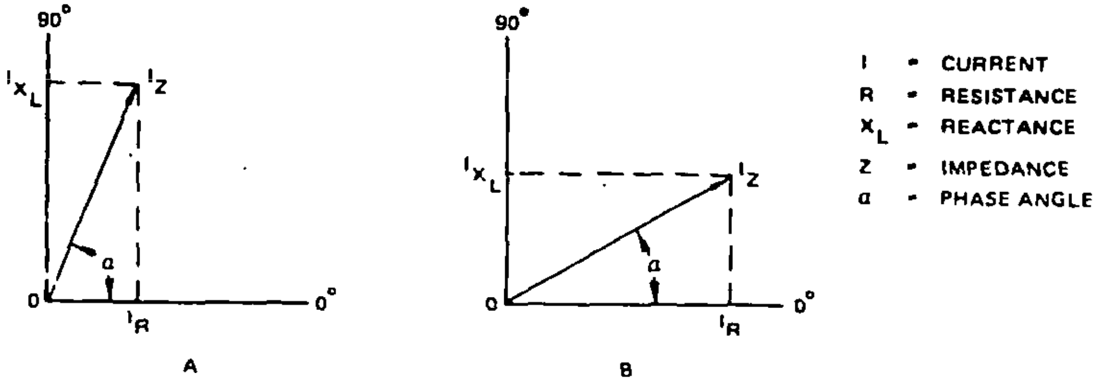

Figure 2.2(9). Current vector diagrams.

As indicated in the previous paragraphs, vector diagrams may be used to show the impedance current, the reactive current, and the resistive current. The same type of diagrams may be used to show applied and induced voltages and to show actual impedance, inductive reactance, and resistance values.

On the electrical circuit shown schematically in Figure 2.2(10); separate electrical symbols are used to indicate the inductive reactance (X_L) and the resistance (R) in the circuit. When an ac voltage is applied to this circuit, the current flows through both the inductive reactance and through the resistance. This current is common to all elements in the circuit.

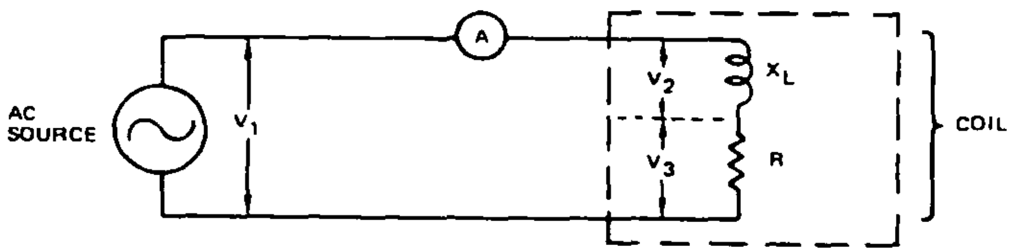

Figure 2.2(10). Inductive reactance and resistance in an ac circuit.

When a sine wave current flows through the inductive reactance a voltage will exist across the inductive reactance. This voltage is identified as V_2 on Figure 2.2(10). The same principle applies to the resistance and this voltage is identified as V_3. The maximum value of either voltage is the product of the maximum current (I) and the inductive reactance (X_L) or the resistance (R). Thus $V_2 = I \times X_L$ and $V_3 = I \times R$.

The maximum voltage (V_2) across the inductive reactance is 90 degrees out of phase with the maximum voltage (V_3) across the resistance. These two voltages can be represented on a graph as shown on Figure 2.2(11). Since voltages are shown, the graph is called a "Voltage-Plane" diagram.

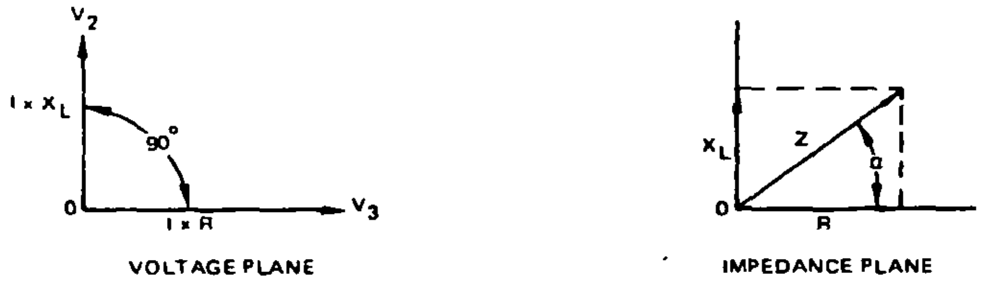

Figure 2.2(11). Voltage-plane and impedance-plane diagrams.

2.2.8 IMPEDANCE-PLANE DIAGRAMS

Since the current through both the inductive reactance and the resistance is the same, the voltage values on the voltage-plane diagram may be divided by the current value to give the values of inductive reactance and resistance in the circuit. The result is also plotted on Figure 2.2(11). The graph is called the "Impedance-Plane" diagram.

The vector addition of the values of inductive reactance and resistance, plotted 90 degrees apart, will indicate the impedance value (Z) and the same phase angle (α) as the current vectors showed in Figure 2.2(8).

2.2.9 EDDY CURRENTS

Eddy currents can easily be explained by taking a transformer as shown in Figure 2.2(5), replacing the dc battery with an ac source as shown in Figure 2.2(6), and then replacing the secondary coil with an electrically conductive test material as shown in Figure 2.2(12). The electrically conductive test material can be viewed as a large number of closed or shorted turns of a secondary coil. The induced current in the "secondary coil" becomes induced current within the test material itself. These currents are called "eddy currents." As these currents flow, they cause an electromagnetic induction that opposes the induction of the primary coil, and the effect will be indicated as changes in the voltage and current values, and/or in their phase relationships, in the primary circuit, or in any other test circuit that is located in their direct vicinity.

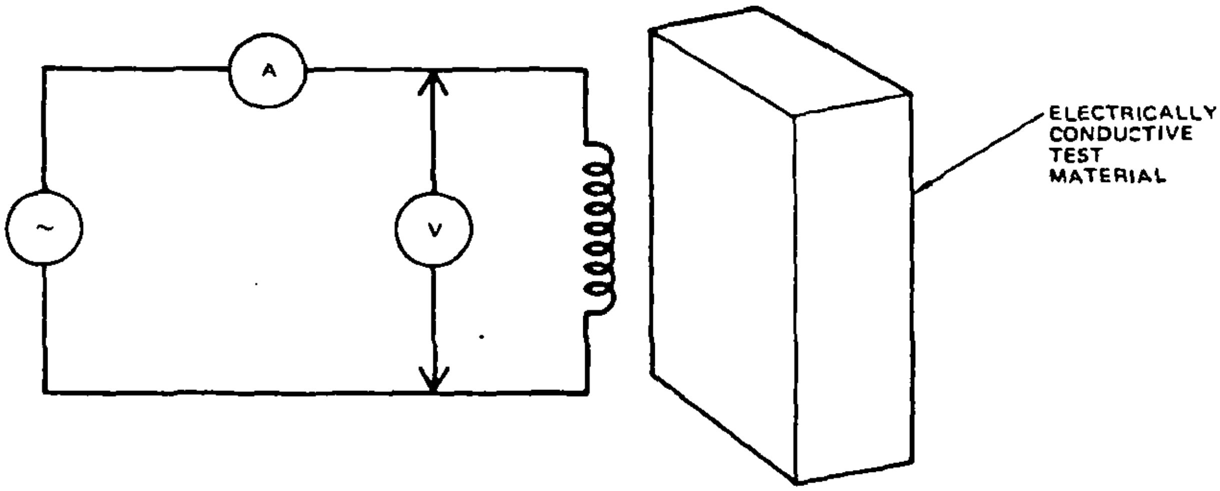

Figure 2.2(12). Induction of eddy currents.

2.2.10 EDDY CURRENT VARIABLES

The variables in the eddy current test circuit can be quickly identified. In the primary (test) circuit, the frequency and magnitude of the source voltage and the resistance and self-inductance of the test circuit are all basic input variables. These variables, along with the number of turns in the coil and the shape and size of the coil, determine the strength and shape of the electromagnetic field that expands and collapses around the test coil. The orientation and location of this coil with respect to the material under test is also an important parameter. The closer the coil is to the material under test, the greater the mutual inductance that is established. These variables all help to determine the magnetic forces induced within the test specimen.

The eddy currents that result from the induced magnetic forces will be a function of certain characteristics of the test specimen. The thickness and other geometric characteristics of the test specimen can affect the amount of current induced into the specimen by the test circuit. As the material becomes very thin or edges are approached, for example, the mutual inductance is decreased which can be considered as a reduction in the number of turns in the secondary coil. The electrical conductivity of the material will also affect the amount of current induced, essentially fixing the resistance of each shorted coil. If any cracks or other material defects are present, which would have the effect of breaking any of these closed current loops, reduced current flow will occur. As these eddy currents flow, first in one direction and then in the opposite direction as the electromagnetic field first expands and then collapses, they set up their own electromagnetic fields.

The sensing of the eddy current electromagnetic fields, or changes in these fields, completes the test. Normally, the test coil is also used as the sensing coil, and the same orientation and proximity relationships required to induce the eddy currents are also used to establish the return induction. This return induction affects the normal voltage-amperage relationship in the primary circuit. This change can be sensed and displayed on one or more amplitude or phase meters, or on an oscilloscope where displays similiar to some of the phase diagrams discussed in 2.2.5 can be observed.

