Nondestructive Examination (NDE) Technology and Codes
Student Manual

Chapter 9.0

Volume 2

Introduction to Eddy Current Testing Examination

TABLE OF CONTENTS

LIST OF FIGURES

9.0 INTRODUCTION TO EDDY CURRENT TESTING EXAMINATION

Learning Objectives:

To enable the student to:

1. Understand the theory and principles upon which eddy current testing (ET) examination is based.
2. Recognize the variables associated with ET.
3. Become familiar with basic instrument types used.
4. Understand the principles of the presentation of ET data on impedance plane displays.
5. Become familiar with the basics of heat exchanger tubing examination using ET.
6. Understand typical reference standards used.
7. Become familiar with code requirements.
8. Recognize the advantages and limitations of ET.

9.1 History

Evolution of the ET method resulted from various discoveries about the relationship between electricity and magnetism. In 1820 Hans Oerstead discovered electromagnetism resulting from electrical current flow through a conductor creating a magnetic field around that conductor.

In 1823 Michael Faraday discovered electromagnetic induction (Faraday's Law), the basic principle of eddy currents: relative motion between a magnetic field and conductor causes a voltage to be induced in that conductor. During an ET examination, alternating magnetic fields indirectly develop circulating electrical currents in an electrically conductive object. The manner in which these currents flow provides data that can be displayed and interpreted.

Eddy currents were identified by James Maxwell in 1864. The term "eddy currents" resulted from the similarity in movement of these circulating electrical currents to the whirlpool activity of so-called "eddies" in liquids. Eddy currents are defined as circulating electrical currents indirectly induced in an isolated conductor by an alternating magnetic field. The alternating magnetic field is developed through and around a coil connected to the AC generator output of an eddy current instrument. When the alternating magnetic field is brought near a metallic material, its flux lines affect the atoms of the material in such a way that electrons are passed from one atom to the next. However, in contrast to electricity conducted along the length of a wire, the electricity generated by the test coil's lines of force has a circular eddy-like pattern.

The extensive use of ET results from the method's sensitivity to the following variables:

- Conductivity variations,
- Presence of surface and subsurface discontinuities,

- Spacing between coil and specimen (lift-off distance),
- Material thickness,
- Thickness of plating or cladding on a base metal,
- Spacing between conductive layers, and
- Permeability variations.

Major application areas include the following:

- In-service examination of tubing at nuclear and fossil fuel power utilities, at petrochemical plants, on nuclear submarines, and in air conditioning systems;
- Aircraft structures and engines;
- Production examination of tubing, pipe, wire, rod and bar stock; and
- Rapid sorting for a wide range of parts.

9.2 Personnel Qualification and Certification

ET is an essential and important NDE method and requires a high degree of expertise, formalized training and significant experience. ET examiners must be highly qualified if ET is to be effective for nuclear power plant examinations.

The 2007 Edition with 2008 Addenda of the ASME Code Section V requires that NDE personnel be qualified in accordance with either:

SNT-TC–1A (2006)
ANSI/ASNT CP-189 (2006 Edition), or
ACCP

Qualification in accordance with a prior edition of either SNT-TC–1A or CP-189 is considered valid until recertification. Recertification must be in accordance with SNT-TC-1A (2006 Edition), CP-189 (2006 Edition), or ACCP.

Section XI requires that personnel performing NDE be qualified and certified using a written practice prepared in accordance with ANSI/ANST CP-189 as amended by Section XI. IWA 2314 states that the possession of an ASNT Level III Certificate, which is required by CP-189, is not required by Section XI. Section XI also states that certifications to SNT-TC-1A or earlier editions of CP-189 will remain valid until recertification at which time CP-189 (1995 Edition) must be met.
A Level II Eddy Current examiner, who is a high school graduate, must complete one of the following for Section V and only the CP-189 requirements for Section XI.

The SNT-TC-1A requirements are:

	Training	Experience
Level I	40 hrs	210* hrs / 400**hrs
Level II	40 hours	630* hrs / 1200**hrs

NOTES:

1. To certify to Level II directly with no time at Level I, the training and experience for Level I and II shall be combined.

2. Training hours may be reduced with additional engineering or science study beyond high school. Refer to Chapter 2 and SNT-TC-1A.
3. There are no additional training requirements for Level III. Refer to Chapter 2 of this manual for Level III requirements.

The CP-189 requirements are:

	Training	Experience
Level I	40 hours	200*/400**
Level II	40 hours	600*/1200**

* Hours in ET/** Total Hours in NDE

NOTES:

Experience is based on the actual hours worked in the specific method.

A person may be qualified directly to NDT Level II with no time as certified Level I providing the required training and experience consists of the sum of the hours required for NDT Level I and NDT Level II.

The required minimum experience must be documented by method and by hour with supervisor or NDT Level III approval.

While fulfilling total NDT experience requirement, experience may be gained in more than one (1) method. Minimum experience hours must be met for each method.

In addition, Section XI Appendix IV specifies performance demonstration requirements for ET examination procedures, equipment, and personnel used to detect and size flaws in piping and components not including steam generator heat exchanger tubing examination. Appendix IV specifically applies to the acquisition process and not to personnel involved in the acquisition process. Such personnel are covered under the employer's program.

This appendix includes Scope, General System, and Personnel Requirements, Qualification Requirements, Essential Variable Tolerances and Record of Qualification.

There is also a supplement to Appendix IV that addresses the essential variables associated with ET data acquisition instrumentation and establishes a methodology for variable measurements.

9.3 Principles

In ET examination, the instrument and coil assembly function together. The instrument's AC generator applies an alternating voltage of a certain frequency to the coil (illustrated in Figure 9-1), which causes an alternating current to flow through the coil.

9.3.1 Electromagnetic Induction

The current in the coil develops a magnetic field, called the primary field, around the coil as illustrated in Figure 9-2. This field becomes the source of two induction processes induced by the

coil's flux: (1) back voltage into the coil that causes inductive reactance (Indicated by X_L on Figure 9-3) and (2) voltage into the specimen that causes eddy currents to circulate (Figure 9-4). The eddy currents cause friction when they circulate, resulting in generation of heat in the test material. Thus, there is a conversion of electrical energy into thermal energy causing an effective resistive load on the test coil. Both types of induction show on the display.

The eddy currents generate a magnetic field of their own, called the secondary field, which reacts with the primary field that the coil is generating (Figure 9-5).

9.3.2 Eddy Current Characteristics

Various material conditions such as the presence of discontinuities, changes in material properties, or changes in material thickness, affect the flow of eddy currents in the material. Changes in the flow of eddy currents cause changes in the magnetic field that the eddy currents return to the test coil. Changes in this magnetic field cause changes in the inductive reactance and effective resistance of the coil that result in changes in the flow of electrical current through the coil. Changes in electrical current flowing through the coil produce a change in the impedance indication on the instrument's display.

Eddy currents flow in closed loops (concentric circular paths) parallel to the turns of the coil and perpendicular to the coil's flux, as illustrated in Figure 9-6. Therefore, the orientation of eddy current flow in the specimen depends upon the orientation of coil flux to the specimen, which in turn depends on the orientation of the turns of the coil to the specimen. Orientation of the coil's turns and, thus eddy current distribution, are determined by the coil's configuration. Basic configurations include surface coils, encircling coils, and internal coils.

Eddy current flow is virtually undisturbed by discontinuities oriented parallel to their flow paths (see Figure 9-7a) and greatly disturbed by discontinuities oriented perpendicular to their flow paths (Figure 9-7b). Since eddy currents attempt to flow in unbroken loops, they follow the path of least resistance around non-conducting obstacles, thereby increasing their resistive path and reducing their amplitude.

The flow of eddy currents is analogous to the flow of compressible fluids. While the flow paths are circular when eddy currents are undisturbed by non-conducting material boundaries and discontinuities (Figure 9-8a), the flow paths distort and compress to accommodate intrusion of their flow, as shown in (Figure 9-8b), illustrating edge effect.

The direction of eddy current travel continually alternates between clockwise and counter-clockwise movement and in the direction opposite to the flow of the primary current.

ET performance is generally described by three criteria:

Sensitivity - This is the minimum size of discontinuity that can be displayed from a given depth distance in the material,

Penetration - Penetration is the maximum depth from which a useful signal can be displayed for a particular application, and

Resolution - Resolution is the degree to which separation between signals can be displayed.

ET performance depends primarily on test material properties, test frequency, and coil design. Because only frequency and coil design are selectable, they are the primary controls over performance. The following sections discuss in more detail the important variables and their effect on ET performance.

9.3.2.1 Material Properties

9.3.2.1.1 Conductivity

Conductivity is a material characteristic that describes the ease with which electrons pass through a given material. Each metal is assigned a conductivity value on a scale called the International Annealed Copper Standard (IACS). According to the IACS, conductivity values are rated in percent, with the conductivity of pure copper being 100 percent.

An increase in conductivity of the test material causes an increase in sensitivity to discontinuities, but a decrease in penetration of eddy currents into the material. As the coil's flux field expands, voltage is induced first on the surface and then at increasing depths in the material. In high conductivity materials, a considerable eddy current flow (and thus a strong secondary flux field) is developed at the surface. This results in a substantial cancellation of primary flux. Because the primary flux has been greatly weakened, less primary flux is available to develop eddy currents at greater depth.

The following factors can cause changes in conductivity within a material:

Material Hardness - Variations in material hardness affect conductivity. As hardness increases, conductivity decreases and penetration increases. As a matter of interest, greatest conductivity is apparent in the annealed state of nonferrous alloys.

Chemical Composition - Variations in chemical composition within an alloy affect conductivity.

Mechanical Processing - Material processing, such as cold working, affects lattice structure, which causes minor conductivity changes.

Thermal Processing - Thermal processing, such as heat treatment, causes hardness changes that are detectable as conductivity changes.

Residual Stresses - Residual stress in a material causes unpredictable conductivity changes. This is an undesirable condition.

Temperature - Variations in material temperature causes conductivity to change. As material temperature increases, conductivity

decreases. This is an undesirable condition. As a result, care must be taken that material temperature does not vary during an examination and that reference standards are the same temperature as the test specimen.

9.3.2.1.2 Permeability

Permeability is the relative ability of a material to become magnetized when subjected to a magnetizing force, that is, when placed in a magnetic field. Ferromagnetic metals (including iron, carbon steels, 400-series stainless steel, nickel, and cobalt) have high permeability. The alternating magnetic field of an eddy current coil becomes highly concentrated in such materials and overpowers the eddy current response, causing the system to display permeability rather than conductivity variations. However, since essentially the same factors that influence conductivity also influence permeability, the permeability signals can provide useful information.

As material permeability increases, signals resulting from permeability variations increasingly mask eddy current signal variations. This effect becomes more pronounced with increased depth. Permeability thus limits the effective penetration of eddy currents.

9.3.2.1.3 Test Display of Material Property Variations

Care must be taken during examination to ensure separation of variables on the display. Since meter instruments can display only up-scale or down-scale deflections, the instruments must be operated so that only one material variable is displayed. However, with impedance plane display cathode ray tube (CRT) instruments, each type of material condition presents data in a characteristic manner, which results in the separation of variables and facilitates the interpretation of signals.

9.3.2.2 Frequency

As test frequency is increased, the density of eddy currents on the surface increases and sensitivity to surface discontinuities also increases, permitting increasingly smaller surface discontinuities to be detected. As frequency is decreased, material penetration depth increases, and the eddy current density decreases on the surface.

Eddy currents are subject to “skin effect”, in which current density is maximum at the material surface and decreases rapidly (exponentially) with depth. The material depth at which current density decreases to 36.8 percent of surface current density is called the standard depth of penetration.

In addition, eddy currents experience a linear phase lag with depth. As depth increases, eddy current activity is progressively delayed. Phase lag in the specimen proceeds at the rate of one radian (57.3 percent) per standard depth of penetration. However, phase lag is displayed at approximately twice that amount (Figure 9-9). This is discussed in more detail in Section 9.5.5.

