CHAPTER 8
EDDY CURRENT TESTING

8.1 HISTORY AND DEVELOPMENT

Eddy current testing is one of the oldest nondestructive testing (NDT) methods. However, it wasn't until the last few decades of the twentieth century that the eddy current method started to reach its true potential in the marketplace. One reason for this is that general purpose, user-friendly eddy current instruments are a relatively recent phenomenon. Whereas portable ultrasonic instruments offering considerable versatility have been available since the 1960s, comparable eddy current portables only became available in the 1980s. In addition, it is only recently that eddy current theory became widely understood by NDT professionals. The early 1980s, in particular, produced excellent explanatory material that made eddy current theory understandable to persons without advanced technical backgrounds. Modern microprocessor-based instruments, plus the availability of high-quality operator training, ensure the continued growth of this versatile, high-performance NDT method.

8.1.1 Significant Discoveries about Electromagnetism

Development of the eddy current method was based on certain discoveries made during the early nineteenth century about the relationship between electricity and magnetism. In fact, the relevant electromagnetic principles were discovered in the same sequence in which they occur during an eddy current test.

In 1820, Hans Christian Oersted, a Dane, discovered electromagnetism—the fact that an electrical current flowing through a conductor causes a magnetic field to develop around that conductor. Oerstead discovered electromagnetism accidentally. While demonstrating that heat is developed when an electric current passes through a wire, Oerstead observed that the needle of a magnetic compass deflected perpendicular to the wire while the current was passing through it. Electromagnetism is the principle on which eddy current coils operate. Whereas Oersted was using direct current developed from a battery voltage when he discovered electromagnetism, an eddy current instrument employs alternating electric current flowing through the test coil in order to develop an alternating magnetic field around the coil.

In 1831, an Englishman, Michael Faraday, discovered electromagnetic induction—the fact that relative motion between a magnetic field and a conductor induces a voltage in that conductor, causing an electric current to flow. Consequently, when the alternating magnetic field of an eddy current instrument's coil is brought in contact with a conducting test object, a voltage is developed, causing a current to flow in the test object. Thus, electromagnetic induction is considered to be the operating principle of eddy current testing. Joseph Henry also independently discovered electromagnetic induction in the United States at about the same time. In fact, the unit of measure for induction is named after him.

In 1834, Heinrich Lenz stated the principle that defines how the properties of the test object are communicated back to the test system. Lenz's law states that the direction of current flow in the test object will be such that its magnetic field will oppose the magnetic field that caused the current flow in the test object. This means that, in practice, the eddy currents communicate with the test coil by developing a secondary flux that cancels a portion of the coil's flux equivalent to the magnitude and phase of the flux developed by the eddy currents.

The theory describing the chain of events of an eddy current test may thus be fully described by the discoveries of Oersted, Faraday, Henry, and Lenz. The existence of eddy currents themselves, however, was not discovered until 1864. They were discovered by James Maxwell, who is famous for stating the defining equations of electromagnetic theory. The first use of eddy currents for nondestructive testing occurred in 1879 when D. E. Hughes used these principles to conduct metallurgical sorting tests.

8.1.2 Modern Eddy Current Testing

The development of the eddy current method progressed slowly until the late 1940s, when Dr. Friedreich Foerster founded the Institut Dr. Foerster, which made great strides in developing and marketing practical eddy current test instruments. By the late 1960s the Institute had developed a product line covering virtually every application of the eddy current test method and worked with American manufacturers to firmly establish the method in the United States. Two major contributions of Foerster were the development of impedance plane display, which greatly aided in communication of test information to the practitioner, and formulation of the Law of Similarity, which enables the practitioner to duplicate the same eddy current performance under a variety of test situations.

The next major contribution to the advancement of the method, multifrequency testing, was also developed by an equipment manufacturer, Intercontrolle of France, in 1974. Driving the test coil at multiple frequencies helps to overcome what has traditionally been the major limitation of the eddy current method, the fact that the various conditions to which the method is sensitive can vector into a single displayed signal that is difficult to interpret. Originally developed to suppress the display of undesired test variables, multifrequency testing can also optimize an eddy current test for normally conflicting performance variables such as sensitivity and penetration as well as aid in identifying the nature of a particular test response. Multifrequency testing is a very significant innovation that has markedly advanced the state of the art.

The development of microprocessor-based eddy current instruments since the mid-1980s has also enhanced the potential and user-friendliness of the method. It has improved recording capability, provided sophisticated postinspection signal analysis, and has allowed automatic mixing of multifrequency signals. Modern microprocessor-based eddy current instruments offer a breadth of useful features virtually unimaginable in the days of analog equipment. Manufacturers such as Zetek, Hocking, Foerster, Nortec, ETC, and Magnetic Analysis have been important contributors.

In addition to mainstream eddy current testing, more specialized techniques are employed for certain applications. These include flux leakage, remote field eddy current, and modulation analysis inspection. In classifying nondestructive test methods for the purpose of qualifying and certifying test personnel, the American Society for Nondestructive Testing (ASNT) classifies all of these techniques under the umbrella of the Electromagnetic Testing method (ET).

8.1.3 Material Variables Detectable by Eddy Currents

During more than a century of development as a test method, eddy current testing has found application due to its sensitivity to the following variables:

- Conductivity variations
- Detection of discontinuities
- Spacing between test coil and test material (*lift-off* distance)
- Material thickness
- Thickness of plating or cladding on a base metal
- Spacing between conductive layers
- Permeability variations

Eddy current testing is suitable for inspection of the surface and just beneath the surface of conductive materials, volumetric inspection of thin conductive materials, and lift-off measurement to determine thickness of nonconductive materials adhering to or resting on the surface of conductive materials.

8.1.4 Major Application Areas

The versatility of the eddy current method has resulted in broad applications usage. However, the major application areas include the following:

- In-service inspection of tubing at nuclear and fossil fuel power utilities, at chemical and petrochemical plants, on nuclear submarines, and in air conditioning systems
- Inspection of aerospace structures and engines
- Production testing of tubing, pipe, wire, rod, and bar stock

8.2 THEORY AND PRINCIPLES

Eddy current theory is based on the principles of electricity and magnetism, particularly the inductive properties of alternating current. The discussion begins with a review of some basic principles.

8.2.1 Electricity

All matter is made up of atoms, the atom being the smallest unit of any element that retains the properties of that element. The center of an atom, the nucleus, has a positive electrical charge. Orbiting the nucleus and rotating on their own axes are negatively charged particles called electrons. As shown in the illustration of the copper atom (Figure 8-1), orbits of electrons around the nucleus resemble the orbits of planets around the sun in that there can be several orbits, called "shells." However, atomic structure differs from the solar system in that a given shell can contain multiple electrons.

From the perspective of eddy current testing, one is concerned specifically with the outer shell of a material's atoms, because the number of electrons in the outer shell determines whether the material will conduct electricity. The outer shell can contain a maximum of eight electrons, and when the outer shell contains as many as seven or eight elec-

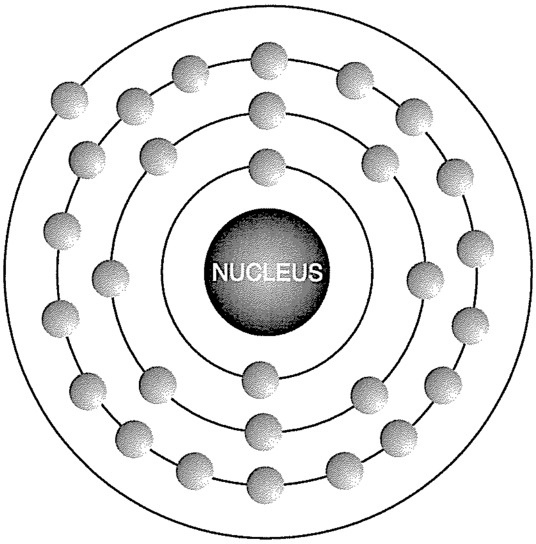


FIGURE 8-1 Copper atom.

trons, the material will not conduct electricity and is called an insulator. However, materials whose atoms have only one, two, or three electrons in the outer shell can conduct electricity and are, in fact, called conductors. Materials whose outer shells contain an intermediate number of electrons are called semiconductors and, although important in the design of computer circuitry, are not significant here.