If the test material exhibits any magnetic permeability effects, the entire interaction will be greatly affected, both with respect to the effect of the initial induction from the test coil, and any subsequent return induction from the eddy current flow. If the magnetic permeability of the material interferes with the eddy current testing (that is, it is not the variable being measured), its effects can be removed by using a strong, fixed, external magnetic field that holds the test material at magnetic saturation.

2.2.11 EDDY CURRENT LIMITATIONS

The electromagnetic induction of the eddy currents opposes the electromagnetic induction of the test coil. This opposition has the effect of restricting eddy currents to the surface or near surface region of the test specimen. Any eddy current present at the surface of the test material will reduce the induction effect of the test coil in the deeper regions of the material, and eddy currents therefore fall off at an exponential rate. Therefore, eddy current testing must normally be limited to locating those variables that are at or near the surface of the inspected parts.

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2.3 EQUIPMENT AND METHODS

A variety of commercial eddy current test instruments are available. They are often designed to measure, detect, or gage specific parameters of the test material such as conductivity, flaws, and thickness. Specific systems are not discussed, but some of the ranges of choices are indicated.

2.3.1 ABSOLUTE AND DIFFERENTIAL INSTRUMENTS

Basically, as shown in Figure 2.3(1), there are two types of instruments: differential instruments and absolute instruments. The number of test probes associated with an instrument is indicative of its type. For example, a differential instrument has two identical test probes (coils) that are electrically opposed. The absolute test instrument has only one test coil or probe associated with it.

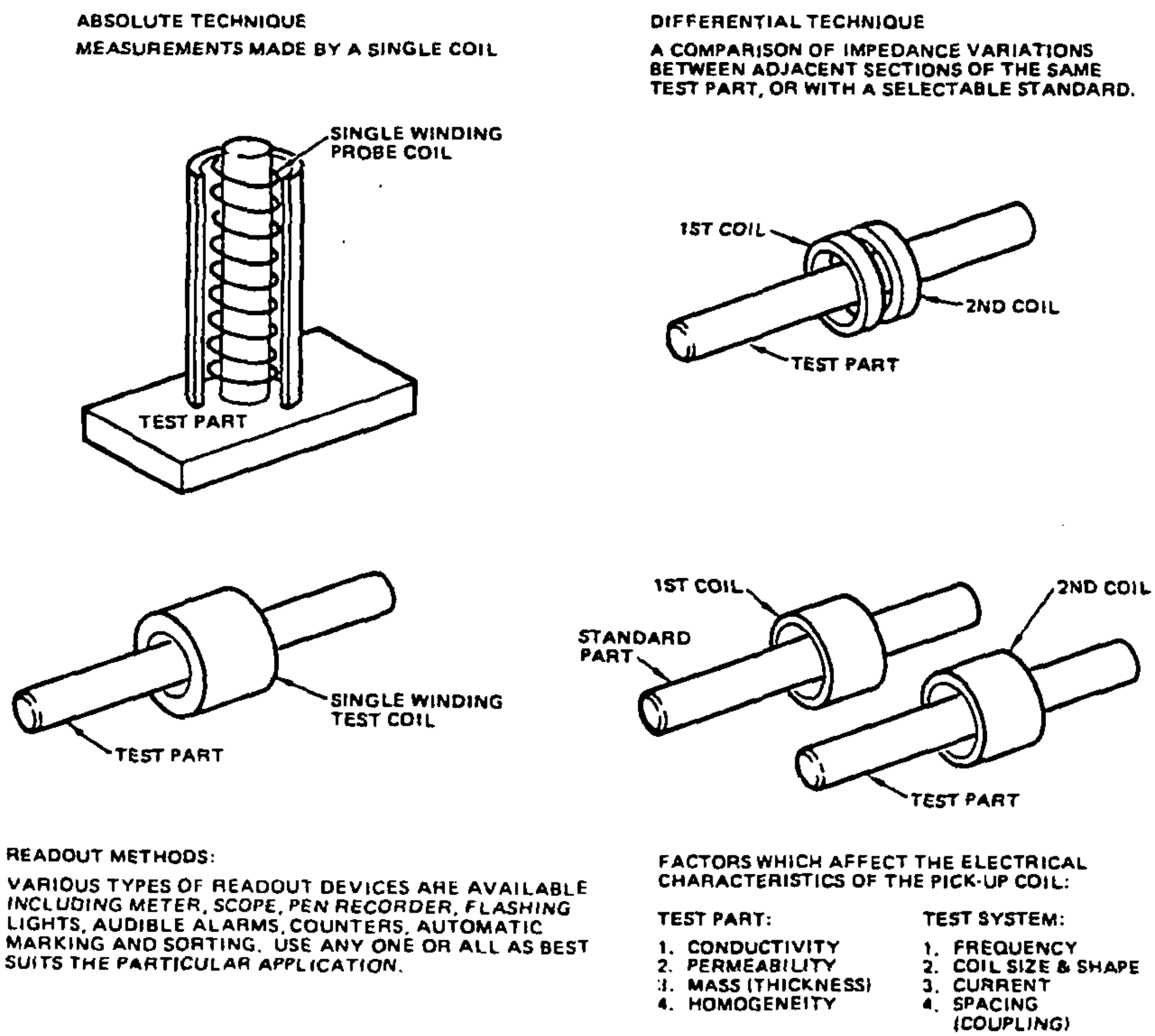


Figure 2.3(1). Absolute and differential coils.

In the differential instruments the signal displayed is the difference between variables simultaneously affecting two coils, while in the absolute instrument it is the change in the signal of the single coil from one position to another that must be attributed to differences in the variables being tested. Both instruments therefore produce similar information regarding the properties of the test item, but their operating characteristics are quite different. This difference in operation plays a large role in the selection of an eddy current instrument for a given application.

In metallurgical evaluations of a test item, the differential type instrument offers an inherent stability which allows a high degree of sensitivity and repeatability. These qualities make this type of instrument ideal in an automated system for high-volume and high-speed inspections. For flaw detection inspections, both test probes of a differential instrument are placed on the same test object and scanned over the surface of the test object. When the two test elements are over a homogeneous flaw-free area of the test item, there is no differential signal developed between the elements since they are both inspecting identical material. However, when first one and then, a moment later, the other of the two test elements is passed over a flaw, a large differential signal, first in one direction and then in the opposite direction, is produced. Even though the differential flaw-detection instrument has a high degree of sensitivity and stability, it is fairly independent of the type of material and the metallurgical properties of the material being tested.

The absolute type of eddy current instrument is characterized by the ease of operating a single test coil or probe, and is more easily related to specific properties or variables.

2.3.2 TEST COILS

It is the coil size and shape that ultimately governs the resolution capabilities of the test. The exact dimensions or location of a flaw cannot normally be determined within tolerances that are much less than certain critical dimensions of the probe. Also, because each probe forms a direct part of the test circuit, the probe will often have a direct effect on the frequency applied to the test circuit. The choice of coil will often limit the power output, with the overheating of the coil setting the upper limit. Therefore, the choice of the coil is one of the more important factors in a successful eddy current test.

Figure 2.3(2) illustrates the three basic types of test coils that are used in eddy current testing: the surface coil, the encircling coil, and the internal, or bobbin-type, coil. Because the positioning of the surface coil relative to the material differs from that of the encircling and internal coils, the eddy current geometry differs since eddy currents always have a definite spatial relationship with the magnetic fields producing them. Understanding this coil to eddy current spatial relationship is very important when looking for, or recognizing the presence of, discontinuities.

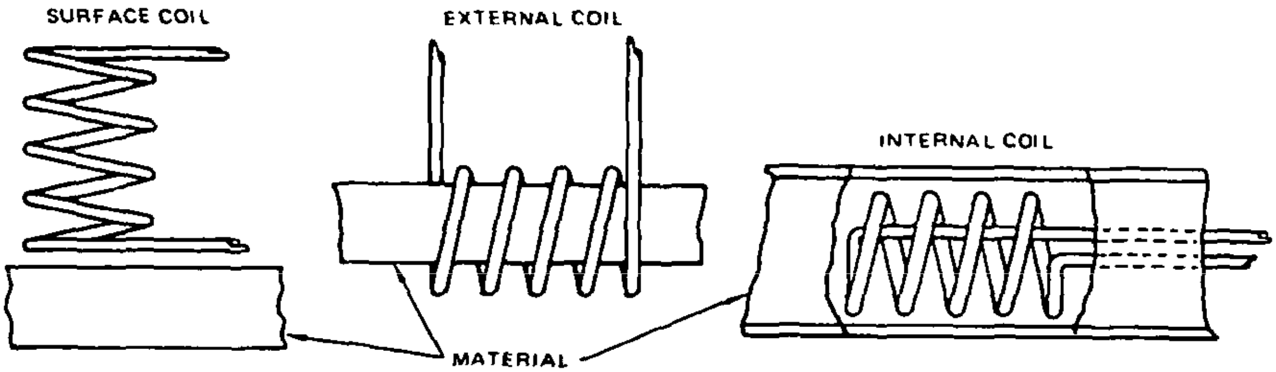


Figure 2.3(2). Basic test coil types.

Eddy currents produced by test coils essentially flow parallel to the plane of the coil producing them. Eddy currents are strongest near the surface of the material and their strength decreases with depth. A discontinuity whose major axis lies parallel to the eddy current flow will not have as great an effect on the eddy currents as one whose major axis cuts across the flow of current; and a deep lying discontinuity will not have as great an effect as one lying near the surface.