9.3.2.3 Test Specimen Geometry

Test specimen geometry restricts eddy current flow due to physical differences such as size or thickness.

Material Thickness - Thickness can be measured because changes in thickness affect eddy current flow in the test material. As the material becomes thinner, eddy current flow becomes restricted.

Material Discontinuities - These discontinuities cause indications relative to the extent that the size and depth of the discontinuities disturb eddy current flow. Thus, discontinuities whose major dimensions are perpendicular to eddy current flow paths and which are located near the test surface provide the strongest indications. Additionally, since eddy currents attain peak amplitude progressively later as depth increases, display of this "phase lag" information can indicate discontinuity depth.

Material Boundaries - Restriction of eddy current flow called "edge effect" occurs when a surface coil approaches the edge of a plate, as shown in Figure 9-8. Similarly, a current flow restriction called "end effect" occurs when an encircling or internal coil approaches the end of a tube or pipe. Both conditions produce strong signals. The effects are intensified by the wider eddy current fields developed by large diameter coils and lower test frequencies.

9.3.2.4 Coil Design

Penetration and sensitivity are affected by coil geometry. As a rule of thumb, eddy current penetration is limited to coil diameter. However, since a small surface discontinuity causes a proportionally greater disturbance in the field of a smaller coil, smaller coils are preferred for detection and localization of small surface discontinuities.

9.3.2.4.1 Coil Coupling (Lift-Off)

When distance between the coil and specimen varies, the intensity of the induced flux field likewise varies. The spacing between a surface coil and the specimen is called "lift-off" (Figure 9-10).

The spacing between either an internal coil or encircling coil and concentrically positioned specimen is called "fill factor". Sensitivity to lift-off and fill factor depends on flux density and thus decreases as distance between coil and specimen increases.

The decrease in sensitivity is nonlinear due to the decrease in flux density according to the Inverse Square Law. Lift-off is useful for measuring the thickness of paint or other nonconductive coatings on the surface of a metal. It can also be used to measure the thickness of nonconductive materials, as long as such materials are placed on a conductive object. Fill factor deflections can indicate material variations such as wall thickness changes or ovality conditions.

9.3.2.4.2 Edge Effect

Restriction of current flow called "edge effect" occurs when an eddy current surface coil

approaches the edge of a geometric change (Figure 9-8). Similarly, as mentioned above, a current flow restriction called “end effect” occurs when an encircling or internal coil approaches the end of a tube or pipe. Both effects produce strong signals. The effects are intensified by the wide eddy current fields developed by large diameter coils and lower test frequencies.

Edge effect can be eliminated by scanning the coil parallel to the material edge at a constant distance from the edge; simple fixtures to accomplish this can be easily fabricated. This technique maintains edge effect at a constant value. Interception of a discontinuity then causes a signal change. The use of smaller diameter coils reduces edge effect and the use of shielded coils virtually eliminates it.

9.4 Equipment

A variety of ET instruments are available for use, from simple to complex. Although these instruments vary greatly in applications flexibility as well as size, most of them operate on similar principles.

Multifrequency instruments offer potential for substantial enhancement of performance. Use of more than one test frequency has three advantages:

- Signals generated by the various frequencies can be “mixed” to prevent display of undesirable signals; suppression of signals from steel supports during examination of nonferro-magnetic tubes is an example. Each additional frequency enables an additional variable to be isolated.
- Use of multiple frequencies allows more than one frequency to be used simultaneously. For example, during in-service tube examination, a higher frequency provides sensitivity to inner diameter discontinuities and a lower frequency provides sensitivity for responding to outer diameter discontinuities.
- Use of multiple frequencies aids signal analysis. The various conditions that can be detected by ET exhibit different responses as frequency is varied.

9.4.1 System Components

All ET instruments require at least three circuit components: alternating current generator, coil, and processing/display circuitry. The level of flexibility designed into each of these elements generally determines how ET instruments differ from each other. ET coils can be classified according to both basic configuration and mode of operation. Coil design, as well as magnitude and frequency of the applied current, all affect the electromagnetic field developed by the coil.

Basic ET equipment consists of an alternating current source (oscillator), voltmeter, and probe. When the probe is brought close to a conductor or moved past a discontinuity, the voltage across the coil changes and this is read off the voltmeter. The oscillator sets the test frequency and the probe governs coupling and sensitivity to discontinuities.

Most ET instruments use an alternating current bridge for balancing but use various methods for lift-off compensation. Send-receive instruments should be used for accurate absolute measurements in the presence of temperature fluctuations. Multi-frequency instruments can be used to simplify discontinuity signals in the presence of extraneous signals.

ET instruments and recording equipment have a finite frequency response which limits the examination speed.

The main functions of an ET instrument are illustrated in the block diagram in Figure 9-11. A sine wave oscillator generates sinusoidal current, at a specified frequency, that passes through the test coils. Since the impedance of two coils is never exactly equal, balancing is required to eliminate the voltage difference between them. Most ET instruments achieve this through an alternating current bridge or by subtracting a voltage equal to the unbalance voltage. In general they can tolerate an impedance mismatch of 5 percent. Once balanced, the presence of a discontinuity in the vicinity of one coil creates a small unbalanced signal, which is then amplified.

The most troublesome parameter in ET is lift-off (probe-to-specimen spacing). A small change in lift-off creates a large output signal.

Figure 9-12 shows a typical eddy current instrument with various control functions. The frequency selector sets the desired test frequency. Frequency is selected by continuous control or in discrete steps from about 1 kHz to 2 MHz.

The balancing controls, labeled X and R are potentiometers. They match coil impedance to achieve a null when the probe is in a discontinuity free location on the test sample. Most instruments have automatic balancing.

The bridge output signal amplitude is controlled by the GAIN control. In some instruments it is labeled as sensitivity. GAIN controls the amplifier of the bridge output signal and does not affect current going through the probe.

Following amplification of the bridge unbalance signal, the signal is converted to direct current signals. Since the alternating current's signal has both amplitude and phase, it is converted into quadrature X and Y components. ET instruments do not have a phase reference. To compensate for this they have a phase shift.

Crack Detection Instruments - Crack detector instruments contain only one coil, with a fixed value capacitor in parallel with the coil to form a resonant circuit. At this condition the output voltage for a given change in coil impedance is maximum. The coil's inductive reactance, X_L, must be close to the capacitive reactance, X_C.

Crack detectors that operate at or close to resonance do not have selectable test frequencies. Crack detectors for non-ferromagnetic, high electrical resistivity materials such as Type 304 stainless steel typically operate between 1 and 3 MHz; those for

low resistivity materials (aluminum alloys, brasses) operate at a lower frequency, normally in the 10 to 100 kHz range. Some crack detectors for high resistivity materials can also be used to examine ferromagnetic materials, such as carbon steel, for surface discontinuities. Normally a different probe is required; however, coil impedance and test frequency change very little.

Crack detectors have a meter output and three basic controls: balance, lift-off, and sensitivity. Balancing is performed by adjusting the potentiometer on the adjacent bridge arm, until bridge output is zero (or close to zero). GAIN (sensitivity) adjustment occurs at the bridge output. The signal is then rectified and displayed on a meter. Because the signal is filtered, in addition to the mechanical inertia of the pointer, the frequency response of a meter is very low (less than 10 Hz). LIFT-OFF control adjusts the test frequency (by less than 25 percent) to operate slightly off resonance. In crack detectors the test frequency is chosen to minimize the effect of probe wobble (lift-off), not to change the skin depth or phase lag.

9.4.2 Data/Displays

Since the impedance plane is a graphic plot of ET information, resistance values are shown on the X axis; inductive reactance values, on the Y axis. Impedance plane display instruments thus present both impedance amplitude and impedance phase angle simultaneously on a CRT screen.

Data on an impedance plane instrument is interpreted by observing the movement of the display dot on a CRT screen while the coil interacts with the specimen. Each type of condition that ET can detect is characterized by a certain pattern of display dot movement. Variables are, in fact, arranged along curves or “loci” on the impedance plane. Generally there are separate curves for each variable. Distribution of information on the impedance plane can be altered by changing frequency. Redistribution of information on the impedance plane by adjustment of frequency is a key technique in optimizing performance.

Sections 9.4.2.1 through 9.4.2.4 describe several types of curves displayed on the CRT.

9.4.2.1 Lift-Off Curves

The zero conductivity point, also called the coil in air or empty coil point, is typically located at a position of low resistance, but of moderately high inductive reactance. This is the impedance point for a coil whose flux is not near any conductive material. However, as a coil is moved toward a conductor, secondary flux changes the coil’s impedance and the display dot moves. The position where movement terminates depends on the conductivity of the test material. The more conductive the test material, the greater the cancellation of primary flux, which causes a greater drop in inductive reactance and movement further downward by the dot. Because the coil and specimen are coupled, the specimen acts as a load on the coil and the effective resistance of the coil also changes. The movement of the display dot is, therefore, a combination of variations in both inductive reactance and effective resistance.

9.4.2.2 Conductivity Curve

Originating at the zero conductivity point is the conductivity curve, sometimes called the comma curve, because of its shape. Different positions along this curve represent non-ferromagnetic materials of different conductivities, whose thicknesses are infinite relative to electromagnetic penetration. That is, the flux lines entering the material, as well as the eddy currents that they generate, are not perceptibly affected by the bottom surface of the material. The counterclockwise extreme of the conductivity curve represents zero conductivity, whereas the clockwise extreme of the curve represents infinite conductivity.

As the frequency is increased, the impedance points for the various conductivities move clockwise along the curve; the lower conductivity materials spread apart along the curve while the higher conductivity materials become compressed at the bottom end of the curve (Figure 9-13). Higher frequencies provide greater separation for conductivity tests on lower conductivity materials (Figure 9-14a). As the frequency is decreased, the impedance points for the various conductivities move counterclockwise along the curve (Figure 9-14b); the higher conductivity materials spread apart while the lower conductivity materials become compressed at the top end of the curve. Lower frequencies provide greater separation for conductivity tests for high conductivity materials (Figure 9-14c). Frequency adjustment also helps separate the lift-off and conductivity variables during conductivity tests. At low frequencies, lift-off curves for low conductivity materials are almost parallel to the conductivity curve.

As frequency is increased, the operating point moves clockwise along the conductivity curve, increasing the angle between the lift-off curve and conductivity curve. Maximum separation is achieved at the so called “knee” of conductivity curve, where the lift-off curve approaches it almost perpendicularly.

9.4.2.3 Thickness Curves

As previously stated, the conductivity curve consists of impedance points for materials whose thicknesses are infinite, relative to electromagnetic penetration. At lesser thicknesses, eddy current flow in the material becomes restricted and the impedance point moves counterclockwise, spiraling away from the conductivity curve. As thickness approaches zero, the impedance point necessarily approaches the zero conductivity point.

A standard depth of penetration is indicated by the δ symbol. It is approximately located on thickness curve at a point slightly to the right of the intersection with the conductivity curve. Again, frequency adjustment optimizes performance. As frequency is decreased, material penetration increases, but thickness resolution on thinner materials decreases. As frequency is increased, material penetration decreases, but thickness resolution on thinner materials increases.

9.4.2.4 Discontinuity Signal Display

In an ET examination, a discontinuity is an interruption of conductivity. The magnitude of an ET discontinuity signal depends on the quantity of interrupted current flow. Length, width, and depth of a discontinuity all affect signal magnitude to the extent that discontinuity, volume, and shape obstruct the greatest amount of electron flow. Because ET density decreases exponentially with depth, a given discontinuity volume disturbs increasingly fewer electrons with depth. The depth of the disturbance, however, causes a linear phase lag of the signal (Figure 9-15).