If undisturbed by outside forces, a conductor's electrons will repeatedly orbit the nucleus. However, when voltage [also called electromotive force (EMF) or potential] is applied to a conductor, its electrons will advance from one atom to the next. That is, there is a flow of electrical charges called current or electricity. Voltage causes electrons to flow because it can attract and repel them; that is, voltage applies polarity to electrons. A battery is an example of a voltage source. Electrons, being negatively charged, will be attracted to a battery's positive terminal and repelled by its negative terminal. As shown in the illustration of a flashlight circuit (Figure 8-2), electrons flow through the bulb's filament from the negative to the positive terminal of the battery.

Although a conductor's atoms will permit current flow when voltage is applied, there is always some opposition to flow, due to the attraction of electrons to their atoms. This opposition varies among the atoms of different materials. Willingness of a test specimen to allow current flow is a key point in eddy current testing, detailed in the following definitions:

- *Conductivity* is the relative ability of a material's atoms to conduct electricity.
- *Resistivity* is the opposition of a material's atoms to the flow of electricity; it is the inverse of conductivity.
- *Conductance* is the ability of a particular component to conduct electricity. Conductance depends on a component's conductivity, length, and cross section.
- *Resistance* is the inverse of conductance. It is the opposition that a particular component offers to the flow of electricity. Like conductance, it depends on a component's conductivity, length, and cross section.

Conductivity is the material property of most interest to us in eddy current testing, whereas resistance is an important element in the display of test information. Material

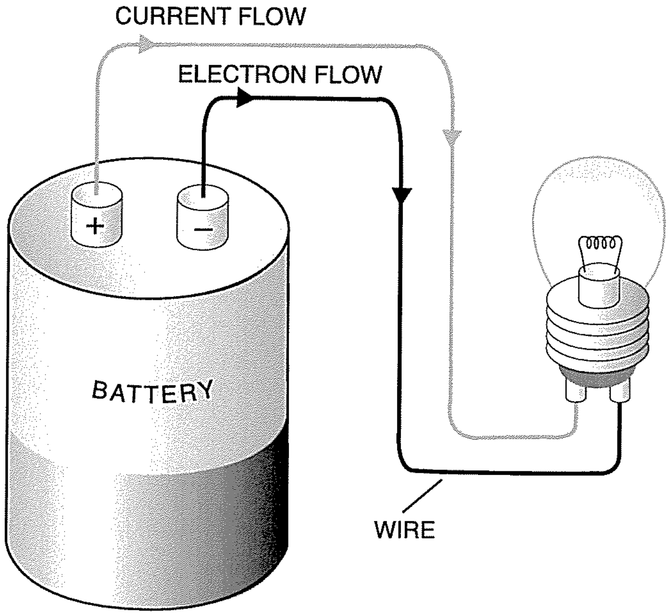


FIGURE 8-2 Flashlight circuit.

conductivities are compared on a scale called the International Annealed Copper Standard (IACS). Pure unalloyed annealed copper at 20°C is the base value on this scale, with a value of 100%. Other materials are assigned a percentage depending on their ability to conduct electricity relative to copper.

Having now identified resistance, as well as voltage and current, these terms can be tied together, showing their units, using the most basic formula of electricity, Ohm's law:

$$I = \frac{V}{R}$$

where
I = current in amperes
V = voltage in volts
R = resistance in ohns

Thus, current flow increases when voltage increases and current flow decreases when resistance increases. There are two types of current: direct current (dc), which flows in only one direction; and alternating current (ac), which continually reverses direction.

8.2.2 Magnetism

Magnetism is a mechanical force of attraction or repulsion that one material can exert upon another. The opposite ends of a magnet exhibit opposing behavior called *polarity*. Thus, the ends of a magnet are called poles—one north and one south.

A magnet has a force field that can be visualized as a number of closed loops that flow through the magnet, travel around the outside of the magnet, and then reenter the magnet at the other end (Figure 8-3). These magnetic loops are called *lines of force* or *flux lines*. The word "flux" literally means "flow" and relates to the fact that the lines of force flow

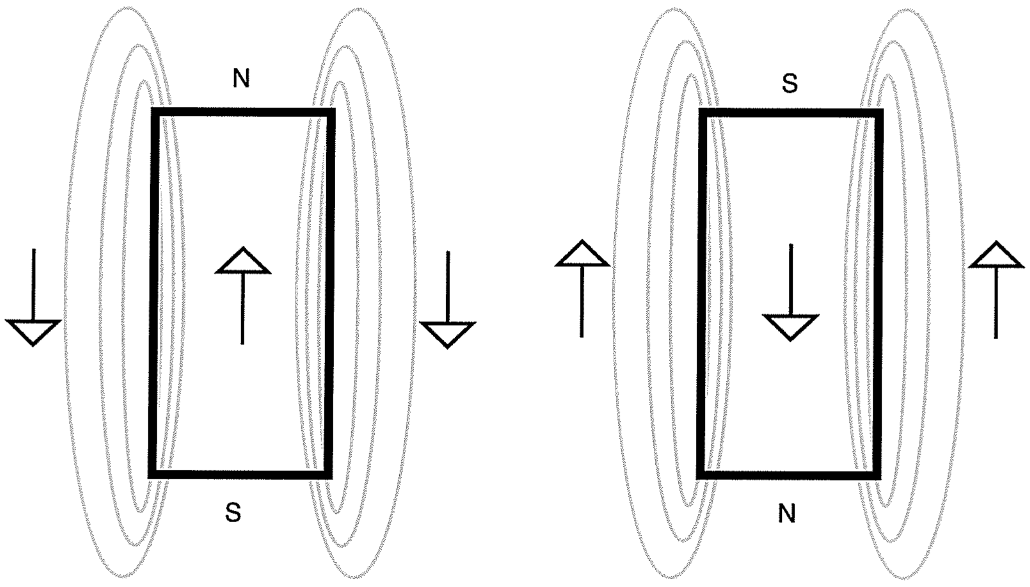


FIGURE 8-3 Magnetic polarity.

from the north to the south pole around the outside of a magnet, and from the south to the north pole within the magnet. Units of measurement and definitions for magnetism include the following:

Magnetic Flux (Φ or phi) is the entire set of a magnet's flowing lines of force.

Flux density (B) is the number of flux lines per unit area, perpendicular to the direction of flow.

The *maxwell* (Mx) is one magnetic field line or line of force.

The *weber* (Wb) is 1×10^8 lines or maxwells.

The *gauss* (G) is one line of force per square centimeter.

The *Tesla* (T) is one weber per square meter.

Field intensity depends on flux density. Flux density is greatest within the core of a magnet and at the poles. Flux density decreases with distance from the magnet according to the inverse square law (Figure 8-4); that is, flux density is inversely proportional to the square of the distance from the poles of the magnet.

When like poles of two magnets are brought together, the magnets push apart as their force fields repel each other. When unlike poles of two magnets are brought together, the magnets attract as the two force fields attempt to combine.

There are two types of magnets: permanent magnets and electromagnets. Permanent magnets are physical materials, having a property called ferromagnetism, which means that they can become magnetized when their *domains* have become aligned (Figure 8-5). Domains are miniature magnets consisting of groups of atoms or molecules present within a material's individual grains.