Figure 2.3(3) shows a surface probe as it is placed near the surface of a test article. The alternating magnetic field of the coil is essentially perpendicular to the face of the coil. The induced eddy current flows at right angles to the magnetic fields. Therefore, the induced eddy currents flow parallel to the surface when the surface probe is held perpendicular to the surface.

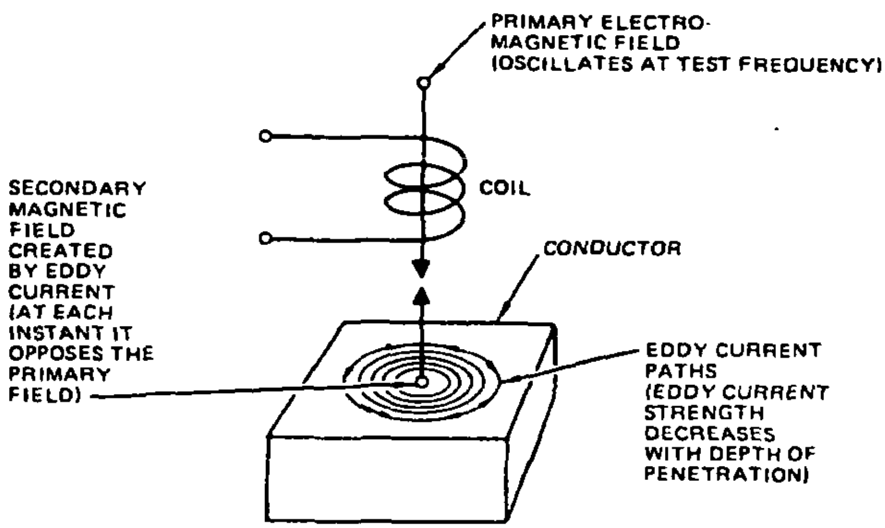


Figure 2.3(3). Eddy currents produced by a surface coil.

Figure 2.3(4) shows an encircling coil installed around a rod. Here, eddy currents flow in the same direction as the current flow in the coil; i.e., around the circumference of the rod. Thus the encircling coil is especially adapted to locating those discontinuities that are parallel to the length of the rod.

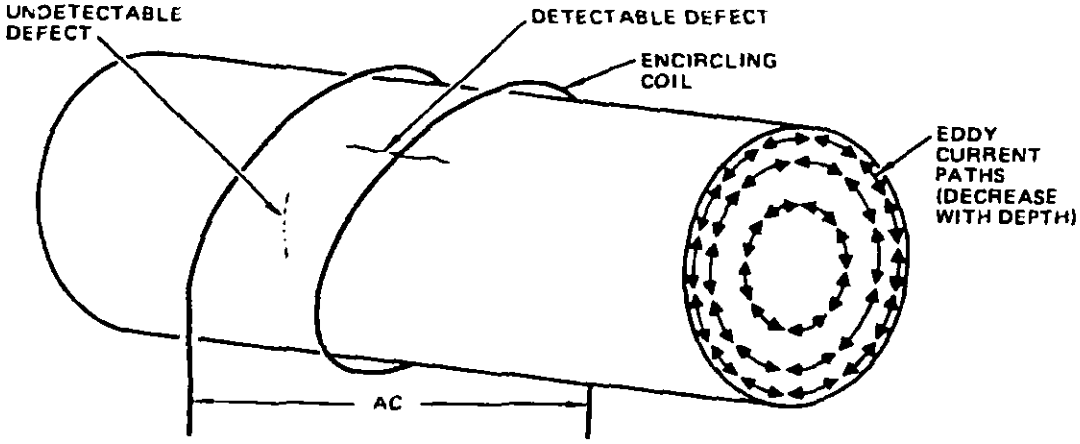


Figure 2.3(4). Eddy currents produced by an encircling coil.

The eddy currents induced by an internal coil will be the same as an encircling coil, except the eddy currents will be concentrated on the inner surface and not on the outer surface.

Lift-off and fill factor are terms that define the space that exists between the article under test and the inspection coil as shown on Figure 2.3(5). Each has an identical effect on the eddy currents. Lift-off and fill factor are essentially the same thing; lift-off is the term applied to surface coils and fill factor is applied to encircling and internal coils.

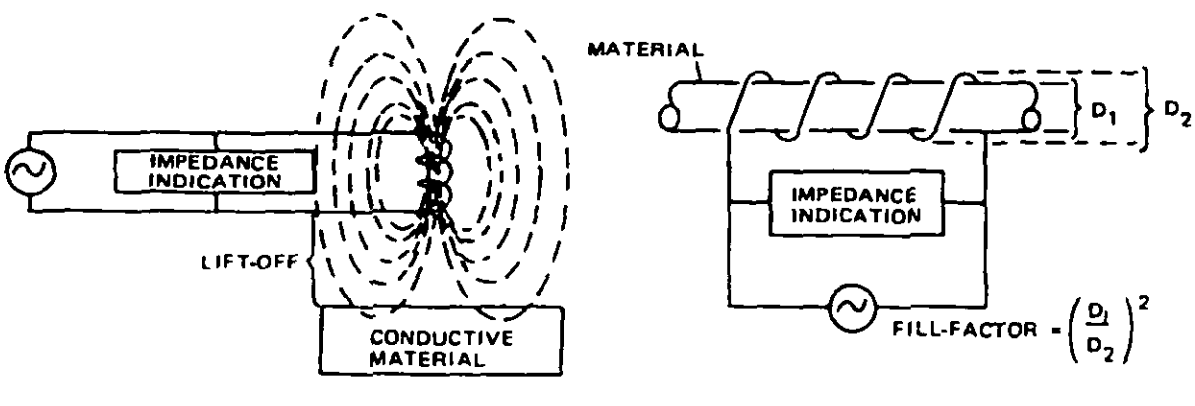


Figure 2.3(5). Lift-off and fill factor.

a. Lift-off. When a surface coil is energized and held in air above a conductor, the impedance of the coil has a certain value. As the coil is moved closer to the conductor the initial impedance value of the coil will change when the field of the coil begins to intercept the conductor. Because the field of the coil is strongest close to the coil, the impedance value will continue to change until the coil is directly on the conductor. Conversely, once the coil is on the conductor, any small variation in the separation of coil and conductor will change the impedance of the coil. The lift-off effect is so pronounced that small variations in spacing can mask many indications.

b. Fill Factor. In an encircling coil, or an internal coil, fill factor is a measure of how well the test specimen (conductor) fits the coil. It is mathematically the square of the ratio of the specimen's diameter to the coil's diameter. The closer the fill factor is to 1 the more sensitive and precise the test.

It is necessary to maintain a constant relationship between the diameter of the coil and the diameter of the test specimen. Again, small changes in the diameter of the test specimen can cause changes in the impedance of the coil. This effect can be useful in detecting changes in the diameter of the test specimen but it can also mask other indications.

Because of the necessity to maintain lift-off effects at a constant value (assuming no change in the diameter of the rod or tube under test) it is necessary to provide the means to guide the specimen through the center of the coil as shown in Figure 2.3(6).

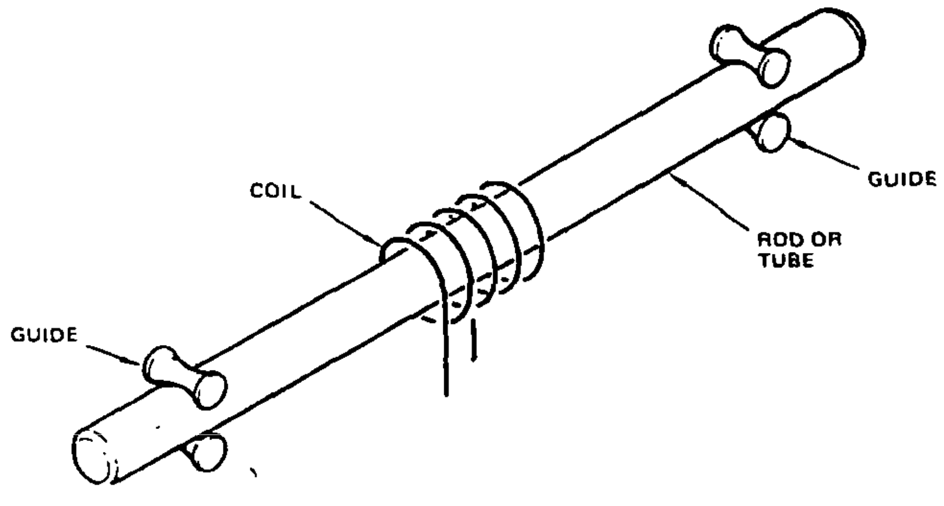


Figure 2.3(6). Guides ensure constant lift-off.

A test coil must therefore be chosen that will have an acceptable fill factor and the necessary adjustable guides or controls that will maintain a reasonably constant position and orientation with respect to the article tested.

When a test coil approaches an edge or the end of a part, as shown in Figure 2.3(7), the eddy currents become distorted, producing a false indication known as "edge effect." Since, to the test circuit, the edge of a part looks like a very large crack or hole, this strong response masks all other variables that may be present, and therefore limits the usefulness of the eddy current test near these areas. These limits are affected by the size of the coils. The smaller the coil and its magnetic field, the closer the edge can be approached without encountering "edge effects."