9.4.3 Basic Coils

The basic coil configuration determines how the coil is packaged to "fit" the object being examined. There are three basic configurations, described in sections 9.4.3.1 through 9.4.3.3.

9.4.3.1 Surface Coils

Surface coils are built into probe type housings for scanning material surfaces. The coil axis is usually perpendicular to the specimen's surface. Surface coils are available in different shapes and sizes to meet different application needs (Figure 9-16). Larger surface probes permit faster scanning and deeper penetration, but cannot pinpoint the location of small discontinuities (Figure 9-17). They are useful for conductivity examination because they tend to average out localized conductivity variations along material surfaces. Conversely, narrow coils are preferred for detecting and pinpointing the location of small surface discontinuities. Because of their smaller diameter electromagnetic fields, narrow coils are less susceptible to edge effect.

9.4.3.2 Encircling Coils

Encircling coils (Figure 9-18) completely surround the specimen, thus they are normally used for production examination of rods, wire, bar stock, pipes, and tubing. Because of "center effect", eddy currents oppose and therefore cancel themselves at the center of solid cylindrical materials examined with encircling coils. Thus, discontinuities located at the center of rods and bar stock cannot be detected with encircling coils. Encircling coils examine the entire circumference of the specimen; however, they cannot pinpoint the exact location of a discontinuity along the circumference.

9.4.3.3 Internal Coils

Internal coils (Figures 9-19 and 9-20) pass though the cores of pipes and tubes; thus, they are normally employed for in-service examinations. Like encircling coils, standard bobbin-wound internal coils examine the entire circumference of the specimen at one time but cannot pinpoint the exact location of a discontinuity along the circumference.

Both manual and automatic means are used to propel internal coils down the length of a long tube. Flexible "u-bend" assemblies are available for navigating extreme curvature of tubing.

9.5 Techniques

During examination, ET instruments and recording equipment are typically connected as in Figure 9-21. The eddy current signal is monitored on a storage CRT and recorded on X-Y and two-channel recorders. Recording on a magnetic tape recorder for subsequent playback is also common.

9.5.1 Impedance Plane Fundamentals

The essential features of impedance plane analysis are:

- The separation of the voltage drop across the eddy current probe coil(s) into voltage drop due to pure resistance and the voltage drop due to inductive reactance.
- The presentation of the impedance vector due to resistance changes and inductive reactance changes as a “spot” on an oscilloscope (Figure 9-22).
- The movement of the impedance spot in different directions is caused by the following different factors:
  - A change in conductivity (or resistivity),
  - A change in lift-off (separation of the probe from the test surface),
  - A change in probe frequency,
  - A change in geometry,
  - A change in probe, or
  - A change in permeability (or reluctance).

9.5.2 Impedance Plane Response to Conductivity Variations

Presentation of conductivity changes on the impedance plane are shown in Figure 9-22. The point where the probe is balanced (nulled) is known as the operating point. It is from this point that all movement of the “spot” is originated.

Measurement of conductivity can be made:

- By setting an intermediate operating frequency that will not exceed 30 percent thickness of the test material for one standard depth of penetration.
- By balancing (nulling) the equipment and calibrating the CRT display as shown in Figure 9-23 to display two known conductivities bracketing the unknown conductivity.

NOTE: The use of reference calibration samples is essential for this task. Reference calibration samples should both bracket and approximate the unknown conductivity for higher accuracy.

9.5.3 Sorting

In the same way that conductivity can be measured, materials can be sorted. Different heat treatments or different alloys, even different permeabilities, are easily discriminated permitting material sorting.

9.5.4 Discontinuities

Location of surface breaking discontinuities is dependent on frequency. Presentation of frequency changes on the impedance plane are shown in Figure 9-24.

Calibration is formally defined as comparison of the instrument to a reference standard. During an actual ET examination, calibration is the process of adjusting the instrument display to represent a known reference standard so that the examination can be a comparison between the specimen and the reference standard. The validity of the examination thus depends upon the validity of the reference standard.

Since there is an infinite variety of a discontinuity condition, it is neither possible nor practical to have a set of reference standards so complete as to replicate every possible condition that could be detected during an examination. Therefore, it is not practical to match each signal with an identical reference signal. Instead, one obtains practical reference standards that contain a manageable number of representative discontinuity conditions. Signals that vary from these must then be interpreted through techniques such as impedance plane analysis.

9.5.4.1 Discontinuity Location in Installed Nonferrous Steam Generator Heat Exchanger Tubing

ET equipment capable of operation in the differential mode or the absolute mode, or both, should be used for this examination. A device for recording data, real time, in a format suitable for evaluation and for archival storage, should be provided when required by the referencing Code Section.

Electronic instrumentation of the ET system should be calibrated at least once a year or whenever the equipment has been overhauled or repaired as a result of malfunction or damage.

Single frequency or multiple frequency techniques are permitted for this examination. Upon selection of the test frequency(s) and after completion of calibration, the probe should be inserted into the tube where it is extended or positioned to the region of interest. Resulting ET signals at each of the individual frequencies should be recorded for review, analysis, and final disposition.

The calibration tube standard (Figure 9-25) should be manufactured from a length of tubing of the same nominal size and material type (chemical composition and product form) as that to be examined in the steam generator. The intent of this reference standard is to establish and verify system response. The standard should contain calibration discontinuities as follows:

- A single hole drilled 100 percent through the wall;
- A flat bottom hole 0.109” in diameter and 60%throuigh the tube wall from the outer surface.
- Four flat bottom holes, 3/16 inch diameter, spaced 90° around the circumference at 20% through wall from the outside surface;

- A 1/16-inch wide, 360° circumferential groove, 10 percent through from the inner tube surface (optional);

Other requirements for the standard include:

- All calibration discontinuities should be spaced so that they can be identified from each other and from the end of the tube.
- Each standard should be identified by a serial number.
- The dimensions of the calibration discontinuities and the applicable ET response should become part of the permanent record of the standard.

9.5.4.2 Calibration Procedure

The examination system should be calibrated utilizing the standard. A summary of the calibration steps follows:

Calibration Using Differential Bobbin Coil Technique (Figure 9-26):

1. The ET instrument is adjusted for the frequency chosen so that the phase angle of a signal from the four 20 percent flat bottom holes is between 50° and 120° rotated clockwise from the signal of the through-the-wall hole (Figure 9-27).
2. The trace display for the four 20 percent flat bottom holes should be generated, when pulling the probe, in the directions illustrated in Figure 9-27, down and to the left first, followed by an upward motion to the right, followed by a downward motion returning to the point of origin.
3. The sensitivity should be adjusted to produce a minimum peak-to-peak signal from the four 20 percent flat bottom holes of 30 percent of the full scale horizontal presentation with the oscilloscope sensitivity set at 1 volt per division.
4. It is common to then adjust the phase or rotation control so that the signal response due to probe motion, or the 10 percent deep circumferential inside diameter groove, or both, is positioned along the horizontal axis of the display.

Calibration Using Absolute Bobbin Coil Technique:

1. The ET instrument should be adjusted for a frequency so that the phase angle between a line drawn from the origin to the tip of the response from the through-the-wall hole and the horizontal axis is approximately 40°. The phase angle formed by a line drawn from the origin to the tip of the response of the four 20 percent flat bottom holes and the through-the-wall response line is between 50° and 120°. (Figure 9-28).
2. The sensitivity should be adjusted to produce a minimum origin-to-peak signal from the four 20 percent flat bottom holes of 30 percent of the full scale horizontal presentation with the oscilloscope sensitivity set at 1 volt per division.
3. It is common to adjust the phase or rotation control so that the signal response due to probe rotation, or the 10 percent deep cir-

cumferential inside diameter groove, or both, is positioned along the horizontal axis of the display 5°.

4. The response may be rotated to the upper quadrants of the display at the option and convenience of the operator.
5. Withdrawing the probe through the calibration tube standard at the probe speed selected for the examination should be repeated. The responses should be recorded for the applicable calibration discontinuities and verified that they are clearly indicated by the instrument and are distinguishable from each other, as well as from probe motion signals.

9.5.4.3 Probe Speed

The typical probe speed during examination should not exceed 14 inch/second. Higher probe speeds may be used if system frequency response and sensitivity to the applicable calibration standards.

9.5.5 Thickness

The effects of edge effect have already been described and edge effect should be clearly discernible from other factors effecting eddy currents. Geometry is different from edge effect and can also be described by reduction in thickness (Figure 9-29).

Phase indications on CRTs are related to the phase change as the eddy currents penetrate the material under test. As the phase change occurs into the material by 57° per standard depth of penetration, it should be quite acceptable that the same phase change occurs again when sensed by a probe on the surface (sensed at 114° total indicated phase change). This phenomenon can be proven. A discontinuity at exactly one standard depth of penetration will give an indication of 2 x 57° = 114° out of phase with lift-off (Figure 9-30).

9.5.5.1 Location of Secondary Layer Corrosion or Cracking

The frequency should be selected to give 90° phase separation between lift-off and material loss. As one standard depth of penetration gives 114° phase angle, if multiplied by 0.7895, the answer will be 90°. So, for 90° phase separation of subsurface discontinuities, the standard depth of penetration frequency should be multiplied by approximately 0.80.

The equipment should be balanced (nulled), and the lift-off set horizontally from the operating point which should be to the lower right hand quadrant of the CRT.

Thinning is represented by a move of the spot up the calibrated thinning line. Similar results will be seen for subsurface cracks except the move of the spot from the operating point on the conductivity curve will be quicker, and include an integration of the phase change through the depth of the crack. If the material thickens from the balance point, the spot will move down the CRT from the lift-off.

The final result of the variations in thickness on the eddy currents is shown in Figure 9-31.

Note the small "comma" shaped curve is the material thickening from the balance (operating) point.

9.5.6 Coatings

9.5.6.1 Variations in Thickness of Plating or Cladding

These variations combine both conductivity and dimensional variables.

Presentation of lift-off changes on the impedance plane is shown in Figure 9-32. The point where the probe is in the balanced condition (nulled) is known as the operating point. It is from this point that all movement of the spot is originated.

Measurement of non-conducting coating thickness (lift-off) can be made using the following procedure:

- The highest frequency should be chosen to give maximum sensitivity to lift-off (and hence accuracy). The equipment should be balanced. This will bring the operating point to the bottom of the conductivity curve.
- The CRT display should be calibrated as shown in Figure 9-33 to display two known non-conducting thickness (plastic foil or shim calibration samples are used) bracketing the unknown coating thickness.

NOTE: The use of reference calibration shims is essential to this task. Reference calibration shims should approximate the unknown for higher accuracy.

9.6 Interpretation and Code Requirements

9.6.1 Written Procedure

All ET examinations should be performed to detailed written procedures, unless otherwise stated in the reference code.

9.6.2 Description of Method

The procedure for eddy current should provide a sensitivity which will consistently detect discontinuity indications equal to or greater than those conditions in the reference specimen. Parts with discontinuities that produce indications in excess of the reference standards should be evaluated in accordance with the procedure that meets code requirements.

9.6.3 Reference Specimen

The reference specimen should be a part of and be processed in the same manner as the product being examined. It should be of the same dimensions and the same nominal composition as the product being examined. Unless otherwise specified in the referencing Code, the reference discontinuities should be transverse notches, drilled holes, or should simulate as near as possible the conditions to be detected.

The reference specimen should be long or large enough to simulate the handling of the product being examined through the examination equipment. The separation between reference discontinuities placed in the same reference

specimen should be not less than twice the length or diameter of the sensing unit of the examination equipment.

9.6.4 Equipment Qualification

The proper functioning of the examination equipment should be checked and calibrated by the use of the reference specimens as follows:

- At the beginning of each production run of given dimensions of a given material,
- After each hour during the production run,
- At the end of the production run, and
- At any time that malfunctioning is suspected.

Acceptance requirements shall be as specified in the referenced code.