Permanent magnets were discovered in ancient times and are often produced in bar and horseshoe shapes. The fact that they retain a magnetic field without activation by electrical current is what distinguishes them from electromagnets. *Permeability* is the measure of a material's ability to be magnetized; that is, a material's ability to concentrate

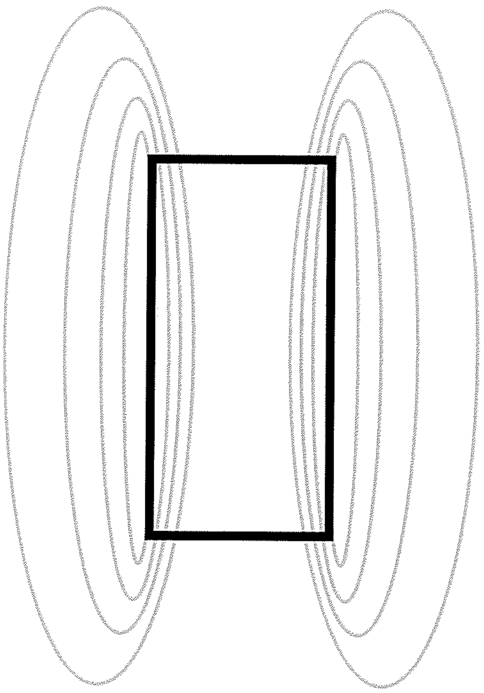
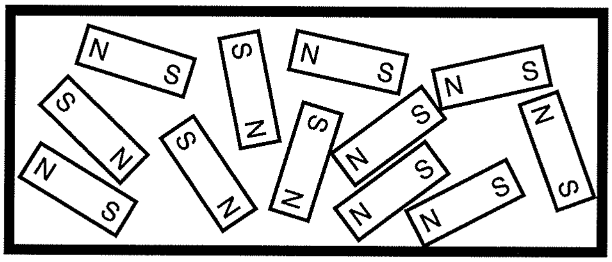
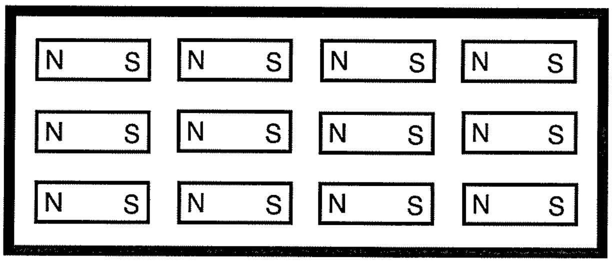


FIGURE 8-4 Flux density distribution.



Domains Unaligned



Domains Aligned

FIGURE 8-5 Magnetic domains.

magnetic flux. The more flux density obtained from a material by a given quantity of applied magnetizing force, the greater the permeability of that material.

Materials may be classified as *magnetic* or *nonmagnetic.* Although there are three types of magnetic materials—*ferromagnetic, paramagnetic,* and *diamagnetic*—the term "magnetic" usually refers to *ferromagnetic* materials, which have much higher permeability than the other two types. The different magnetic materials may be characterized as follows:

1. Ferromagnetic materials become strongly magnetized in the same direction as the magnetizing field in which they are placed. Their permeability ranges from approximately 50 to more than 100,000. Examples are iron, carbon steel, 400 series stainless steel, and nickel.
2. Paramagnetic materials become slightly magnetized in the same direction as the magnetizing field. Their permeability is slightly more than 1. Examples are aluminum, chromium, platinum, and oxygen gas.
3. Diamagnetic materials become weakly magnetized in the opposite direction from the magnetizing field. Their permeability is slightly less than 1. Examples are copper, gold, silver, and hydrogen.

8.2.3 Electromagnetism

Electromagnetism is the phenomenon whereby the passage of electrons through a conductor causes a magnetic field to develop concentrically around the conductor, perpendicular to its axis. A concentrated magnetic field, similar to that obtained from a bar magnet, can be obtained by winding a conductor into a coil. A coil functioning as an electromagnet is called a solenoid, although an ideal solenoid has a length much greater than its diameter. A solenoid concentrates a magnetic field inside the coil, with opposing poles at each end of the coil, and flux lines completely encircling the loops of the coil. If direct current is applied to the coil, its magnetic field will flow in only one direction and it can perform the same work of attracting ferromagnetic materials as a permanent magnet. In addition, the coil can be wound around a ferromagnetic core for increased field strength.

If the current is alternating, the electromagnetic field will likewise alternate and the coil will exhibit a quality called inductance, *L,* whose unit is the henry. Inductance is the ability of a conductor to induce voltage in itself or in a neighboring conductor when the current varies.

8.2.4 Permeability

Electromagnets are used to produce permanent magnets. A conducting wire or cable is wound around the ferromagnetic material to be magnetized. Direct current is passed through the conductor, causing it to function as an electromagnet. When the resulting magnetic field enters the material to be magnetized, the material's domains become aligned. The higher the number of turns of wire or cable and the stronger the applied current, the greater the *magnetizing force.*

As stated earlier, permeability defines a material's ability to be magnetized, it's ability to concentrate magnetic flux. Numerical permeability values for different materials, termed relative permeability (μ_r) are stated in comparison to the permeability of air or a vacuum. Permeability can be quantitatively expressed as the ratio of flux density to magnetizing force. Permeability can be a problem in eddy current testing because the relative

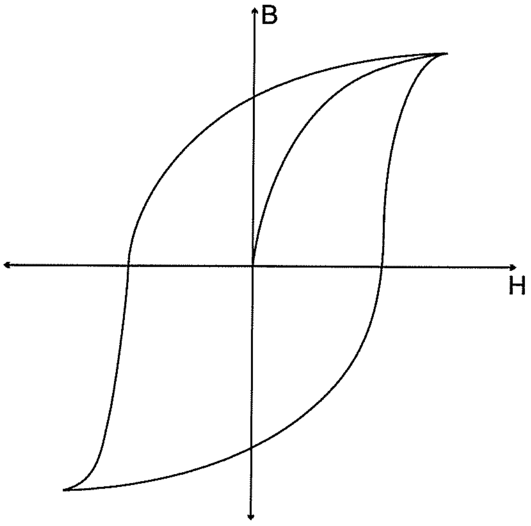


FIGURE 8-6 Hysteresis loop.

permeability of a given ferromagnetic material can vary during testing, causing permeability noise signals that can override the eddy current signals being sought. A *hysteresis loop* (Figure 8-6) is a plot of a material's flux density (B) variations as magnetizing force (H) is varied. By magnetically saturating the test material, permeability becomes constant and eddy current testing can proceed without interference from permeability variations.

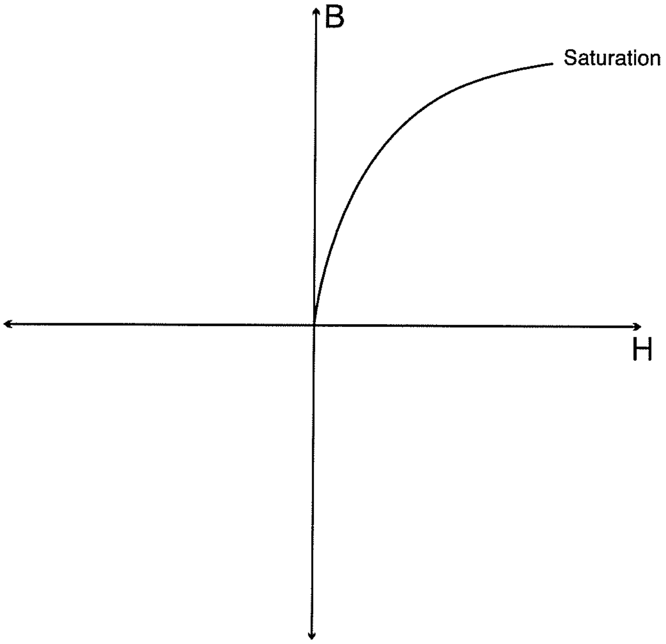


FIGURE 8-7 Magnetic saturation.

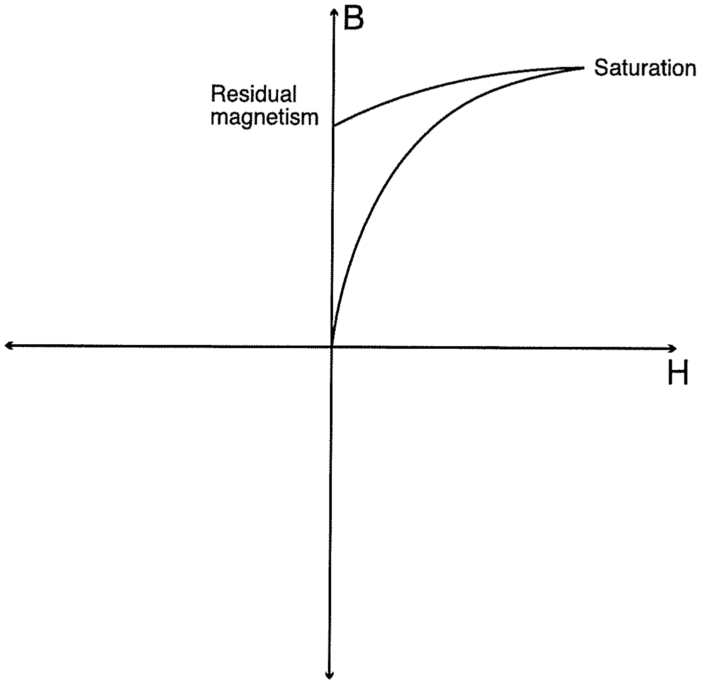


FIGURE 8-8 Residual magnetism.