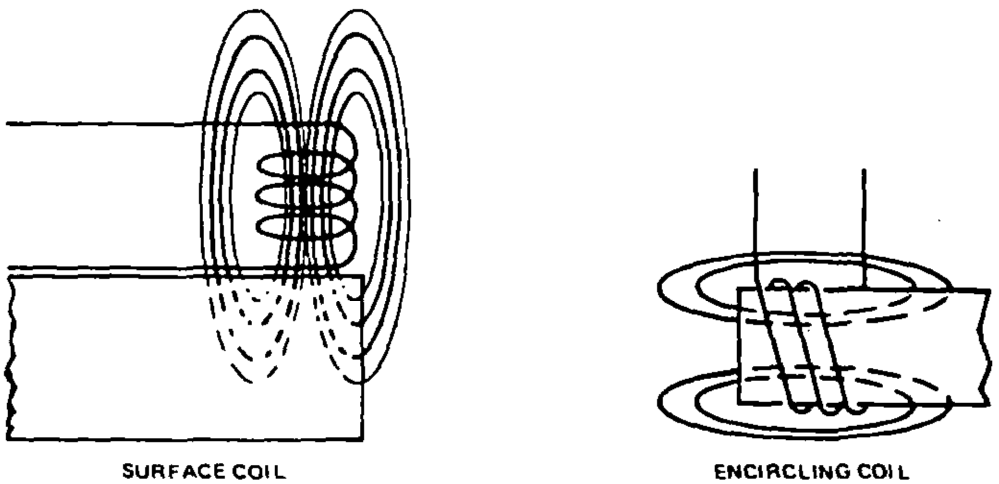


Figure 2.3(7). Distortion of eddy currents due to edge effect.

2.3.3 BASIC BRIDGE CIRCUITS

Since the signals being measured in eddy current testing are often small, a sensitive bridge type circuit is normally employed. A typical example is shown in Figure 2.3(8).

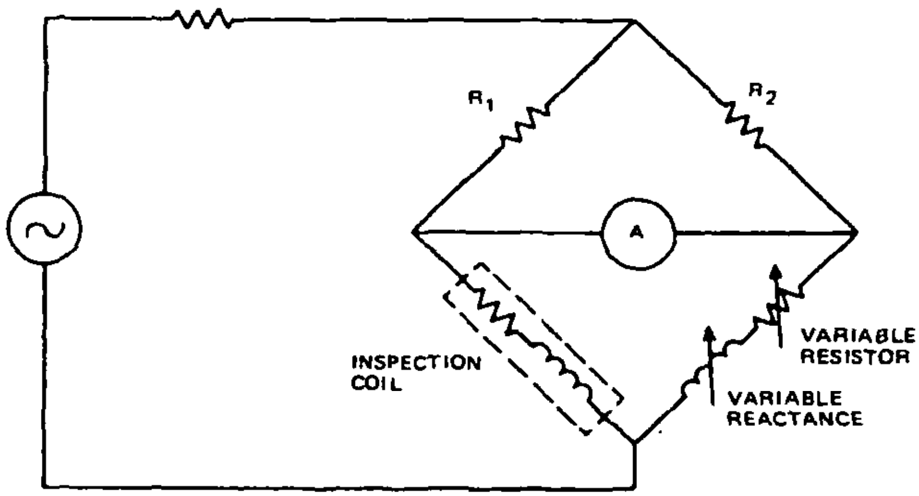


Figure 2.3(8). Bridge circuit with variable resistance and reactance.

In the bridge circuit, the meter reading at A will depend upon the strength of the impressed signal and the electrical unbalance that exists between the legs of the bridge. Theoretically, for any fixed condition existing in the inspection coil, the variable resistor and reactance coil can be adjusted to balance the bridge (make the meter at A indicate zero). Then if any change occurs at the test coil, the meter will respond with a reading.

This type of circuit allows a manual setting of the variable reactance and the variable resistor to set up the bridge to allow measurements from any point on the impedance plane. By adjustment of resistance and reactance in the bridge the circuit can be set up to measure specific variables and ignore others, it can be set up to compare the test material with a standard, or it can be set up to measure actual resistance and reactance values. Since this is a reasonably versatile type of circuit, it will be the circuit that will be used in this chapter for explaining various techniques in the use of eddy current tests.

2.3.4 DATA DISPLAYS

Eddy current data can be displayed by amplitude meters, combined amplitude and phase meters, or by an oscilloscope. Data signals can also be used to turn warning lights off or on, sound alarms, or operate other controls. Data signals can be recorded on X-Y plotters, strip chart recorders, magnetic tape, or other modern recording devices. Oscilloscope displays that simultaneously show amplitude and phase, with superimposed electronic gates, are very convenient for quick set-ups. Greater accuracy and control, however, can be expected with digital meter readouts. The data recorded in most eddy current testing does not normally give a "view" of the specimen as an X-ray or ultrasonic C-scan would do, but such scans have been done and could be used as a permanent record of the part. Normally, however, the data from eddy current testing is not considered to be a permanent record of the part because discontinuity location or part orientation are not usually part of the recorded signal.

2.3.5 NEWEST EQUIPMENT AND METHODS

Advancements in microprocessing, computers, and automation have greatly affected the equipment presently available for eddy current testing. The actual data obtained are essentially the same, but the ease of setup, data computations, and display has been greatly increased. Many present-day eddy current devices have digital data recordings and displays. This especially allows easy computation and storage of the data. In fact, data from several test specimens and standards can be simultaneously stored, compared, and displayed. Previous storage was limited to the image retention of a phosphor screen, but digital storage time is unlimited. Statistics of the data can often be directly presented, showing means and standard deviations, etc., for any number of data points. These advances are extremely important where large numbers of test items must be compared or processed, and/or where many different test setups or standards are required.

One important advance in eddy current technology is miniaturization of the probes. The smaller the probe, the smaller will be the field extending from the probe. This can increase the potential signal-to-noise ratio for small surface cracks and also allow closer approaches to edges before edge effects occur. Probes of only 0.050-inch diameter have been advertised that can resolve surface cracks less than 0.5 mils deep. Other advances, in controlling the shape of the field by using ferrite cores or yokes, are also able to reduce the effective size of these fields.

Eddy current data inversion processes and other imaging reconstruction methods are being explored. This includes phase multiplication processes and holographic type methods that are presently developed in the ultrasonic testing area.

2.4 BASIC PROCEDURES AND TECHNIQUES

Eddy current testing is sensitive to many variables. The ultimate utility of eddy current testing will therefore be dependent upon the ability of the operator to separate out or identify the effects of the desired variable or variables from the effects of all other non-critical or unimportant variables. The use of eddy current testing becomes limited when discrimination between the effects cannot be accomplished. In this section, several basic procedures and techniques are presented in detail. An understanding of these examples will make it possible to apply eddy current techniques to most situations. These techniques will include lift-off compensation, thickness measurements, and conductivity measurements. Basically, these techniques involve the separation of the effects of one variable from those of another. Until separation of effects is accomplished and verified, the reliability of the testing will always be in doubt.

2.4.1 LIFT-OFF COMPENSATION

As was mentioned (in section 2.3.2 on coil lift-off effects and in section 2.2.10 on distance effects), changes in the space or distance between a coil and the test material can cause large changes in the signal, or meter readings. If it is desired to detect a material property that does not relate to lift-off, then meter reading changes due to lift-off effects should be suppressed. Where probes are hand held or moved over a surface that is not perfectly smooth, some lift-off effects, due to slight tilting or other reasons, will almost always be present.

If an instrument uses a bridge circuit as shown in Figure 2.3(8), where the reactance and resistance can be manually adjusted, the meter can be "zeroed," or minimized, for any existing test condition. When a zero point is established, the reactance and resistance of the dials can be read, recorded, and plotted on an impedance-plane diagram (see Section 2.2.8) as a point representative of that particular test condition. Figure 2.4(1) shows an impedance plane diagram with one point plotted, representing a resistance dial setting of 15 ohms and a reactance dial setting of 5 ohms.

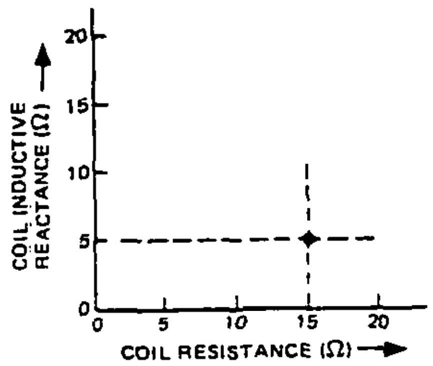


Figure 2.4(1). Impedance plane diagram.

If resistance and inductive reactance readings are taken on a series of materials that vary only in their conductivity, and these readings are plotted on an impedance-plane diagram, the result is a curve that represents the effect of changes in conductivity for that particular test setup. Then if a series of resistance and inductive reactance readings are taken as the test coil is lifted off the material that is to be tested and these readings are plotted on the same impedance-plane diagram, the result is a second curve that represents the effect of changes in lift-off for that particular material in the same test setup. Figure 2.4(2) shows how lift-off effects, in general, vary from conductivity effects for a particular test setup. When the conductivity and lift-off points plot at different positions on the impedance-plane diagram, then the effect of a change in lift-off can be separated from the effect of a change in conductivity by selecting particular test points from which the bridge circuit operates.