9.6.5 Procedure Requirements

The written procedure should include at least the following:

- Frequency,
- Type of coil or probe (e.g., differential coil),
- Type of material and sizes to which applicable,
- Reference specimen notch or hole size, and
- Additional information as necessary to permit retesting.

9.7 Advantages and Limitations of ET Examinations

ET can provide a variety of useful information about an object. In addition, an extensive selection of equipment is available to fit the examination to the application. Frequency adjustment and coil selection are the examiner's primary controls over performance. Information is obtained by monitoring changes in coil impedance caused by variations in the specimen. However, because the process is complex, examiner skill is a critical variable especially for the examination of heat exchanger tubing.

9.7.1 Advantages

The following are advantages of ET:

- This method is sensitive to numerous material variables. Consequently, any of several material properties can be measured providing the other variables are either separately identifiable or suppressed.
- Much of the equipment is portable, light-weight, and battery powered.
- This method is nondestructive. No couplant, powders, or other physical substances are applied to the specimen. The only link between the probe and specimen is a magnetic field.
- Results are instantaneous. As soon as the test coil is applied to the specimen, a qualified examiner can interpret the results. An exception, however, is computer analysis of tape recorded multichannel test data.
- ET testing is ideal for "go/no-go" examinations. Audible and visual alarms, triggered by threshold gates or box gates, are available for high-speed examination.
- There is no danger from radiation or other such hazards.

- Material preparation is usually unnecessary; cleanup is not required.

9.7.2 Limitations

ET also has several limitations:

- The material must be electrically conductive. It is possible to measure the thickness of nonconductive coating on conductive materials.

- ET normally cannot penetrate ferromagnetic materials. Consequently, examination of ferromagnetic material is limited to surface discontinuities only, unless the material has been magnetically saturated using direct current field coils. Magnetic saturation is limited to certain geometries only. In addition, magnetically saturated objects may have to be demagnetized after testing is completed.
- Even for non-ferromagnetic materials, the ET method has limited penetration.