Saturation (Figure 8-7) occurs at that point on the loop where further increases in magnetizing force do not cause significant increases in flux density.

At the completion of testing, the material will retain a certain amount of *residual magnetism* (Figure 8-8), the amount of flux density remaining in the material after the magnetizing force has been reduced to zero. The residual magnetism must be eliminated by demagnetization, to prevent problems such as the material attracting ferromagnetic debris.

8.3 ALTERNATING CURRENT PRINCIPLES

8.3.1 Sinusoidal Variation

Alternating current flows in a cyclical manner, behavior that is accurately illustrated by a sine curve (Figure 8-9).

The current begins its cycle at zero amplitude and, as time elapses, rises to a peak in one direction, falls back to zero, rises to a peak in the opposite direction, and falls back to zero again to complete the cycle. The end of one cycle is the starting point of the next cycle. One complete 360° cycle is called a *sinusoid.* Activity exhibiting the behavior of a sinusoid is termed sinusoidal.

The 360 degree points of a sinusoid correspond to the 360 degree points of a complete circle. Thus, both a sinusoid and a circle express one complete cycle. However, the sinusoid adds dimensions of amplitude and polarity to the cycle concept. Recall that the distance from the center of a circle to the edge is its radius. The portion of a circle's arc that corresponds to the length of its radius is called a *radian,* which occupies an arc of 57.3°.

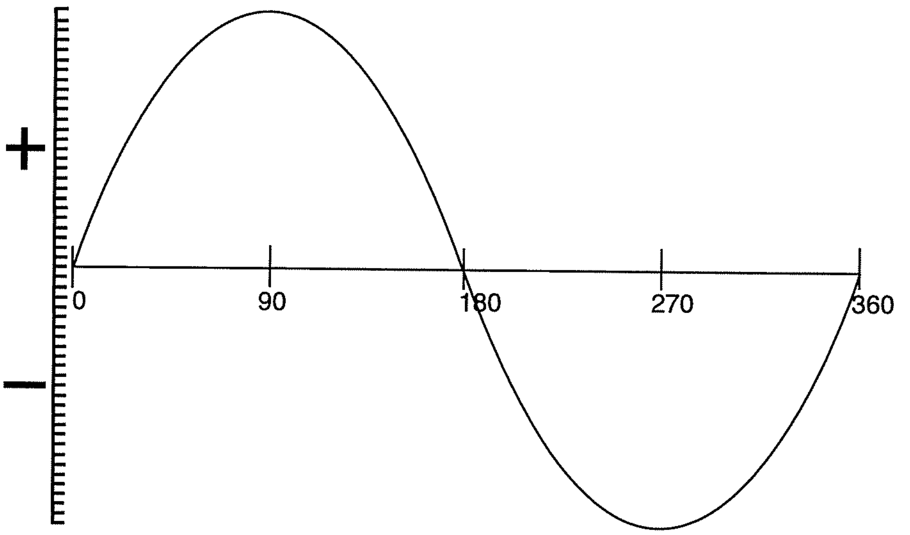


FIGURE 8-9 Sinusoid.

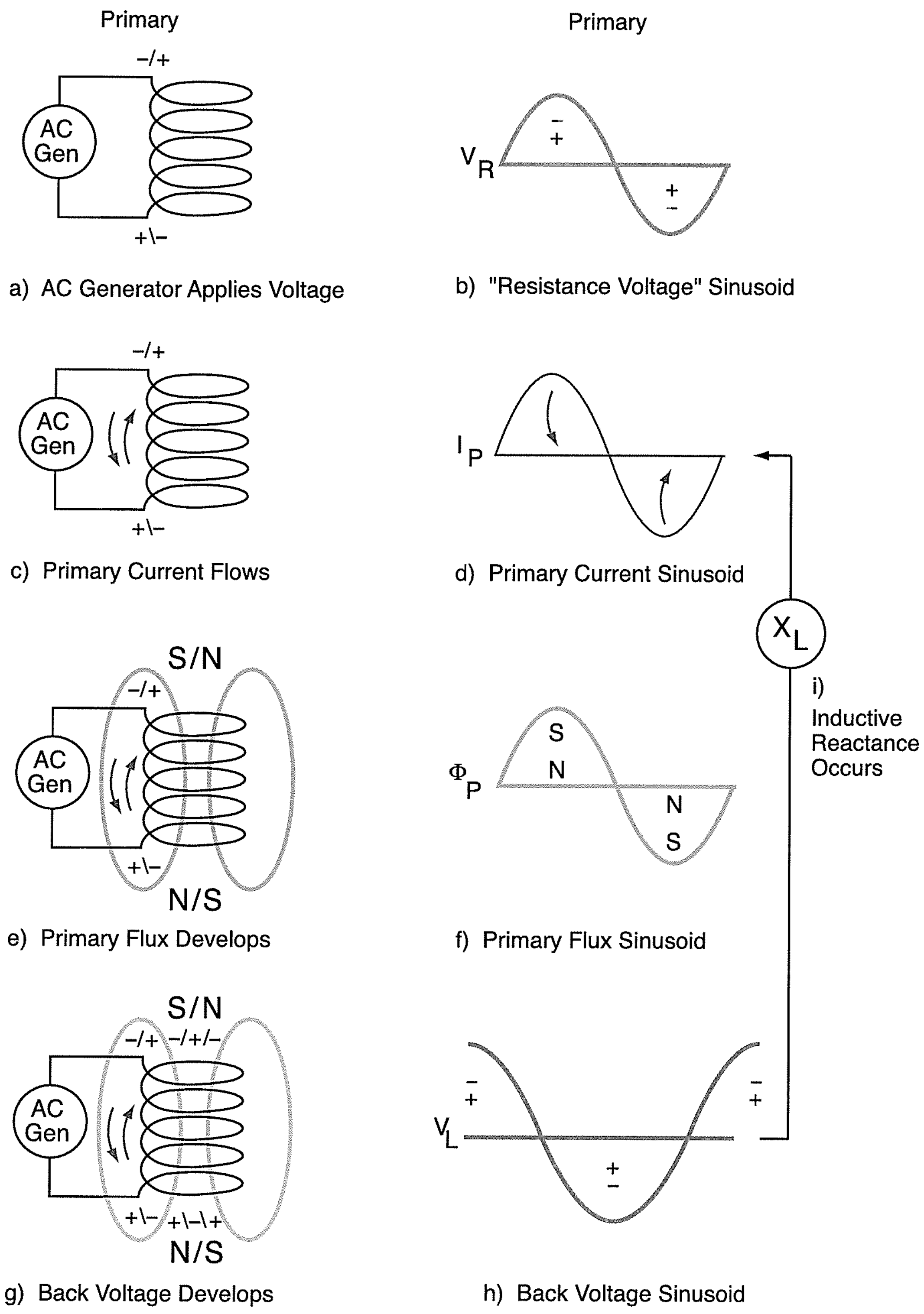
360° divided by 57.3° equals 6.28 or 2π, an important constant in alternating current calculations.

8.3.2 Electromagnetic Induction

Prior to discussing eddy currents, the induction process will first be modeled using a pair of coils as primary and secondary elements of a mutual induction circuit. Sinusoids are included to illustrate time and polarity relationships. The symmetry of two coils aids in explanation of the polarity relationships that occur in mutual induction processes such as eddy current tests. This illustration models an eddy current test in its most basic configuration, where a single coil is the primary circuit and the test material is the secondary. Initially, the primary coil will be examined without the influence of a secondary. The primary coil will be multiturn to represent a typical eddy current test coil. The secondary, when introduced, will be a single-turn coil, which validly represents any eddy current test specimen. It must be remembered that the secondary coil in this discussion represents strictly the test specimen, *not* the second coil of various multicoil configurations that will be described later in this chapter.