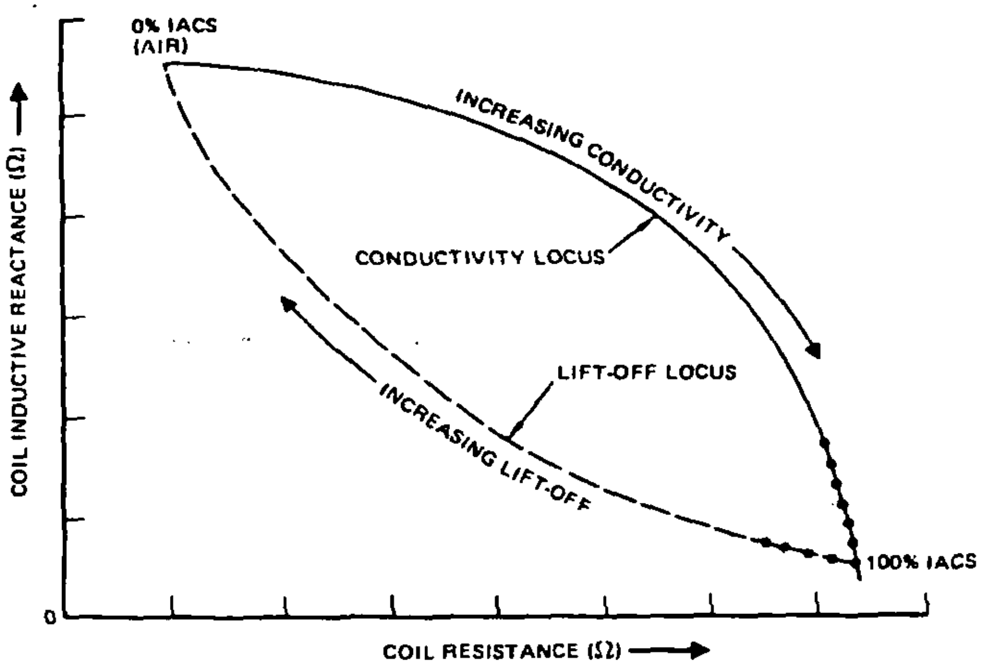


Figure 2.4(2). Lift-off locus on impedance-plane diagram.

The signal or meter reading will depend upon the degree of unbalance of the bridge. This degree of unbalance of the bridge corresponds to the magnitude of the line on the impedance plane that connects the point that represents the dial setting from the point that represents the conditions of the probe. Therefore, the impedance-plane diagram becomes a means of determining the signals that will be seen on the meter. If a point on the impedance-plane diagram can be found which shows little change in distance from the points of one variable, but a large change in distance with the points that represent changes in another variable, then that point could be selected for proper testing of that variable where the changes are large.

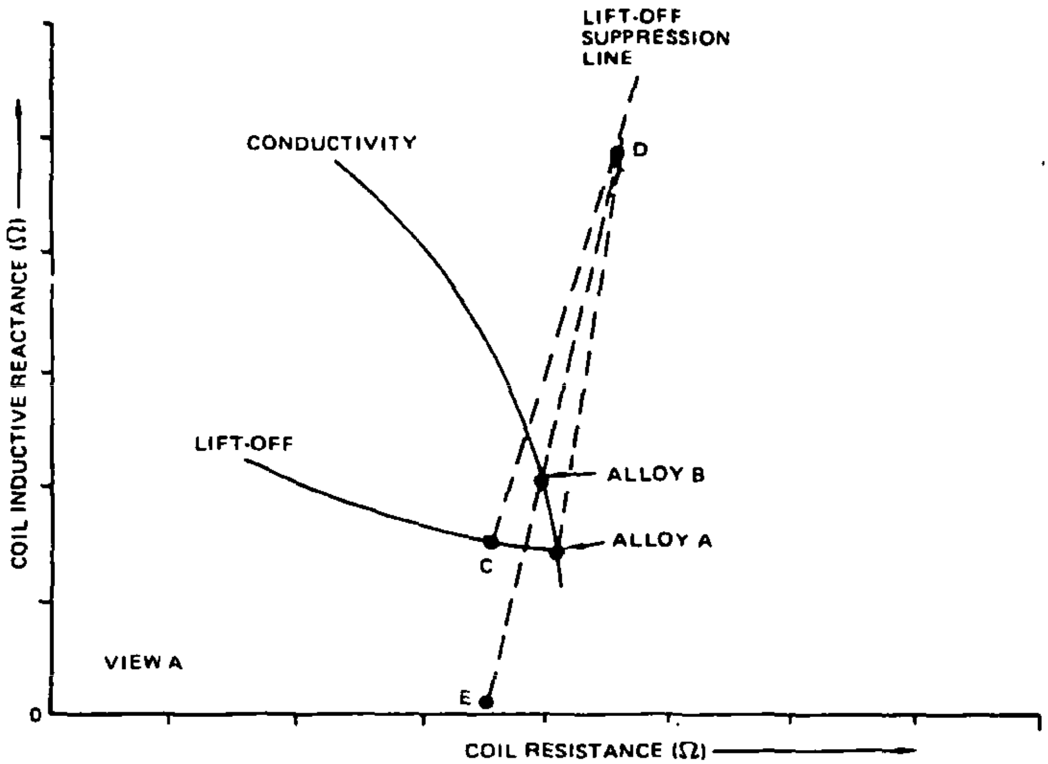


Figure 2.4(3). Test point selection.

Therefore, with the instrument dials set to a particular reactance and resistance value of the impedance-plane diagram, and the test coil placed on the test object, the meter reading will correspond to the difference in impedance from the set test point value to the value being sensed by the test coil. If the set test point is selected so that the meter reading varies only slightly as lift-off varies and varies markedly as conductivity varies, an acceptable test point has been selected. Point "D" in Figure 2.4(3) illustrates a point that would meet this requirement. In this example, the change in the meter readings, as the probe is moved from alloy A to alloy B, would indicate the change in conductivity between alloys A and B, and not a difference in lift-off that might be present, as indicated from alloy A to point C.

In using this approach, it is important to know the general relationship expected with the variables of interest. Figures 2.4(4) through 2.4(6) show several examples of general relationships between several variables for particular test setups. These figures cannot be used for any other test setup since the settings on dials are often arbitrary and do not directly translate from one equipment to another. However, the curves on impedance-plane diagrams are extremely useful to determine the degree of separation between variables that might be possible, and to help ensure that plottings are adequate to account for these expected variances.

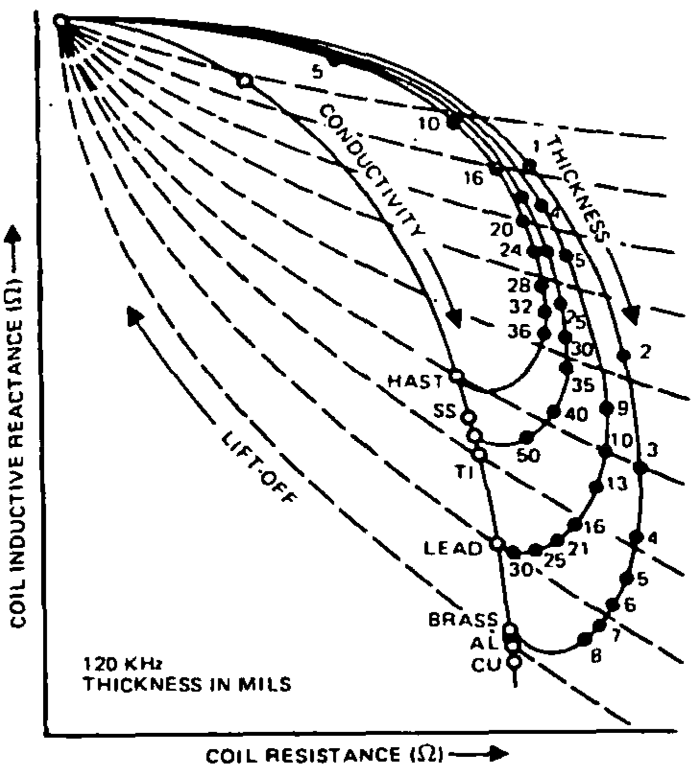


Figure 2.4(4). Thickness variations of several metals on the impedance-plane diagram.

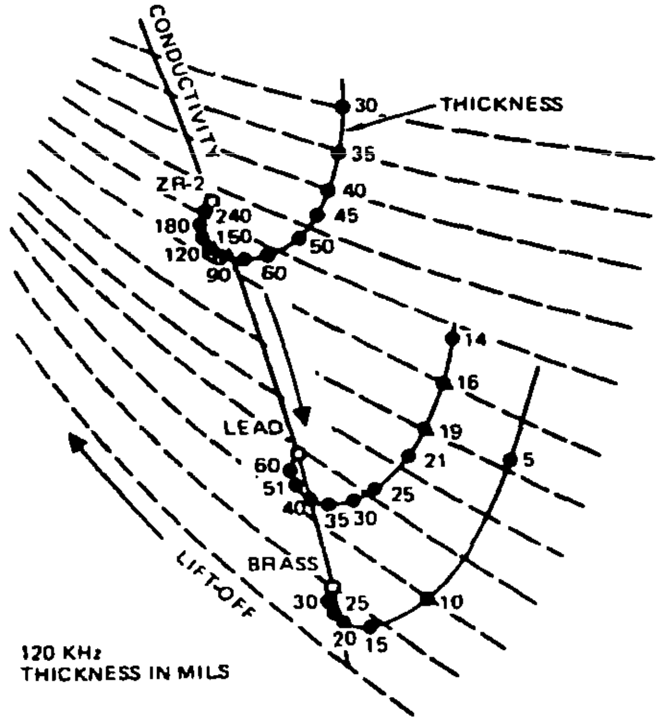


Figure 2.4(5). Thickness variations - expanded scale.