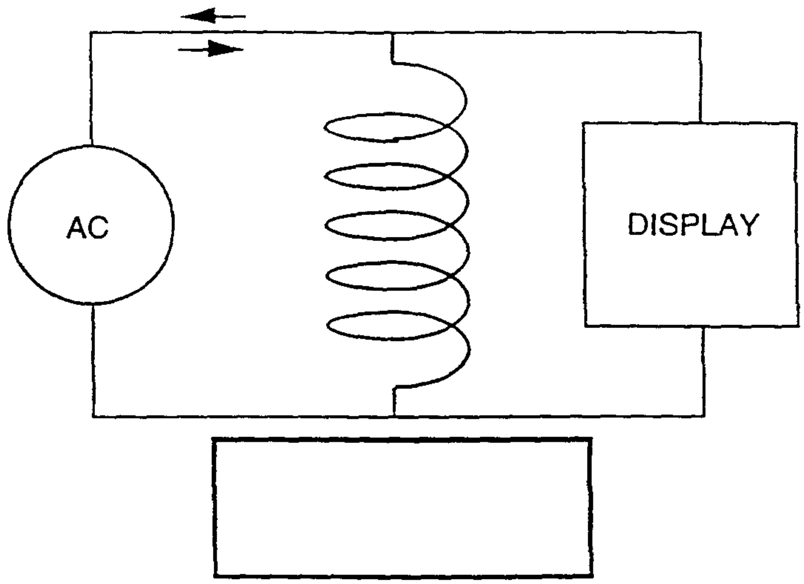


Figure 9-1 Alternating Current Flowing Through Test Coil

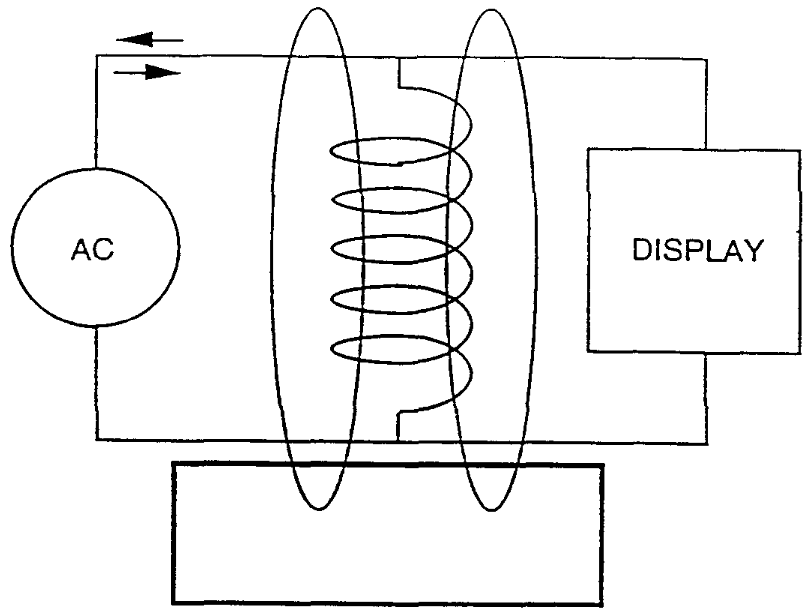


Figure 9-2 Primary Magnetic Field Develops

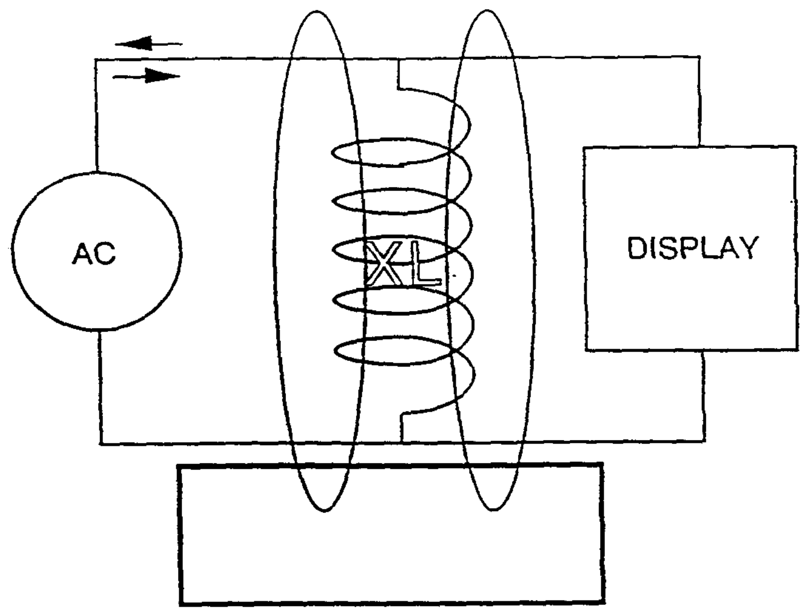


Figure 9-3 Inductive Reactance Occurs

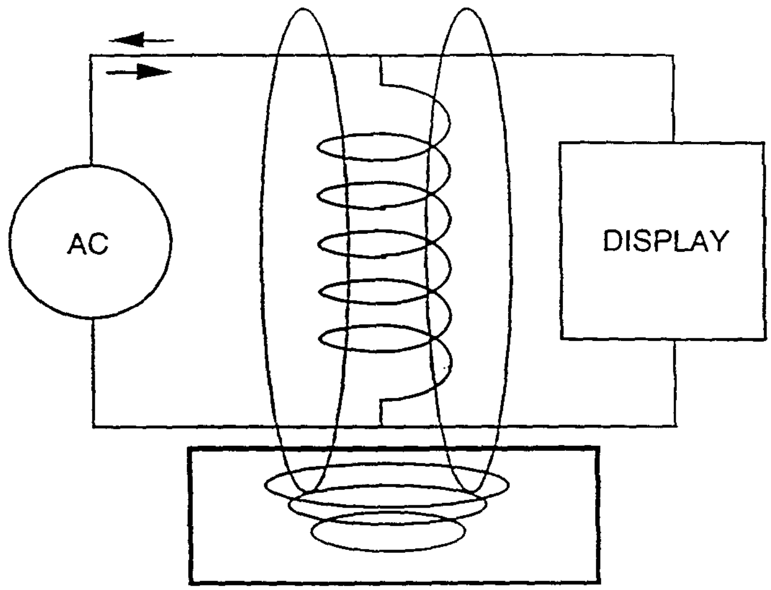


Figure 9-4 Eddy Currents Develop

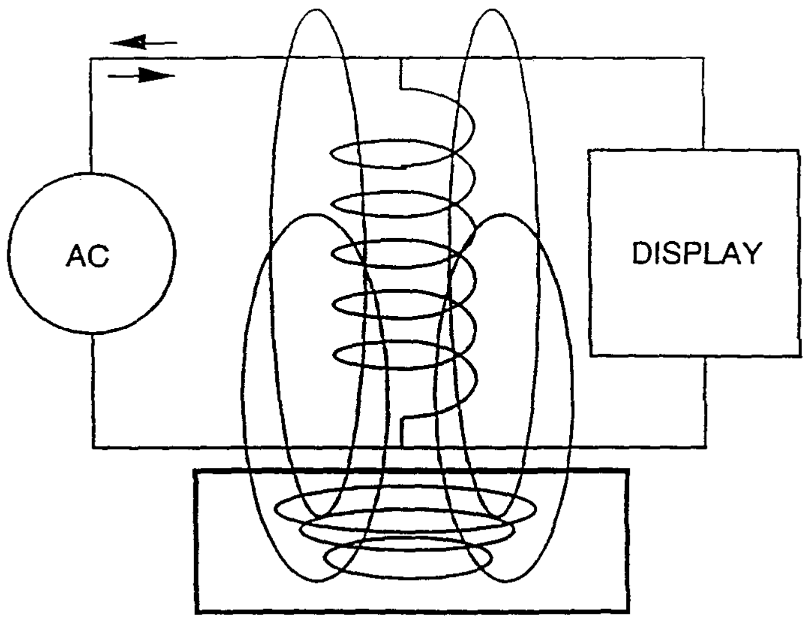


Figure 9-5 Secondary Field Develops

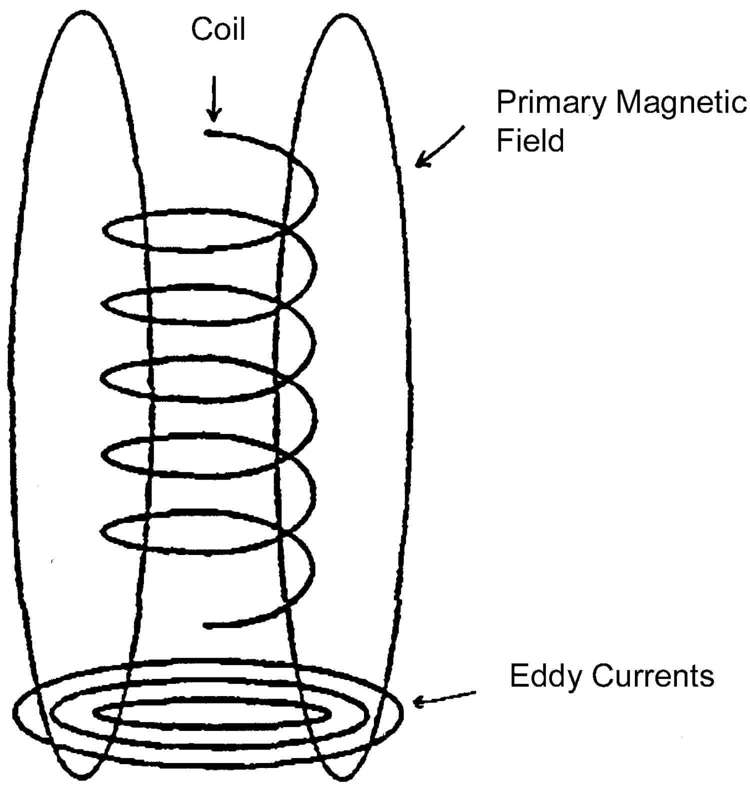


Figure 9-6 Eddy Currents Develop Parallel to the Coil's Turns

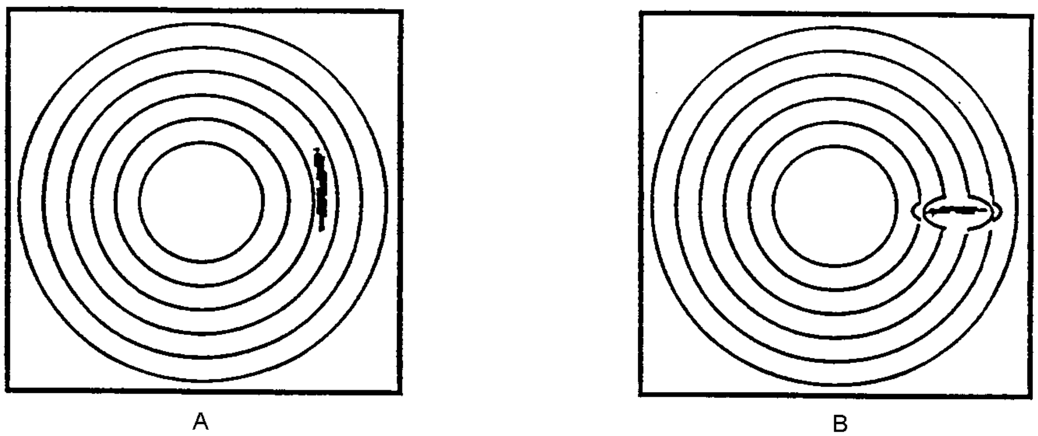


Figure 9-7 Effect of Variation in Discontinuity Orientation on Eddy Current Flow Paths

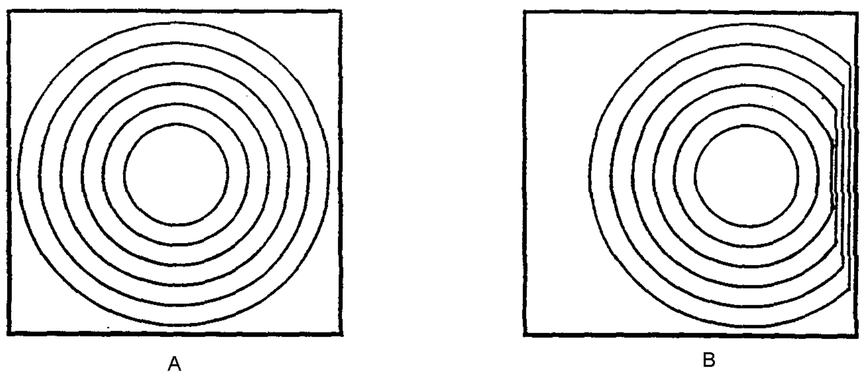


Figure 9-8 Compression of Eddy Current Flow Paths by Material Edge

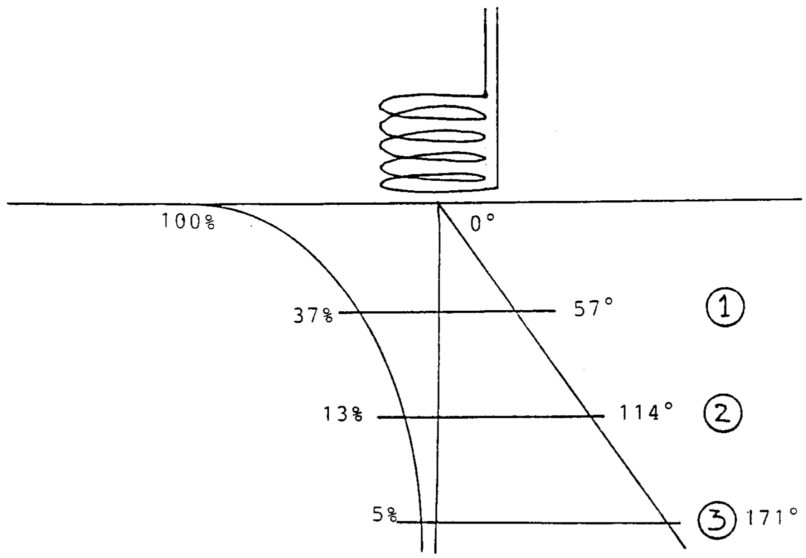


Figure 9-9 Attenuation and Phase Lag of Eddy Currents Penetrating into a Conductive Material

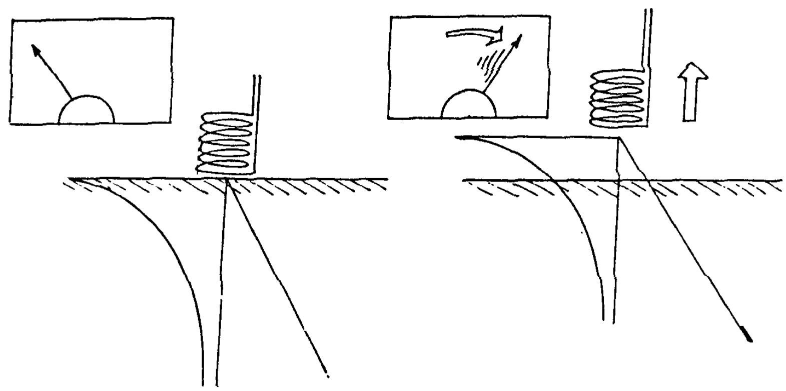


Figure 9-10 Reduction in Eddy Current Strength with Lift-Off Results in Positive Meter Movement Unless Lift-Off is Compensated

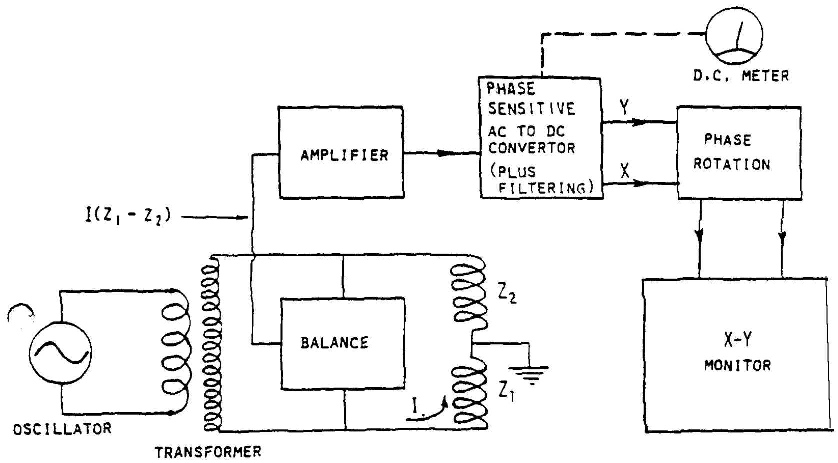


Figure 9-11 Block Diagram of Eddy Current Instrument

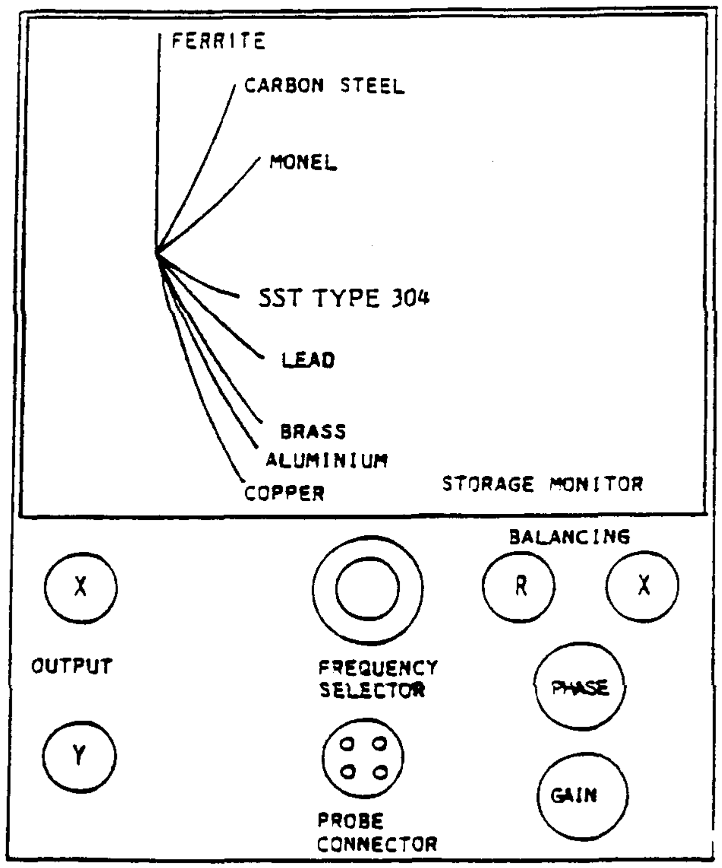


Figure 9-12 Typical Eddy Current Instrument with Storage Monitor

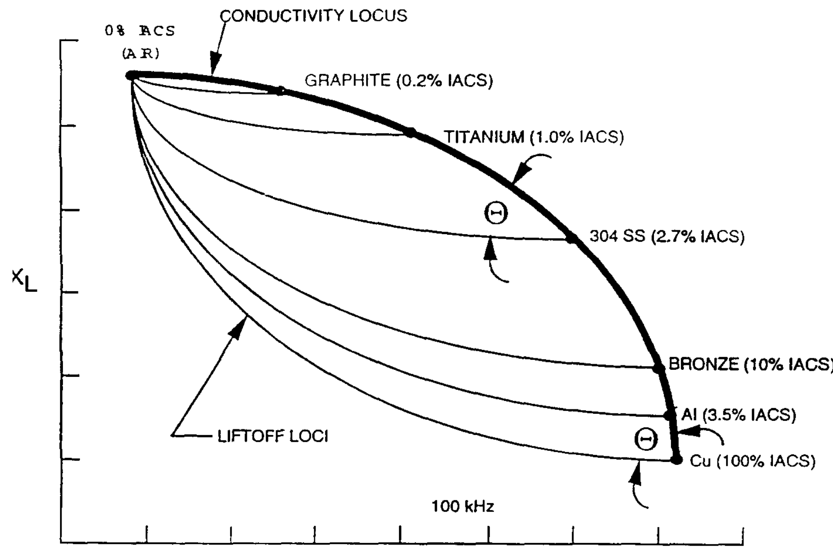


Figure 9-13 Conductivity Curve

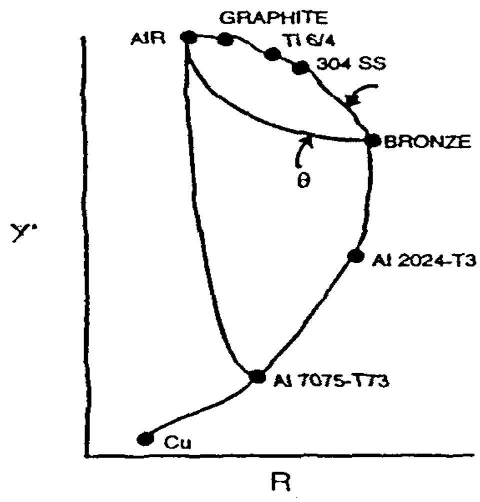


Figure 9-14 (a) Low Frecuency (20 KHz)