The Induction Process

1. An alternating current generator applies alternating voltage to a coil circuit (Figure 8-10a). A portion of this voltage, V_R, is applied across the resistance of the coil wire. The V_R amplitude rises from zero amplitude at zero degrees (Figure 8-10b). The "R" subscript in V_R identifies this voltage, sometimes called "resistance voltage," as a force needed to move current through the resistance of the coil wire. V_R is a component of the circuit's total voltage, V_T, which will be explained later.
2. V_R causes a current, I_P, to flow through the coil (Figure 8-10c), in phase with V_R (Figure 8-10d). The "P" subscript in I_P identifies the coil current as the primary current.



a) AC Generator Applies Voltage

b) "Resistance Voltage" Sinusoid

c) Primary Current Flows

d) Primary Current Sinusoid

e) Primary Flux Develops

f) Primary Flux Sinusoid

g) Back Voltage Develops

h) Back Voltage Sinusoid

FIGURE 8-10 Self-induction process. (a) AC generator applies voltage. (b) "Resistance voltage" sinusoid. (c) Primary current flows. (d) Primary current sinusoid. (e) Primary flux develops. (f) Primary flux sinusoid. (g) Back voltage develops. (h) Back voltage sinusoid. (i) Inductive reactance occurs.

3. *Electromagnetism* occurs. The alternating current flowing through the coil causes an alternating magnetic field, Φ_P, the primary flux, to develop around the coil (Figure 8-10e), in phase with V_R and I_P (Figure 8-10f).
4. *Self-induction* occurs. Since the coil is standing in the field of its own varying flux, Faraday's law applies and electromagnetic induction is imposed on the coil wire. That is, Φ_P induces an additional voltage, V_L, often called "back voltage," into the coil (Figure 8-10g). The "L" subscript identifies V_L as an "induced voltage." This voltage is separate from the V_R voltage that caused I_P to flow. According to Faraday's law, the quantity of induced voltage is proportional to the rate of flux variation. Since Φ_P is varying the most through the 0°, 180°, and 360° points, and not varying through the 90° and 180° points, the back voltage is induced 90° out of phase (Figure 8-10h) with the coil current and flux.
5. *Inductive reactance* occurs. Since the back voltage is 90° out of phase with the coil current, it will oppose changes in the coil current (Figure 8-10i). In that amplitude change is the very nature of alternating current flow, opposition to change in ac is effectively opposition to flow of ac. This opposition, called *inductive reactance,* X_L, is distinct from resistance, R. Resistance simply opposes flow of current and can occur in either a dc or ac circuit. Inductive reactance, which, strictly speaking, opposes *change* of current flow, can occur only in an ac circuit.

   Inductive reactance depends on coil design and test frequency to the extent that, as more flux lines cut across more coil turns per unit time, inductive reactance increases.

   The variables influencing inductive reactance are detailed in the following equations:

$$X_L = 2\pi f L$$

$$L = \mu_r \frac{N^2 \times A}{1} \times 1.26 \times 10^{-6}$$

where
X_L = inductive reactance
f = test frequency
L = coil inductance
μ_r = relative permeability of the coil core
N = number of turns
A = cross sectional area
l = coil length

Note. The permeability of air, 1.26×10^{-6}, must be multiplied by an appropriate value for μ_r, which would be 1(one) for an air core coil or some higher value in the case of a coil with a ferromagnetic core.

6. If a secondary circuit is placed in proximity to the primary, mutual induction will occur and Φ_P will induce a voltage into the secondary circuit (Figure 8-11a). This voltage is appropriately called secondary voltage, V_S, and is 180° out of phase (Figure 8-11b) with the inducing primary flux.
7. V_S causes a current, I_S, to flow in the secondary circuit (Figure 8-11c), with the same phase (Figure 8-11d) as V_S. In an actual eddy current test, where the secondary circuit is the test specimen, I_S will be the eddy currents.
8. With current now flowing in the secondary circuit, electromagnetism will again occur

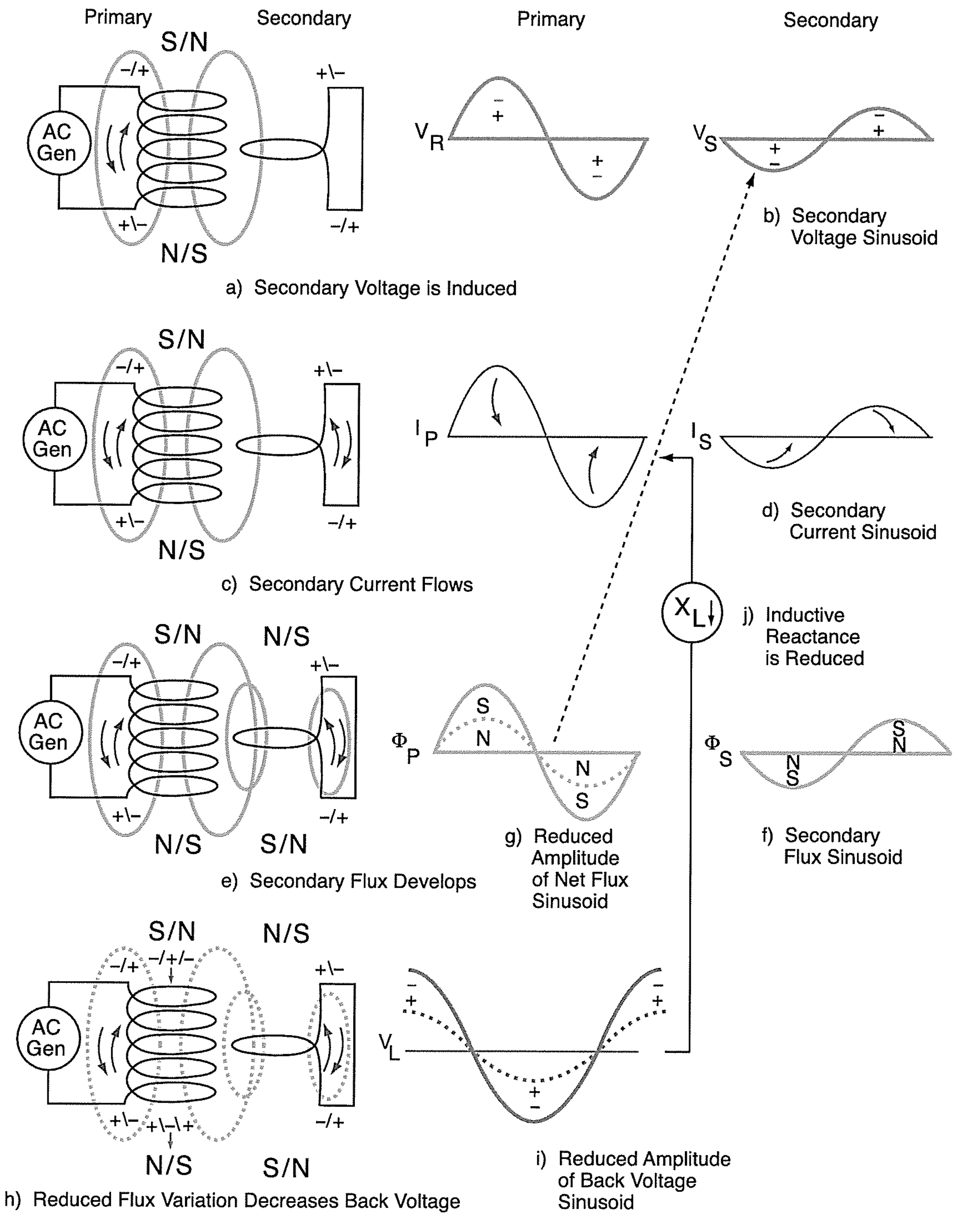


FIGURE 8-11 Mutual induction process. (a) Secondary voltage is induced. (b) Secondary voltage sinusoid. (c) Secondary current flows. (d) Secondary current sinusoid. (e) Secondary flux develops. (f) Secondary flux sinusoid. (g) Reduced amplitude of net flux sinusoid. (h) Reduced flux variation decreases back voltage. (i) Reduced amplitude of back voltage sinusoid. (j) Inductive reactance is reduced.

and a secondary flux, Φ_S, will develop (Figure 8-11e), with its phase (Figure 8-11f) determined by the secondary current.