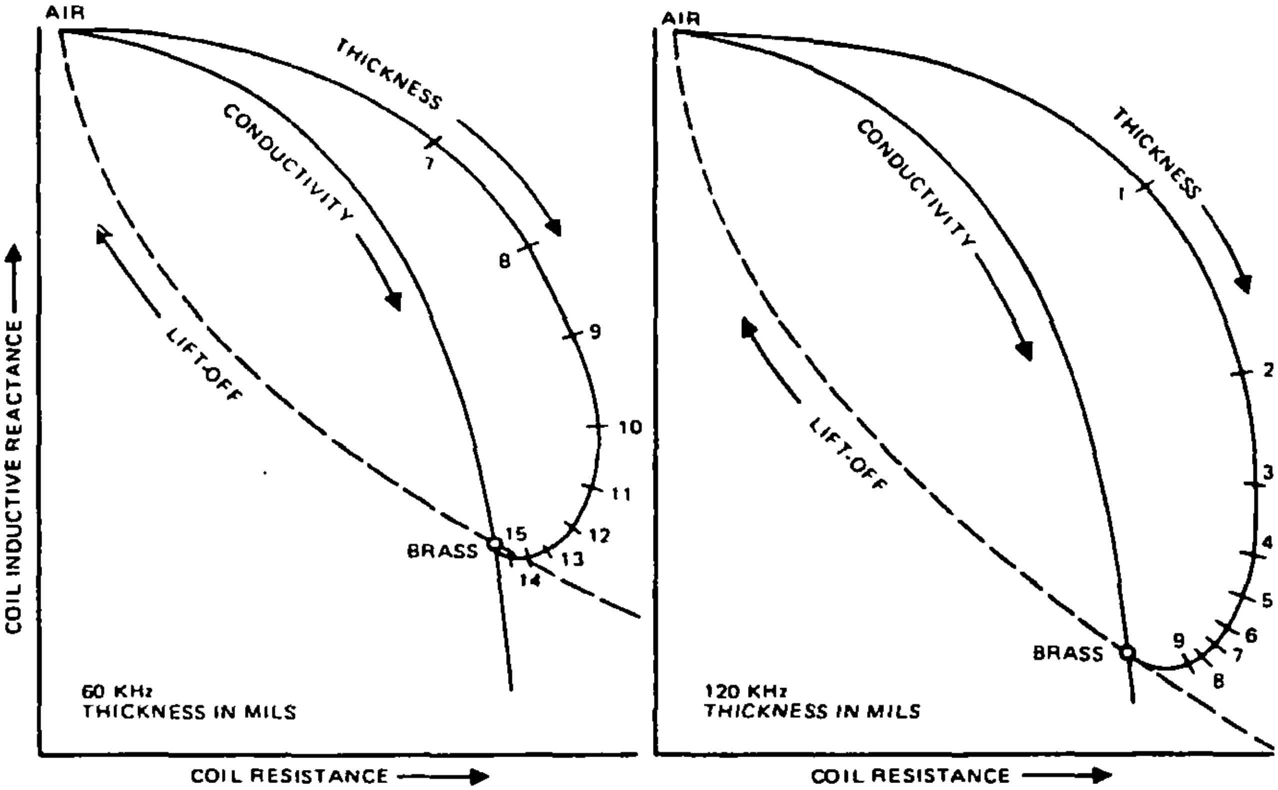


Figure 2.4(6). Effect of frequency on thickness measurements.

The impedance-plane diagram can also indicate whether the meter reading will increase or decrease with a certain change in a variable by showing whether the distance to the test point is getting larger or smaller. The operator can make the meter respond in either way by selecting a test point that lies in a different direction on the diagram. To maximize the indicated change of a specific variable, the operator would choose a point that lies on a line that is tangent to the line that represents that specific variable. To make changes in a variable appear linear, a point would be sought which would result in the most uniform changes in length with uniform changes in the variable. If signal changes are to be either a large or a small percentage of the total signal, then points close to or far from the variable points would be selected. All these relationships can be established from the impedance-plane diagram. Therefore, great care should be taken in the plotting of these diagrams. Normally, for plotting lift-off points, thin sheets of electrically nonconductive material of known thicknesses are placed between the probe and test surfaces. To plot other variables, standards representing those variables (for conductivity, or thickness, etc.) must be available.

2.4.2 THICKNESS MEASUREMENTS

There are three basic situations when eddy current methods are used to determine thickness measurements: 1) the thickness of a nonconductive coating over a conductive material; 2) the thickness of a coating of conductive material over a nonconductive material; or 3) a thin sheet of conductive material. The first measurement method employs the lift-off effect. The thicker the nonconductive coating, the greater is the distance that the probe is held away from the surface of the conductive material. The technique here is identical to 2.4.1, where an impedance-plane diagram is plotted for the range of coating thickness (or lift-offs) that are desired to be measured. A point on the impedance-plane is chosen that will produce the best response to the lift-off variable and the least response to the conductivity variable. Point "D" on Figure 2.4(7) might represent an acceptable test point. If the operator is sure that the coating is nonmagnetic and nonconductive, then calibration can be done with any nonmagnetic and nonconductive material, of appropriate, known thicknesses placed between the probe and a bare surface of the material to be tested. If the coating is reactive in any manner, then standards using that specific material should be used.

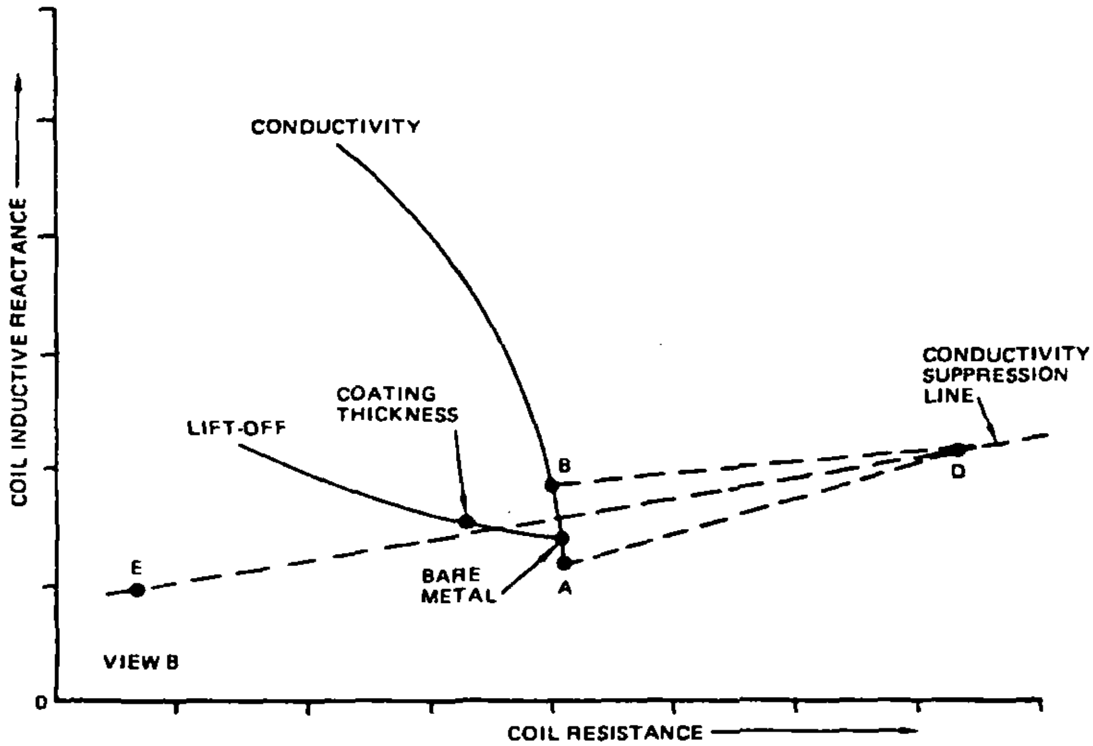


Figure 2.4(7). Test point selection.

In all cases, care must be exercised to ensure that every test variable is present in the data gathering or calibration for the preparation of the impedance-plane diagram that will be present for the actual test. Any variable that is different from those in the actual test and that affects the response will invalidate the calibration. Depending upon the circumstances, this may at times require the same width, the same thickness, the same heat treat, the same surface roughness, or any other variable that is found to influence the test results.

The measurement of the thickness of a conductive coating over a nonconductive surface, or the measurement of the thickness of a thin material, can involve additional considerations. Again, an impedance-plane diagram must be obtained, showing all the variables that are present. In measuring the thickness of a thin conductive layer, one of the critical test parameters is the test frequency. The depth of penetration of the magnetic field decreases as the frequency increases. At relatively low frequencies, eddy currents penetrate more deeply into the material. The thickness of a thin electrically conductive material can only be effectively measured where the depth of penetration of the magnetic field extends through the thickness to be measured.

The standard depth of penetration has been defined as the depth at which the eddy current density is about 37% of the density at the surface. Figure 2.4(8) shows the standard depth of penetration for several materials with different conductivities at various operating frequencies.