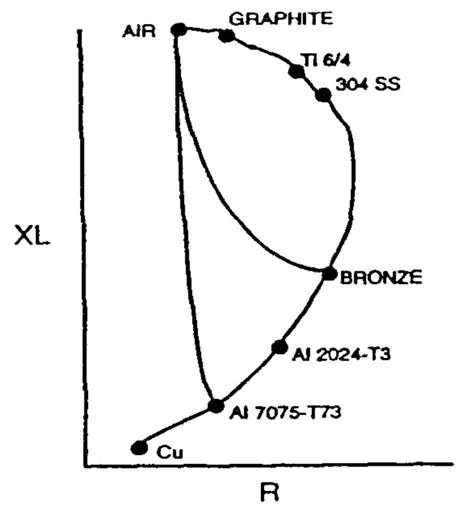


Figure 9-14 (b) Medium Frequency (100KHz)

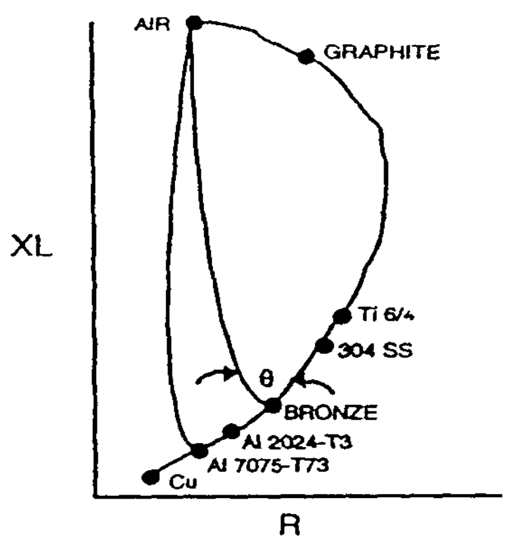


Figure 9-14 (c) High Frequency 1 MHz

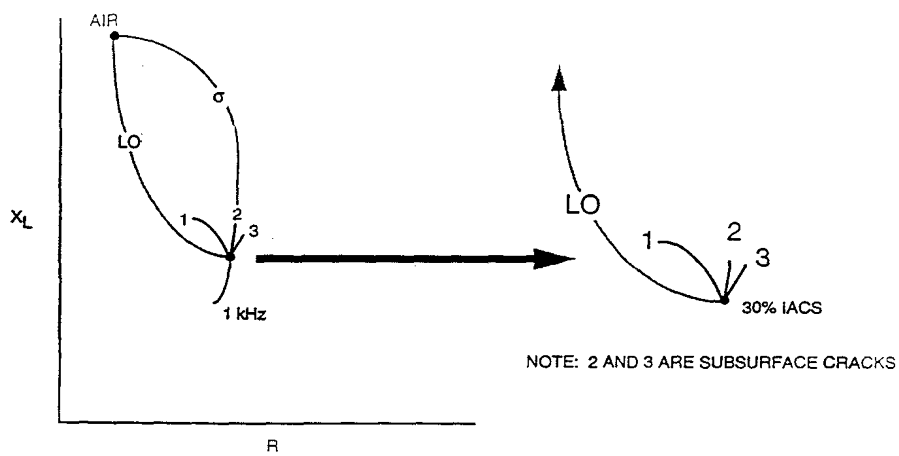


Figure 9-15 Direction of Surface and Subsurface Cracks in Aluminum on the Impedance Plane

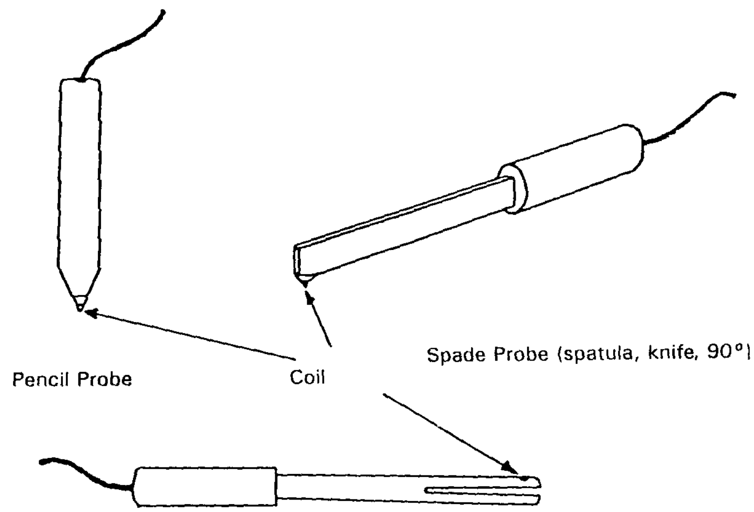


Figure 9-16 Various High Frequency Surface Probes

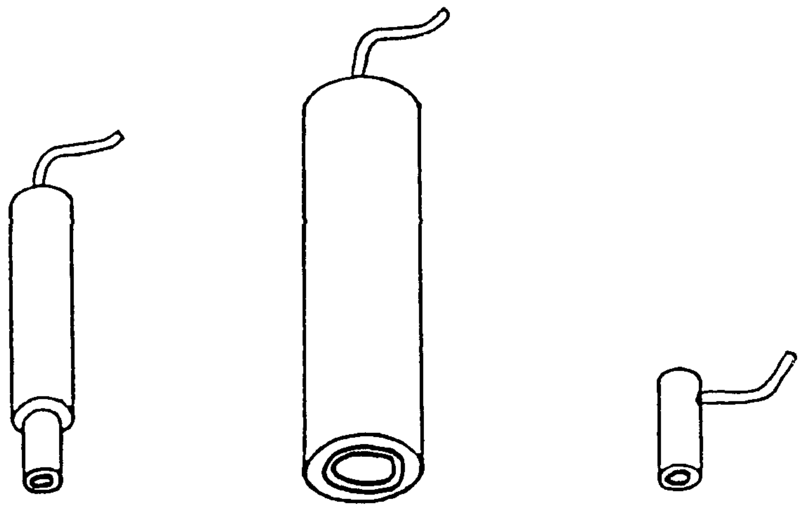


Figure 9-17 Typical Low Frequency Probes

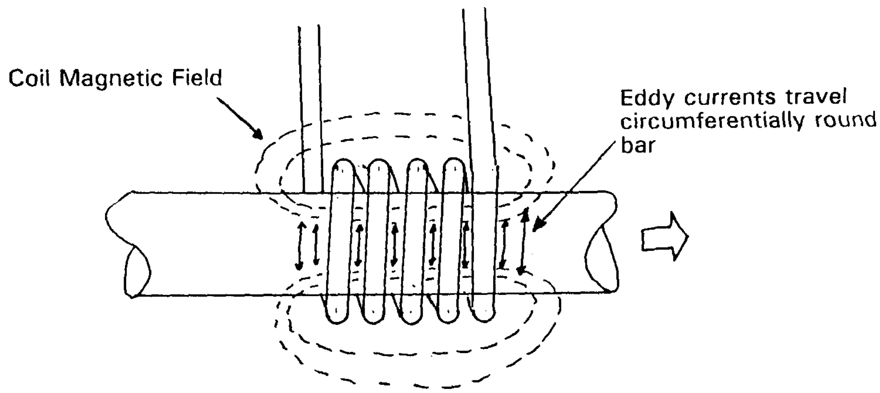


Figure 9-18 Encircling Coil

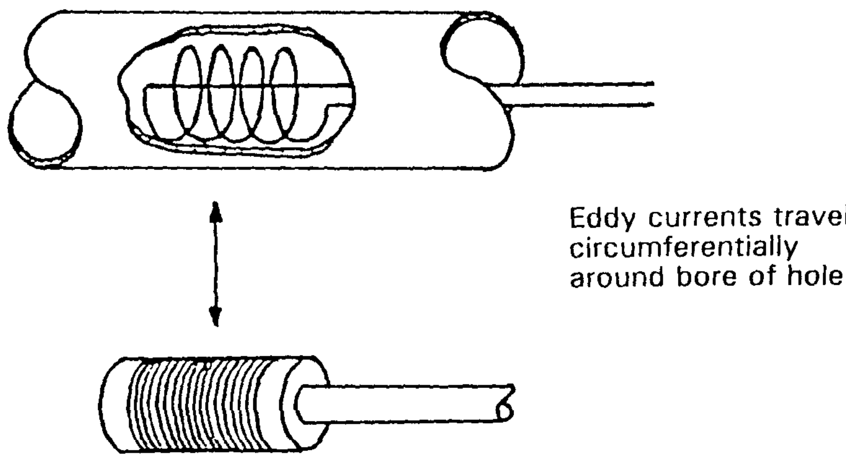


Figure 9-19 Internal Coil (Bobbin Probe)