9. The 180° phase difference between primary and secondary activity indicated in Figures 8-11b, d, and f is the effect of Lenz's law, which states that the induction process in the secondary circuit causes a phase reversal, which results in the secondary flux being opposite in polarity to the primary flux. Due to this state of opposition, the secondary flux will cancel a portion of the primary flux, resulting in an overall decrease in net flux for the two coils. The reduced amplitude of net flux (dashed line in Figure 8-11g) results in a reduced rate of net flux variation. Less flux variation results in reduced back voltage (Figures 8-11h and 8-11i), which results in a reduction of inductive reactance (Figure 8-11j).

Observe that the induction process occurs in a certain order: voltage drives a current, which develops an electromagnetic field, which then induces a voltage to again initiate the process. During an eddy current test, a primary circuit (the test coil) induces eddy currents into a secondary circuit (the test material). Any factors that affect current flow in the secondary circuit, such as primary/secondary coupling or conductance variations, will affect the amplitude of both V_L and of the inductive reactance in the primary circuit.

Variations in the test material change not only the test coil's inductive reactance, but also a quantity called effective resistance. Although the resistance of the coil wire itself does not change, the eddy currents in the test material encounter friction as they circulate, thus dissipating a portion of their energy as heat. That is, the secondary circuit acts as a load on the primary circuit, with electrical energy converting to thermal energy. This energy loss in the circuit is counteracted by an increase in V_R to keep the coil current constant. Thus, both V_R and V_L vary with change of test material properties during an eddy current test.

8.3.3 Signal Output

Voltage Plane

As stated earlier, there is a 90° phase difference between V_R and V_L. These two voltages can be vectorially added to produce a quantity called V_T, which is the total voltage in the primary circuit, the output of the instrument's alternating current generator.

Figure 8-12 illustrates a voltage plane diagram with V_R and V_L values plotted as the base and elevation of a right triangle, and V_T as the hypotenuse. Thus the Pythagorean theorem

$$c^2 = a^2 + b^2$$

may be expressed using voltage values

$$V_T^2 = V_R^2 + V_L^2$$

and restated to solve for V_T by vector addition:

$$V_T = \sqrt{V_R^2 + V_L^2}$$

The basic information available from an eddy current test is the magnitude of V_T and its phase relative to I_P. As shown in the sinusoids of Figures 8-10d and 8-10b, I_P is in phase with V_R. I_P can therefore be placed along with V_L on the horizontal axis of the voltage plane. Although test output could be shown as a sinusoid, indicating variation in magnitude and phase of V_T, a display showing just the tip of the vector arrow as a dot, called "vector point display," provides all necessary information in a simple manner and lends itself especially well to eddy current signal analysis. When the magnitude and phase of V_T

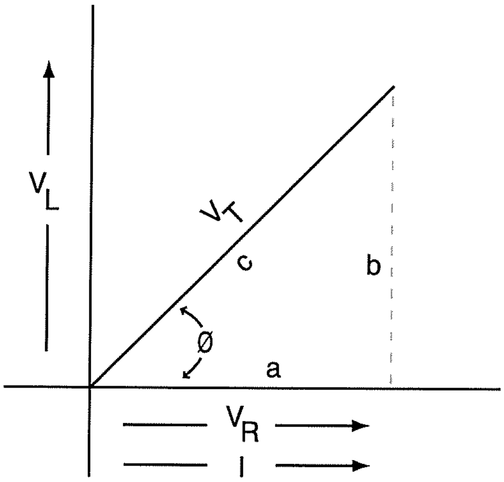


FIGURE 8-12 Voltage plane.

are plotted on the voltage plane, the tip of the V_T vector indicates the magnitudes of V_R and V_L. Figure 8-13 summarizes how the various voltage and impedance components fit into a coil circuit driven by alternating voltage, with the resistive and reactive properties separately identified.

Impedance Plane

Just as V_R and V_L can be combined into V_T, the combined effects of R and X_L on the alternating current in the coil can be expressed as a quantity called impedance. Specifically, *impedance amplitude* (Z) is the magnitude of the vector sum of inductive reactance and resistance, and is the coil's total opposition to current flow. That is:

$$Z = \sqrt{R^2 + X_L^2}$$

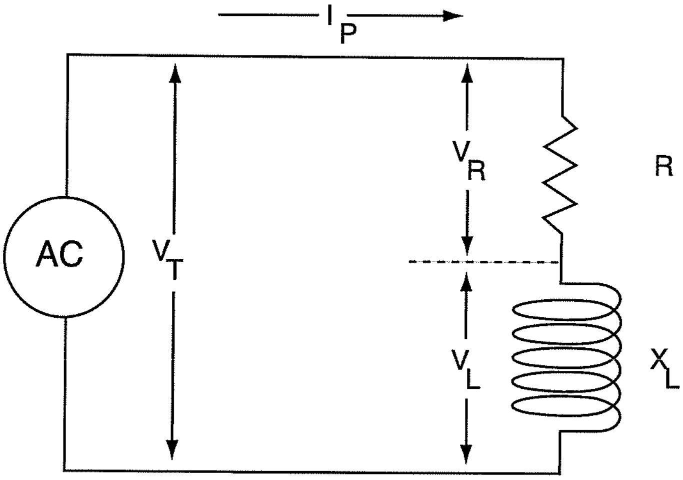


FIGURE 8-13 Coil circuit driven by alternating voltage.

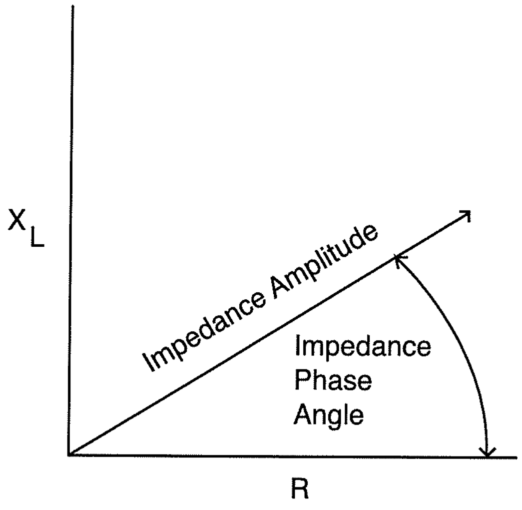


FIGURE 8-14 Impedance amplitude and phase angle.

The *Impedance phase angle* (ϕ), the proportional relationship between inductive reactance and resistance, can be calculated from:

$$\phi = \arctan \frac{X_L}{R}$$

Impedance amplitude and phase angle are illustrated in Figure 8-14.

It is important to understand that there can be only one current in the circuit, flowing through both the resistance and inductive reactance, and influenced by both V_R and V_L. Ohm's law then shows how a voltage plane can be converted into a corresponding impedance plane:

$$R = \frac{V_R}{I}$$

$$X_L = \frac{V_L}{I}$$

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

Although eddy current signal variations represent voltage variations as well as impedance variations, the impedance plane is the convention for expressing eddy current signal variations. That is, voltage variations are used to represent impedance variations in the coil. However, before exploring the different patterns of signal variation, it is necessary to examine how eddy currents behave in the test material in order to produce such patterns.

8.4 EDDY CURRENTS

When a test specimen is brought into proximity to the alternating flux field of an eddy current coil, coil flux causes electrons in the specimen to circulate in a swirling eddy-like pattern; hence the term "eddy currents." Eddy current behavior depends on the properties of both the flux and the specimen itself.