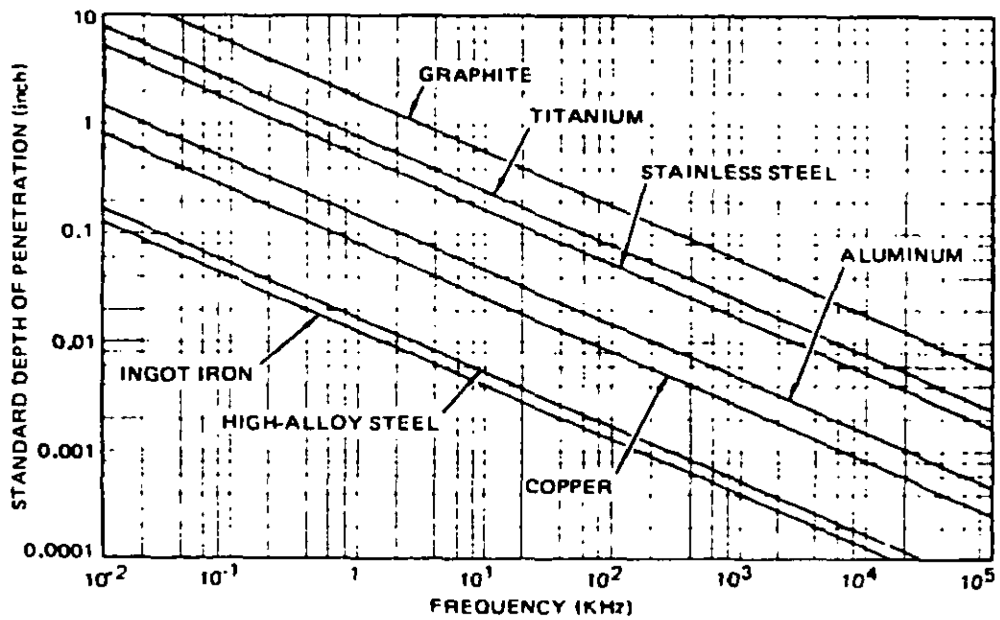


Figure 2.4(8). Standard depth of penetration versus frequency for different types of material.

If the standard depth of penetration exceeds the thickness of the material under test, the restriction of the eddy current paths appears as a change in conductivity of the material. The coil response to the apparent change in conductivity reflects the changes in the thickness of the material. It should be remembered, however, that eddy currents do not cease to exist beyond the standard depth. Normally, the material must have a thickness of two or three times the standard depth before thickness ceases to have a measurable effect on the test coil; see Figure 2.4(9).

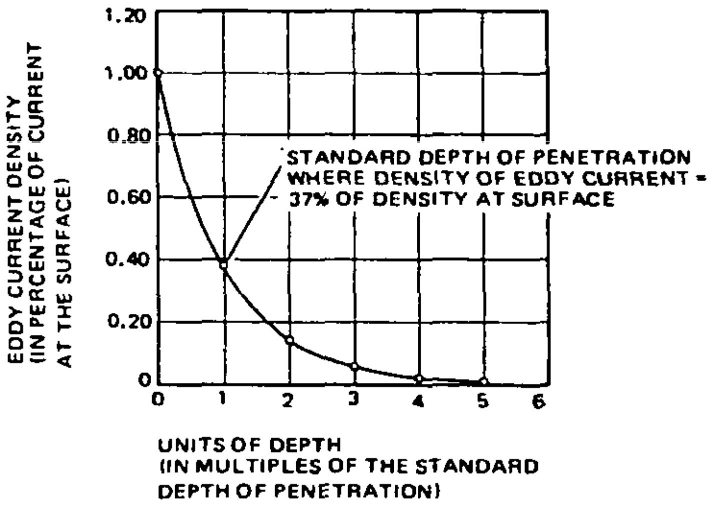


Figure 2.4(9). Variation in eddy current density.

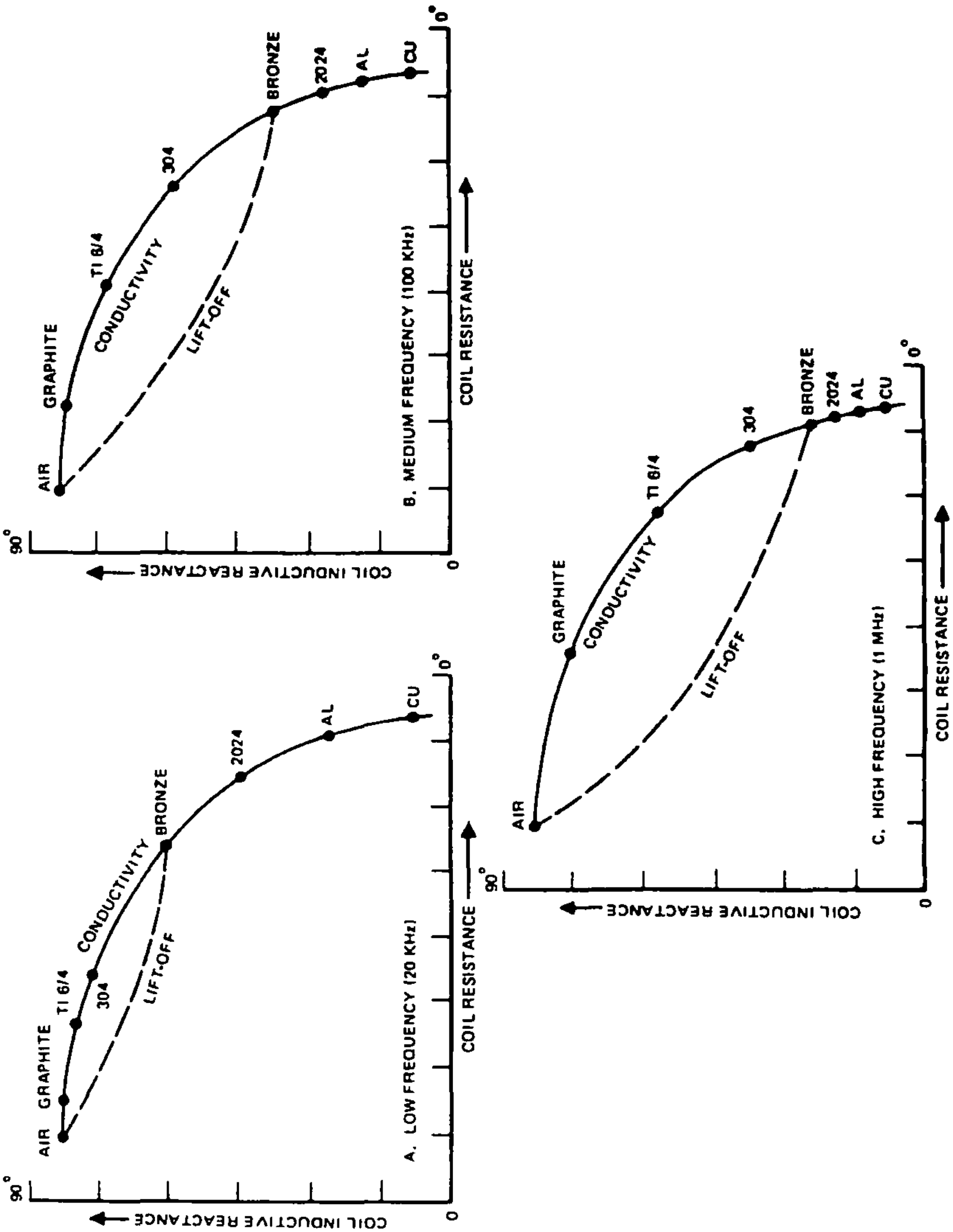
Figures 2.4(4) through 2.4(6) show impedance-plane diagrams with thickness variables indicated. A proper test point would greatly depend upon the particular range of thickness being measured. It is repeated that these curves are frequency dependent; and by changing the test frequency, a shift in the thickness ranges along the curve will occur, as is shown in Figure 2.4(6).

2.4.3 CONDUCTIVITY MEASUREMENTS

Again, an impedance-plane diagram should be constructed including the particular conductivity values to be measured. If lift-off is the largest undesirable variable of concern, then point "D" in Figure 2.4(3), or some other point on the line D to E, such as "E," could be considered as a test point for conductivity variables around alloy A.

Frequency is also a consideration for conductivity measurements. Figure 2.4(10) shows the shift in relative positions on the impedance-plane of the conductivity for various materials. As frequency is changed this shift in conductivity occurs and the angle between the lift-off curve and the conductivity curve changes. As higher frequencies are used, this angle becomes larger, and will allow for better separation between lift-off variables and conductivity variables. This "advantage," however, must always be considered along with any "disadvantages" that may occur because the use of a higher frequency will limit the test to near surface measurements of the conductivity and will not allow deeper penetration.

These specific examples of test methods will prove useful for most eddy current testing. If an oscilloscope display unit is being used, where both resistive and reactive effects are continously displayed, then the test setup would be much easier and quicker. Plotting of individual points can be bypassed, and immediate separation between variables is usually obvious.



2.4(10). Frequency effect on impedance-plane diagrams.

2.5 STANDARDS

Success in eddy current testing will often depend upon the standards available and in their proper use. Both general and specific comments on standards follow.