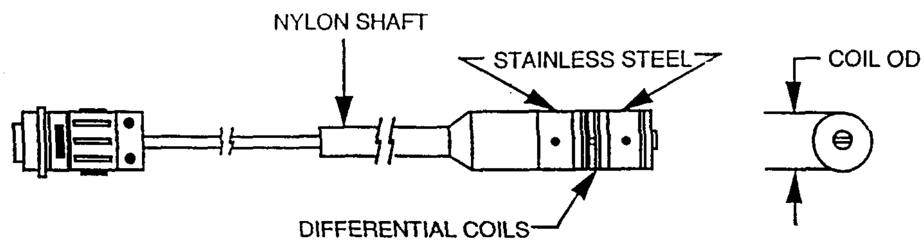


Figure 9-20 Internal (Insertion, Bobbin) Differential Probe

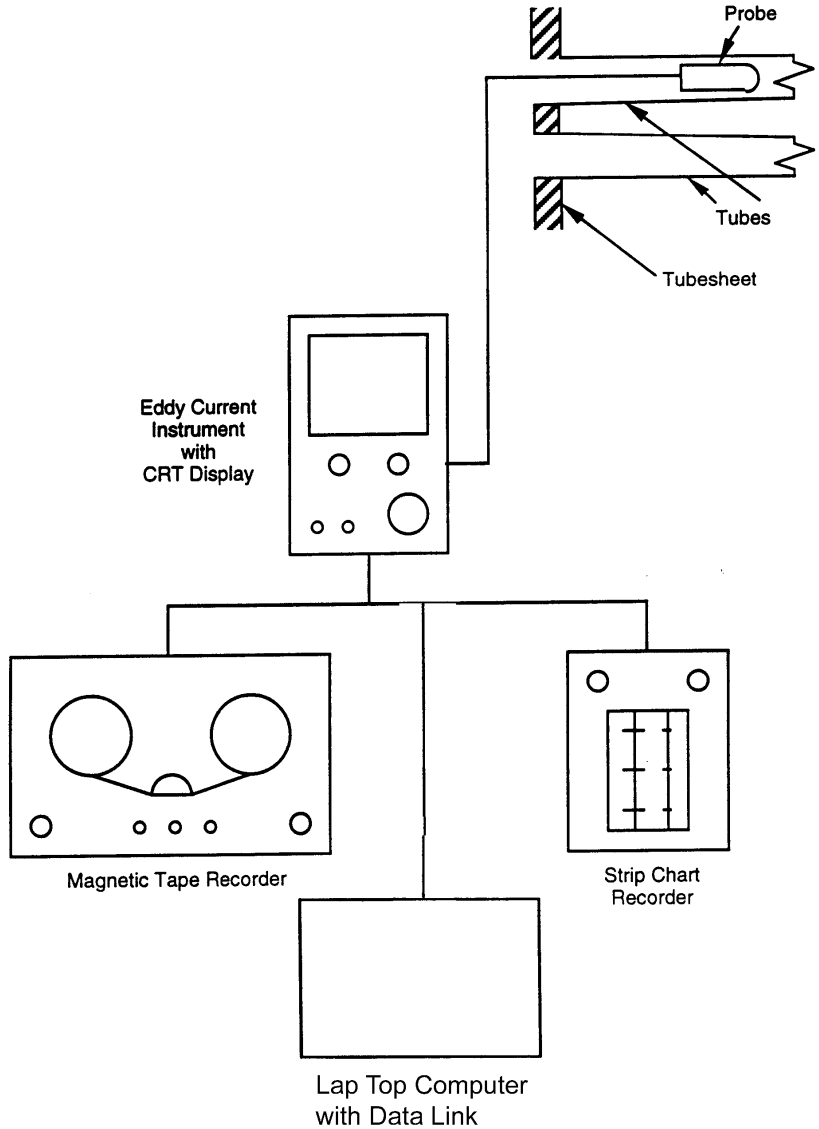


Figure 9-21 Eddy Current Test System

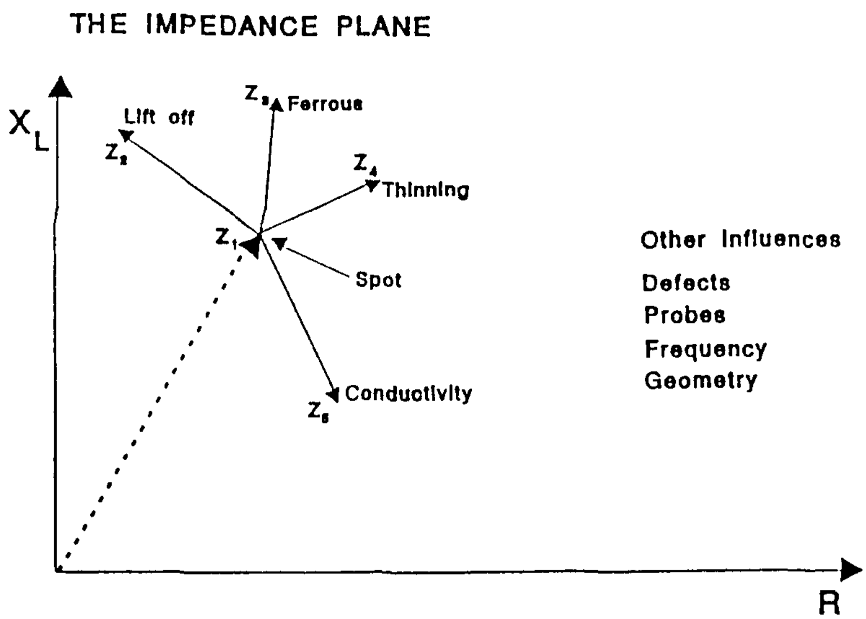


Figure 9-22 Impedance Plane

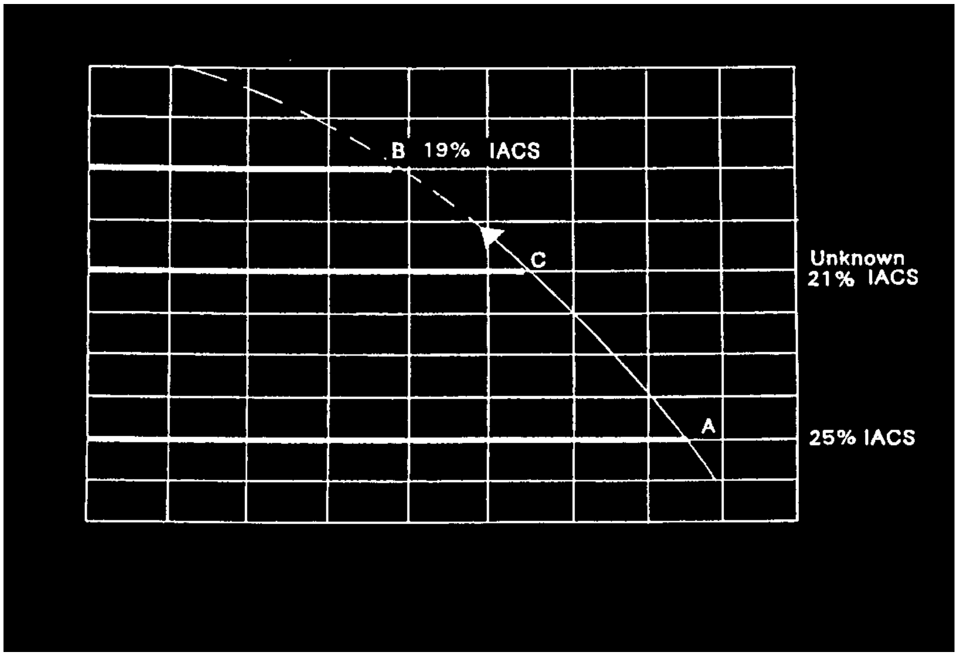


Figure 9-23 Conductivity Measurement

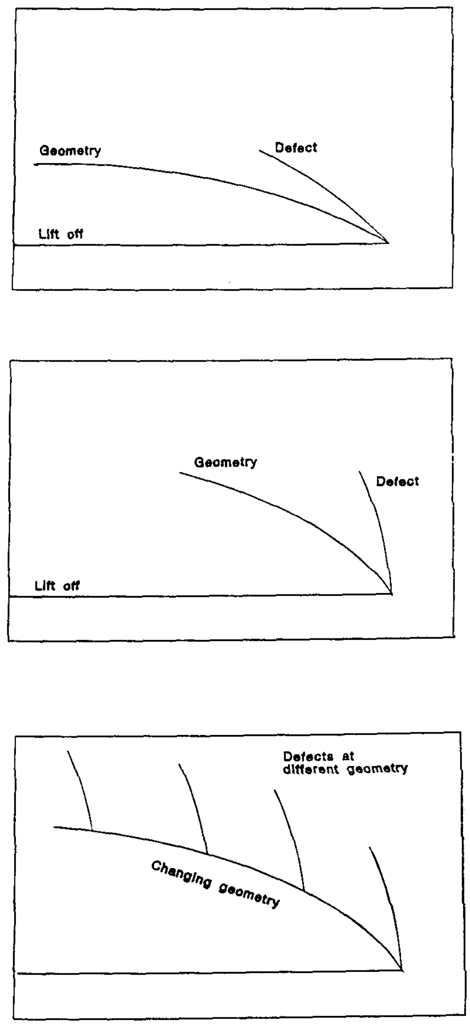
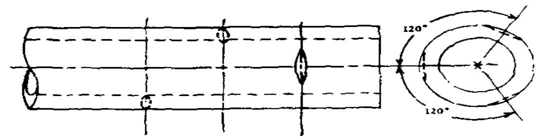
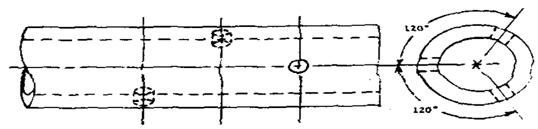


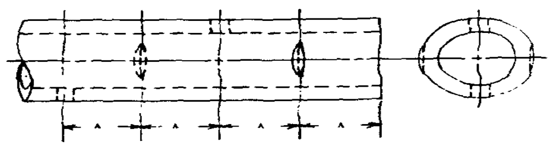
Figure 9-24 Frequency Selection for Crack Resolution



Calibration Standard with Three Notches

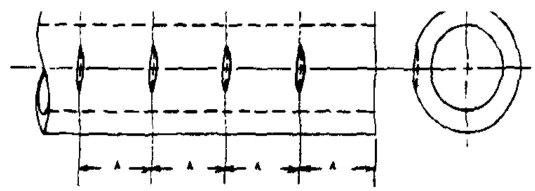


Calibration Standard with Three Holes

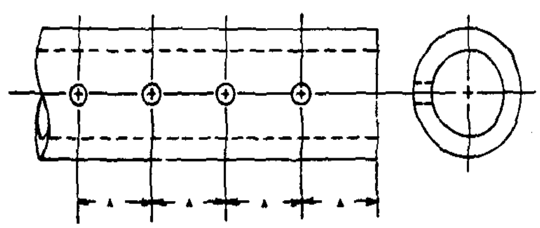


Calibration Standard with Two Notches and Two Holes

Note: A=Space to provide signal resolution adequate for interpretation.



Calibration Standard for Four Notches in Line



Calibration Standard for Four Holes in Line

Note: A=Space to provide signal resolution adequate for interpretation.

Figure 9-25 Tube Calibration Standards

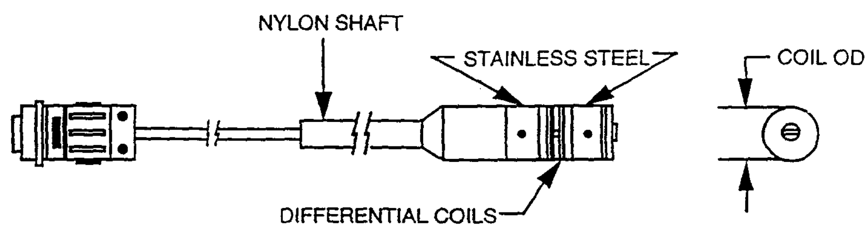


Figure 9-26 Internal Bobbin Probe

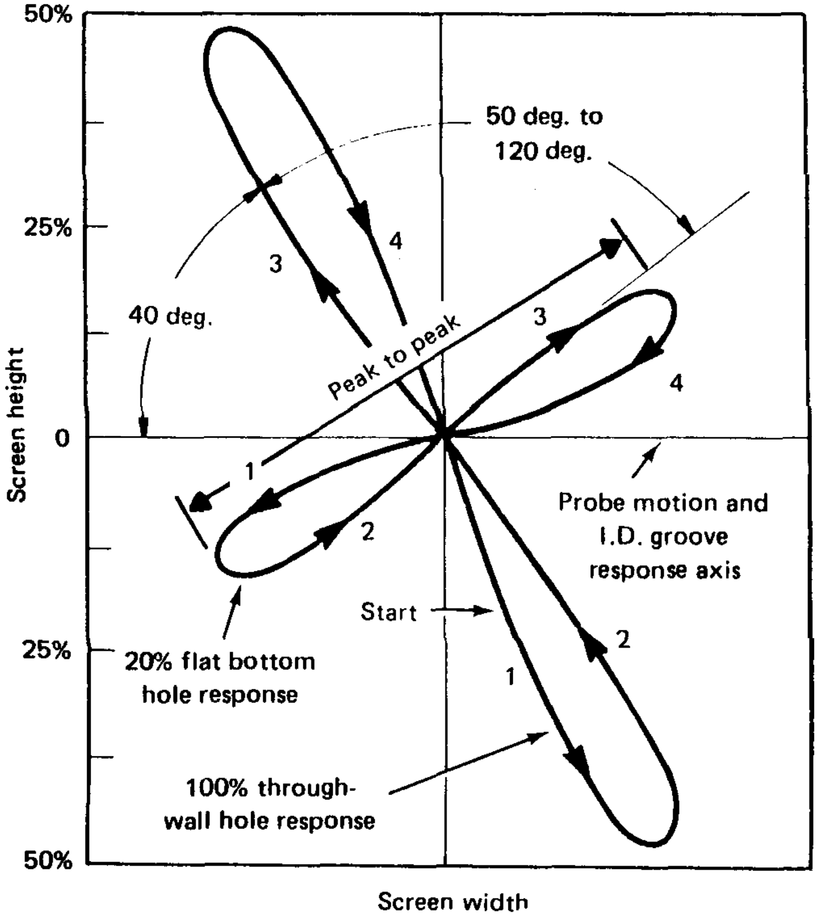


Figure 9-27 Typical Signal Response from a Properly Calibrated Differential Bobbin Coil Probe System