8.4.1 Eddy Current Flow Characteristics

Eddy currents have a number of flow characteristics that affect their test performance:

1. They flow only in closed, concentric loops. Their flow paths are circular when unimpeded by the intrusion of material boundaries or discontinuities. Also, the flow paths are parallel to the turns of the bobbin-type coil in shown Figure 8-15 and perpendicular to the axis of the coil's flux field.
2. The orientation of the coil to the test material therefore determines the orientation of the eddy current flow pattern in the test material. Orientation of the coil to the test material can be controlled and varied for optimum results by selection of the proper coil configuration. Several options are shown Section 8.5.2 of this chapter.
3. Discontinuities are detectable by the eddy current method in proportion to the degree to which they disturb the flow pattern. Thus, a discontinuity is least detectable when its longest dimension is parallel to eddy current flow paths (see Figure 8-16a) and most detectable when the longest dimension is perpendicular to the flow paths (see Figure 8-16b). Discontinuities with smaller volumes may not be detectable when oriented parallel to the flow paths. Ensuring that discontinuities of all likely orientations are detectable is an important part of test coil design and selection. Moreover, eddy currents always follow the path of least resistance around nonconducting obstacles, flowing under long, shallow discontinuities and flowing around short, deep discontinuities.

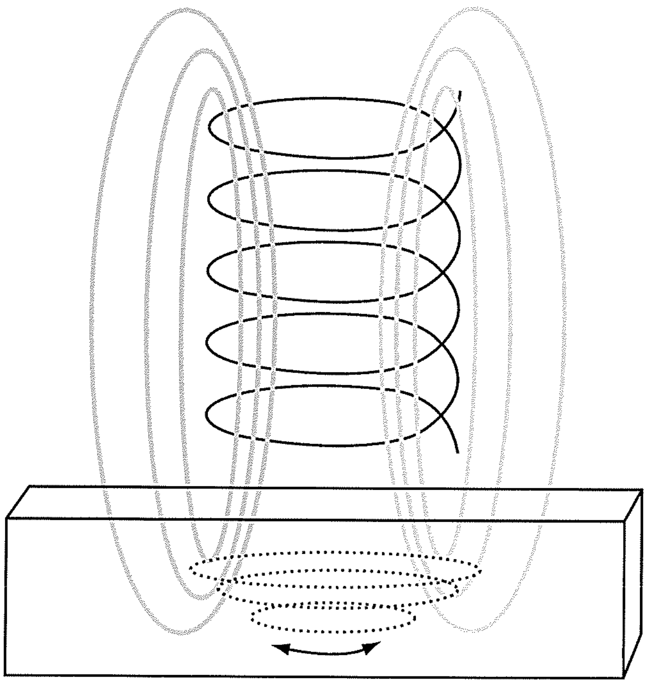


FIGURE 8-15 Bobbin-type coil's flux and eddy currents.

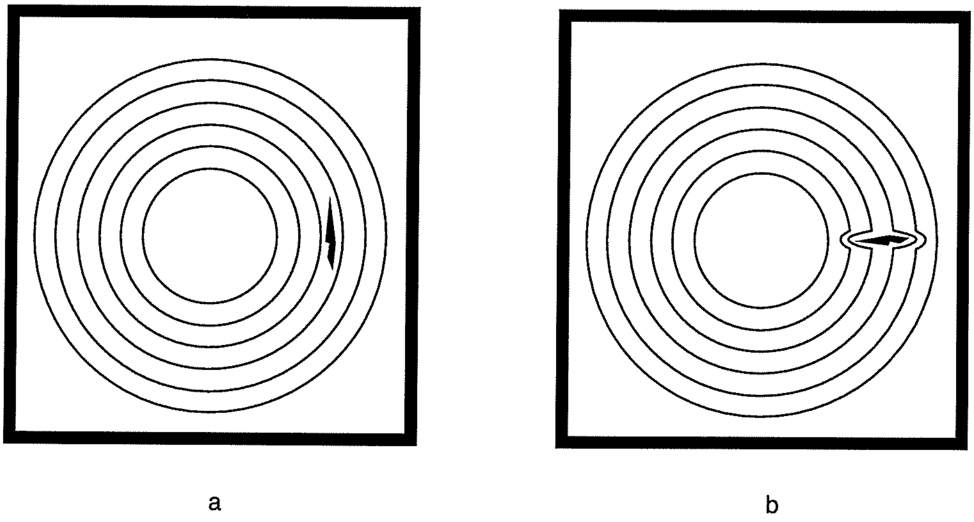


FIGURE 8-16 Discontinuities in eddy current flow patterns. (a) Discontinuity parallel to flow paths. (b) Discontinuity perpendicular to flow paths.

4. Eddy currents behave like compressible fluids. Although the flow paths are circular as long as the eddy currents are undisturbed by nonconducting material boundaries and discontinuities (see Figure 8-17a), the flow paths will distort and compress to accommodate intrusions into their flow (see Figure 8-17b).
5. Since an alternating flux field develops eddy currents, their flow in the test material likewise alternates clockwise and counterclockwise. The frequency of alternation of the eddy currents depends on the frequency of alternation of the flux field.

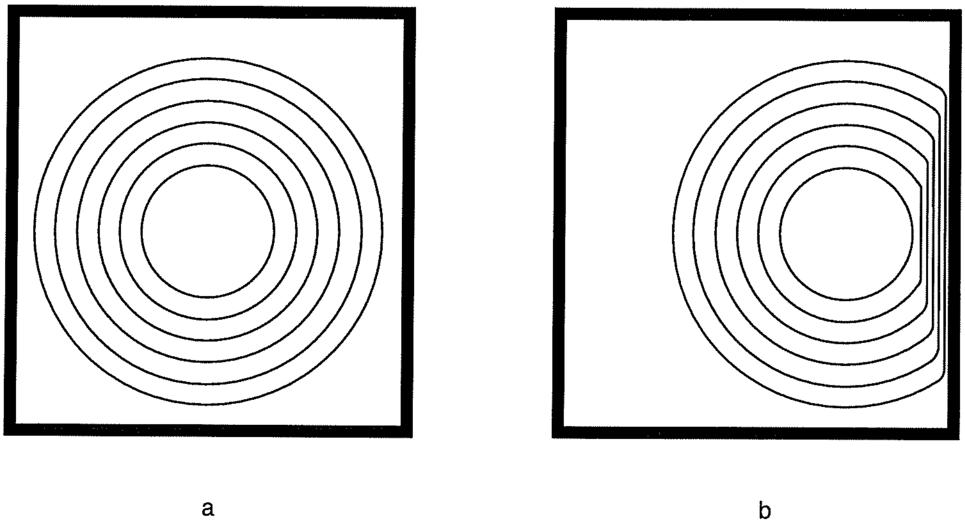


FIGURE 8-17 Effect of material boundaries. (a) Eddy currents undisturbed by material boundaries. (b) Eddy currents compressed by material boundaries .

6. Eddy current density varies in the test material as follows:

   A. Eddy currents exhibit a *skin effect*. That is, current density is maximum at the material surface and decreases exponentially with depth. Thus, in thicker materials, eddy current testing operates only on the outer "skin" of the test material and test sensitivity decreases rapidly with depth. Volumetric tests are possible only in thin specimens.

   Skin depth (δ), also called standard depth of penetration, is defined as the depth at which eddy current density (the portion of electrons active at a particular depth as compared to the material surface) has decreased to $1/e$, where "e" is the so-called natural logarithm, the number 2.71828, a device representing the natural rate of decay for many phenomena. Eddy current density for one, two, and three skin depths calculates as:

$$1\delta = \frac{1}{e} = \frac{1}{2.71828} = 0.368 = 36.8\%$$

$$2\delta = \frac{1}{e^2} = \frac{1}{7.38906} = 0.135 = 13.5\%$$

$$3\delta = \frac{1}{e^3} = \frac{1}{20.08554} = 0.0498 = 5.0\%$$

Beyond three skin depths eddy current density is too small to provide a displayable signal. (See effective depth of penetration in paragraph 6C below.) Standard depth of penetration in English and metric units for a particular material and test frequency can be calculated as follows:

$$\delta\,(\text{inches}) = 1.98\sqrt{\frac{\rho}{f \times \mu_r}}$$

$$\delta\,(\text{mm}) = 25\sqrt{\frac{\rho}{f \times \mu_r}}$$

where:
δ = standard depth of penetration
ρ = resistivity
f = frequency
μ_r = relative permeability

   B. The skin depth formula is truly valid only in the case of infinitely thick test material and large coils. However, at a material thickness of at least five skin depths, where eddy current density is only 0.0067% of surface density, the effect of restriction in thickness is so slight that the material may be considered to be "effectively infinite," rendering the formula accurate enough for practical purposes, providing that coil size is adequate. Conversely, if coil size is adequate but material thickness is restricted, current density at the opposite surface will exceed the calculated values. This is a fortunate circumstance, enhancing the possibility of volumetric inspection on thin-walled specimens.