2.5.1 GENERAL REQUIREMENTS

The variables found in eddy current testing are almost always non-linear. There are some situations where the variables are not even monotonic. Figure 2.4(5), as an example, shows that over certain thickness ranges, the thickness impedance curve reverses directions even though changes in the thickness continued in the same direction. Actually, there are test points on all impedance-plane diagrams where signal reverses will occur. Therefore, intermediate variable standards will often be required in addition to standards that cover the end points of the tested variables. In conductivity tests, minimum standards that are used for calibration are often provided with the equipment. For greater accuracy, however, additional standards that cover the specific range and material being tested are recommended.

Alloy segregation, heat treat testing, hardness determination, and thickness measurement must have standards that properly match all the changes in the variables that might exist in the test. Standardization and setup is extremely critical to inspection for defects . Inspection choices might include different frequencies, different probes, different orientations, or different procedures in order to obtain sufficient information required.

Many standards are commercially available. Some standardization information is provided by the National Bureau of Standards.

2.5.2 SPECIFIC REQUIREMENTS

2.5.2.1 Sorting Standards. In sorting using the absolute (encircling) coil method, a known acceptable calibration standard and a known unacceptable standard are required. When using the comparative (encircling) coil method, usually two known acceptable specimens of the piece tested and one known unacceptable specimen are required. For a three-way sort it is best to have three calibration standards, two of which represent the high and low limits of acceptability for one group or one each of the two unacceptable groups. The third standard represents the acceptable lot of material.

2.5.2.2 Coating Thickness Measurements Standards. Calibration Standards for thickness can be foils of known thicknesses laid on a proper substrate or actual coatings on a prepared substrate.

2.5.2.3 Conductivity Standards. Primary standards are standards which have a value assigned through direct comparison with a standard calibrated by National Bureau of Standards or have been calibrated by an agency which has access to such standards. The primary standards are usually kept in a laboratory environment and are used only to calibrate secondary standards.

Secondary standards are those standards supplied with the instrumentation or standards constructed by the user for a specific test. These standards are used to calibrate the instrumentation during most testing of materials.

2.5.2.4 Standards for Tubular Products. The standard used to adjust the sensitivity of the apparatus shall be free of interfering discontinuities and shall be of the same nominal alloy, heat treatment, and dimensions as the tubular products to be examined. It shall be of sufficient length to permit the spacing of artificial discontinuities to provide good signal resolution and be mechanically stable while in the examining position in the apparatus. Artificial discontinuities placed in the tube shall be one or more of the following types:

a. Notches - Notches may be produced by Electric Discharge Machining (EDM), milling, or other means. Longitudinal, transverse notches, or both may be used. Orientation, dimensions, configuration and position of the notches affect the response of the eddy current system.

b. Holes - Drilled holes may be used. They are usually drilled completely through the wall. Care should be taken during drilling to avoid distortion of the test piece and hole.

2.6 APPLICATIONS

Eddy current testing applications are extensive. They are used in raw material manufacturing plants to inspect tubing, wire, pipe, bolt holes, for small parts and large parts. There are automatic inspection stations where the rate of inspection is limited only by the test frequency used in the test circuits. Eddy current testing is an excellent method to measure paint and coating thicknesses, to separate alloys, to measure electrical conductivity values, indeed almost any electromagnetic property or geometric variable can be considered. The main limitations to the choice of eddy current testing are that the material must include at least one element that is electrically conductive; that eddy current is limited in its depth of penetration, always being more concentrated at the surface than below the surface; and that it is often affected by more variables than desired for measurements. Eddy current testing will be greatly limited when separation of these variables cannot be reasonably achieved. It will also be limited when standards or standardization methods are not available.

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2.7 GUIDELINES FOR SPECIFIC DISCIPLINES

Administrators, designers, production engineers, quality assurance personnel (QA), NDT engineers, and technicians should study section 1.5 (in Chapter 1). Each should study the areas that apply to others as well as their own identified areas.

2.7.1 ADMINISTRATORS

Administrators must recognize that eddy current testing, as with other NDT methods, must have standards. The standards required usually vary with each specific task. Knowing that an eddy current facility exists or eddy current equipment is on hand does not mean that it can be directly applied to a new task. Therefore, administrators must ensure adequate lead time and funding for the ordering or production of proper standards and confirming their adequacy.

2.7.2 DESIGNERS

When designers are aware that eddy current inspections will be required, they should consider the difficulties of using eddy current where edge effects are present, where more than one variable may be present, or where coating thicknesses must be measured and both the coating and substrate are conductive. Also, designers can improve eddy current successes by considering implants that can act as standards. If a component has a set of partially drilled holes, require one or two be drilled to a depth that an eddy current response will occur from the opposite side. If inspections for cracks must be accomplished, present an interface that has a controlled gap that will duplicate an acceptable or unacceptable condition. Certainly, these "implants" cannot always be considered, but often they can be added at almost no additional cost or loss in component efficiency.

2.7.3 PRODUCTION ENGINEERS

It is true that eddy current signals travel with the speed of light, and few nondestructive test methods have quicker response times between testing and results. However, almost all eddy current devices require meter needles to move, or switches to operate, or other actions to occur that do place limits on inspection rates. Also, the basic frequency of the eddy current signal must also place a finite limit on the inspection rate. Therefore, production engineers must consider proper limits on sensor head velocity rates and/or specimen motions in eddy current inspection systems.

2.7.4 QUALITY ASSURANCE PERSONNEL

Proper calibration of eddy current devices will be a concern to Quality Assurance personnel. Proper calibration will often require temperature controls and frequency controls that are not normally established. Although eddy current testing is often simple, because it is potentially affected by a multitude of electromagnetic and geometrical variables, it can in many situations be one of the more difficult methods to apply.

2.7.5 NDT ENGINEERS

To maximize successful eddy current operations, the two most important elements, other than personnel and their training, are the use of adequate equipment and adequate standards. All those involved in eddy current testing should understand the potential complexity of eddy current testing. Standards that represent all the variables that are present should be used.

It is vital to recognize that separation of all variables is not always possible. This does not mean that eddy current testing is of no value under these circumstances. A partial separation may be sufficient when combined with other inspection procedures.

Because of the large number of variables involved, experience with every variable helps in their recognition or identification if they unexpectedly occur in a test. When edge effect, lift-off, magnetic permeability, conductivity (heat treat, alloy, work hardening, temperature, and all other parameters that affect conductivity) are all to be considered along with a multitude of test coil geometries and circuit parameters, an inexperienced operator will often miss observations that are important to the adequate interpretation of the results of the test. Only careful attention to details and procedures, with impedance-plane variables well established by an adequate number of standards, will assure that acceptable results will be attained.

2.7.6 NDT TECHNICIANS

One source of difficulty for technicians will always be the unexpected appearance of an unknown variable while measuring another variable. One of these unexpected variables can be a change in temperature. Temperature changes can be due to normal environmental changes, those seen within each day, or due to the effects of equipment warm-up or overheating, or due to heating or cooling sources introduced by surrounding equipment.

Temperature changes can have a multitude of effects. Sometimes the signal source of the coil is not compensated for temperature changes resulting in frequency and amplitude variations. Figure 2.4(10) shows that a change in frequency can duplicate what is thought to be a change in conductivity. Besides these "artificial" changes, the actual property of the standards and/or specimens may also change with temperature. Therefore, standards and specimens used for setup and test should always be at the same temperature. When testing for very small changes, and when specimen and standards are not at ambient temperature, great care must be exercised by the technician in how he picks up and holds these parts. Many times just the temperature change caused by hand contact is sufficient to introduce an error. It is wise to develop the habit of not directly touching the test standards or parts during a test.

Sometimes, especially when measuring thicknesses of parts, a test being conducted with the parts lying on a bench with a conductive surface will result in misleading readings. Work stations with nonconductive surfaces should be used to preclude such influences.

The beginning and end of every eddy current test should include routine checks of the procedure with standards. Such checks should also be conducted at reasonable time intervals during the testing.

2.8 SAFETY

Personnel safety in eddy current testing involves standard safety practices found in almost all industrial settings. Most eddy current devices require an external electrical power source. Therefore, all safety procedures relating to the handling of power cords, their maintenance and their use, must be observed. Damaged insulation, positioning cords in places where they can be stepped on, or where they can trip passing personnel, or cause equipment to be pulled off of table tops are all safety points that can be monitored.

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2.9 GLOSSARY

Reference ASTM E-268 "Standard Definitions of Terms Relating to Electromagnetic Testing.

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2.11 INDEX

Custodians:

Army -- MR
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Review activities:

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Preparing activity:

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Project No. NDTI-0047

(WP# ID-1337P/DISC-0010v. FOR AMMRC USE ONLY).

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

(See Instructions – Reverse Side)

1. DOCUMENT NUMBER	2. DOCUMENT TITLE
MIL-HDBK-728/2	EDDY CURRENT TESTING

3a. NAME OF SUBMITTING ORGANIZATION

b. ADDRESS (Street, City, State, ZIP Code)

4. TYPE OF ORGANIZATION (Mark one)

- ☐ VENDOR
- ☐ USER
- ☐ MANUFACTURER
- ☐ OTHER (Specify): ______

5. PROBLEM AREAS

a. Paragraph Number and Wording:

b. Recommended Wording:

c. Reason/Rationale for Recommendation:

6. REMARKS

7a. NAME OF SUBMITTER (Last, First, MI) – Optional

b. WORK TELEPHONE NUMBER (Include Area Code) – Optional

c. MAILING ADDRESS (Street, City, State, ZIP Code) – Optional

8. DATE OF SUBMISSION (YYMMDD)

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PREVIOUS EDITION IS OBSOLETE.