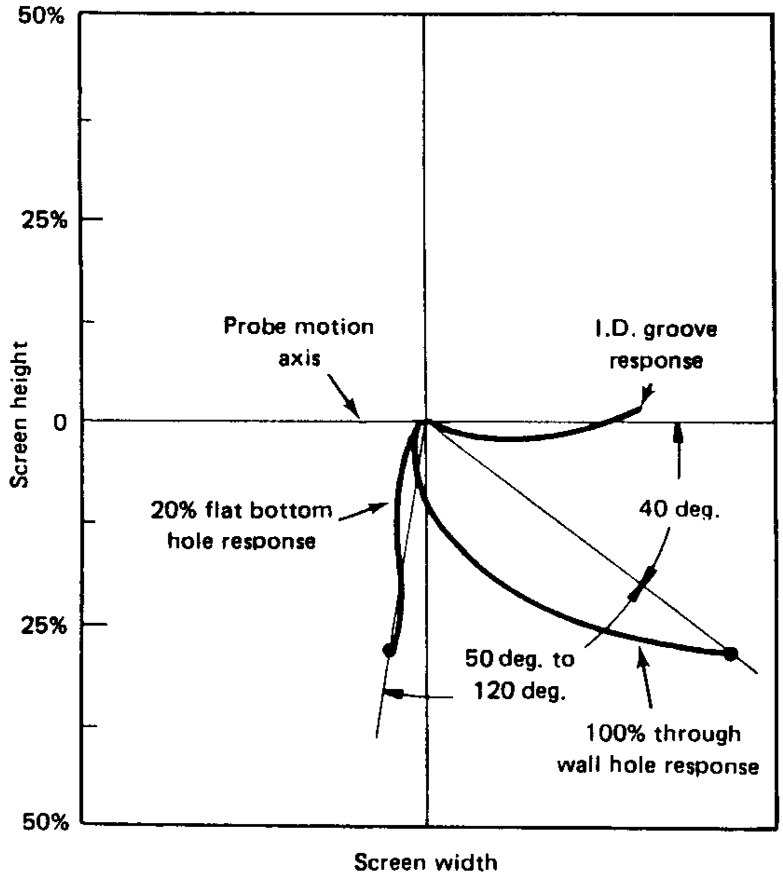
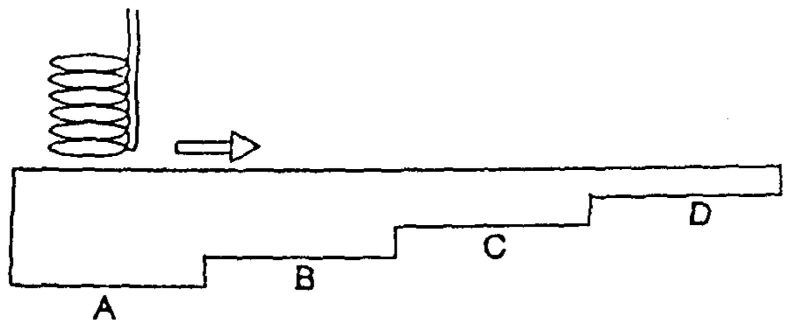


Figure 9-28 Typical Signal Response from a Properly Calibrated Absolute Bobbin Coil Probe System



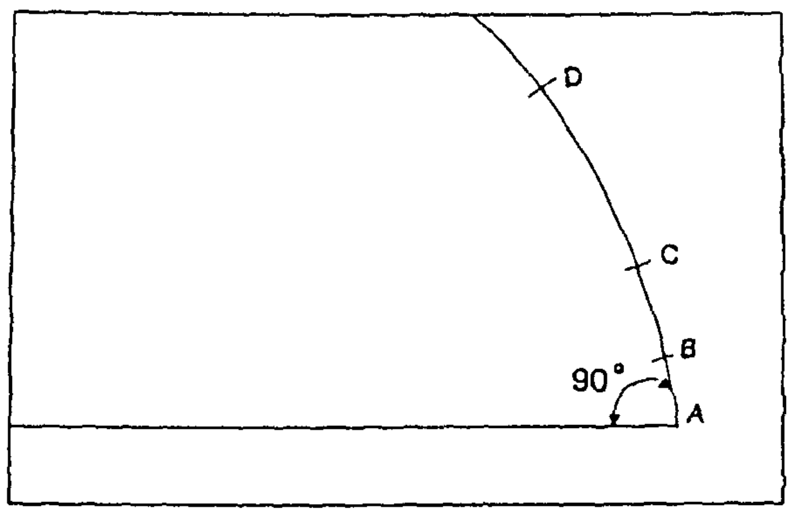


Figure 9-29 Changes in Thickness (Example 1)

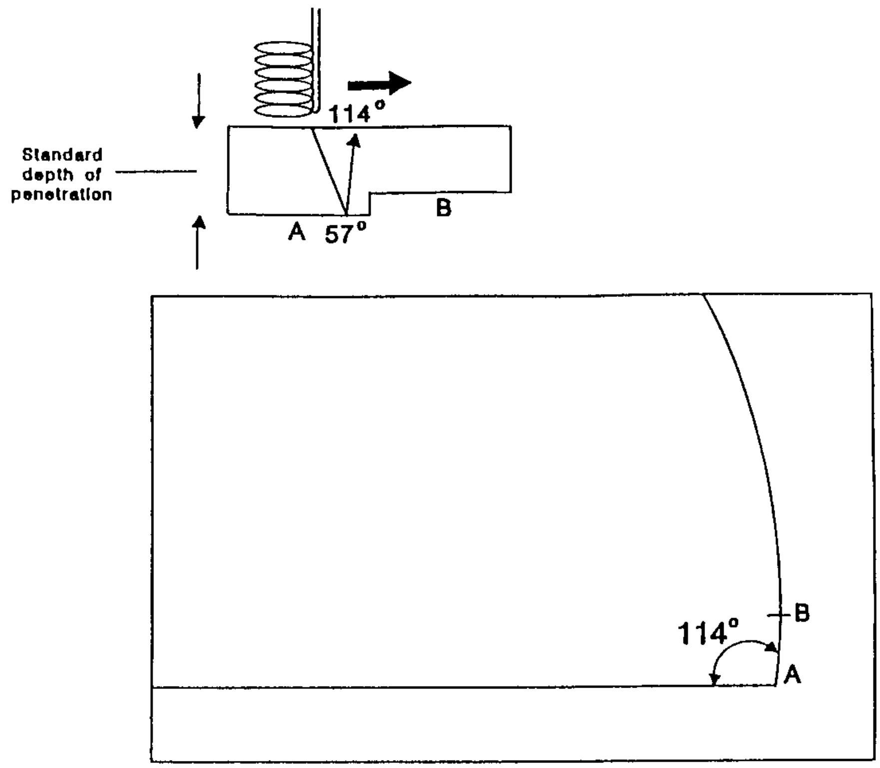


Figure 9-30 Change in Thickness (Example 2)

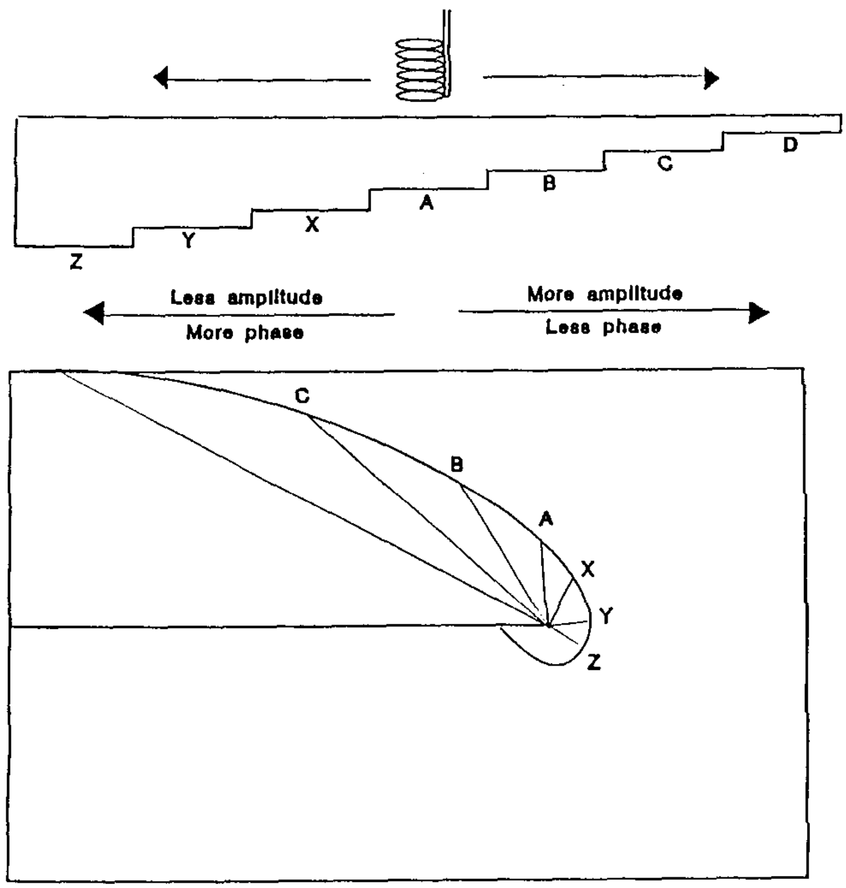


Figure 9-31 Changing Signal Phase and Signal Amplitude with Depth

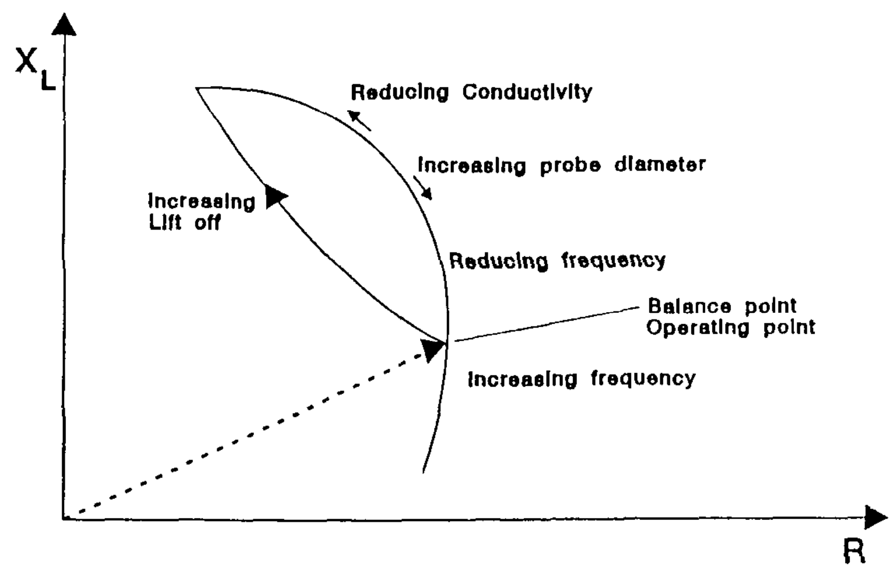


Figure 9-32 Changes in Conductivity, Lift-Off, Probe, and Thickness

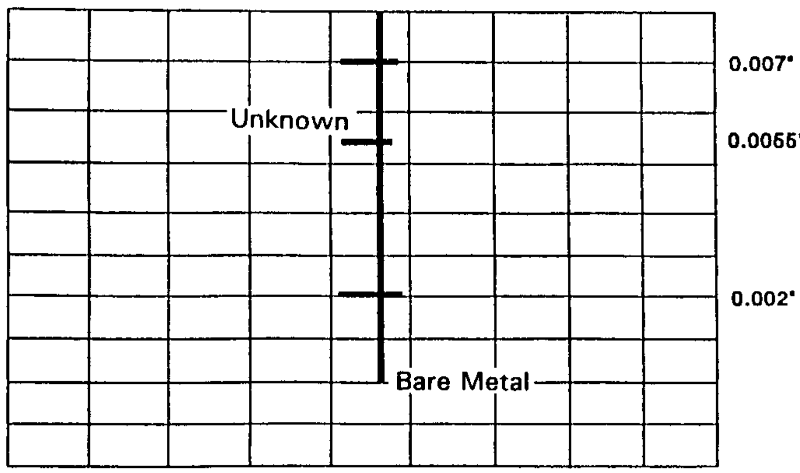


Figure 9-33 Coating Thickness Measurement