   C. The extent of a coil's flux field varies with coil diameter such that effective eddy current penetration is approximately limited to the diameter of the coil. Consequently, if the coil is too small, current density at a particular depth will be less than that indicated by the skin depth equation.

   Effective depth of penetration is defined as the depth at which eddy current density decreases to 5% of surface density. This is the minimum eddy current density necessary to develop sufficient secondary flux to change coil impedance by a dis-

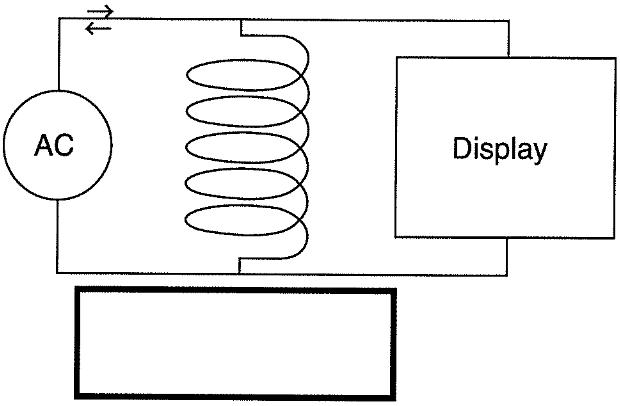


FIGURE 8-18 Voltage causes current to flow.

playable amount. Thus, effective depth will equal three skin depths only where coil diameter is at least as great as three skin depths. Coil diameter, however, is a double-edged sword: as diameter increases, sensitivity to small defects decreases.

7. Eddy currents exhibit a linear phase lag with depth. To visualize the phase lag phenomenon, one may imagine a tall glass of water filled with small ice cubes all the way to the bottom of the glass. If one dips a teaspoon a short distance into the glass and begins to stir, the ice cubes on the surface circulate first and those at greater depths go into motion progressively later as the energy introduced by the spoon proceeds toward the bottom of the glass. In similar fashion, as depth increases, eddy current activity is progressively delayed. Phase lag in the test material proceeds at the rate of one radian (57.3°) per standard depth of penetration. The phase lag signal indicates discontinuity depth and material thickness in eddy current testing.

8.4.2 Eddy Current Test Sequence

The induction process was previously modeled using a pair of coils as primary and secondary circuits. The eddy current test process is now summarized with an actual test specimen as the secondary circuit.

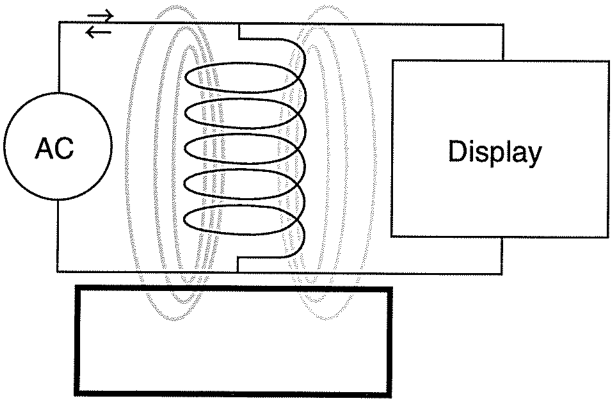


FIGURE 8-19 Electromagnetism.

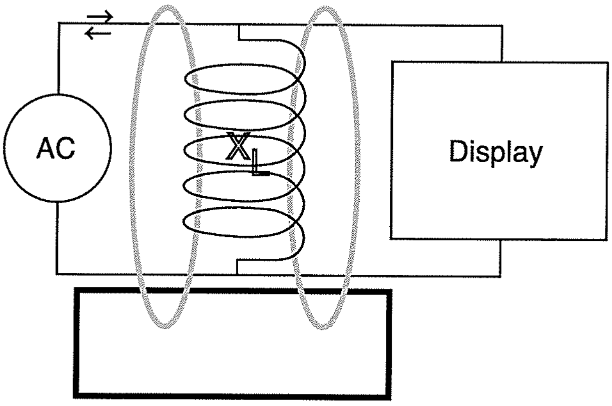


FIGURE 8-20 Varying flux induces back voltage, which causes inductive reactance.

1. The test instrument's AC generator applies an alternating voltage of a certain frequency to the test coil, causing an alternating current to flow through the coil (Figure 8-18).
2. The current in the coil develops a primary magnetic field around the coil (Figure 8-19). The primary magnetic field initiates the following induction processes:
   a. The coil's flux induces a back voltage into the coil, causing inductive reactance (Figure 8-20).
   b. The coil's flux induces a voltage into the test material, causing eddy currents to circulate (Figure 8-21).
3. The eddy currents generate a secondary magnetic field, which reacts with the primary field that the coil is generating (Figure 8-22).

Any changes in the flow of eddy currents will cause changes in the magnetic field that the eddy currents return to the test coil. Any changes in this magnetic field will cause changes in the inductive reactance and effective resistance of the coil, resulting in changes in current flow through the coil.

4. Finally, any changes in current flow through the coil will produce a change in the impedance indication on the instrument's display.

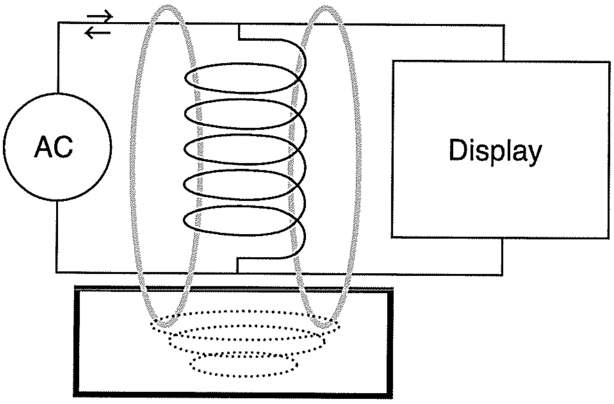


FIGURE 8-21 Eddy currents in test material.

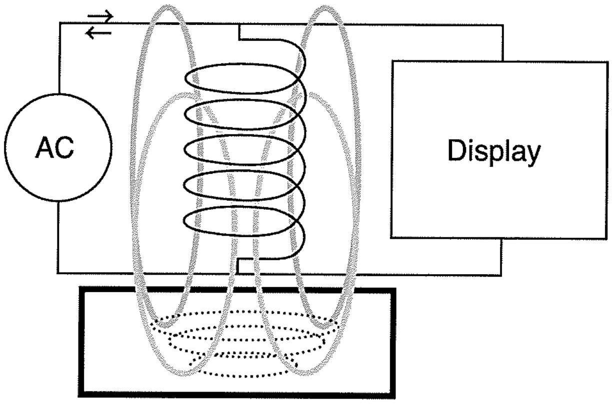


FIGURE 8-22 Secondary flux interacts with primary flux.

8.4.3 Test Performance

Test performance criteria do not seem to be as formally defined for eddy current testing as for ultrasonic testing and radiography. However, the same performance-related terminology can be usefully employed as follows:

- *Sensitivity:* The minimum size of discontinuity that can be displayed from a given material depth. Surface sensitivity is especially important with the eddy current method.
- *Penetration:* The maximum depth from which a useful signal can be displayed for a particular application.
- *Resolution:* The degree to which separation between signals can be displayed.

Test performance depends primarily on material conductivity, permeability, test frequency, coil design, and lift-off. Test frequency and coil design are readily selectable, and are therefore the primary controls over test performance. Guidelines for realizing optimum results for a specific application are given in Section 8.6. The following paragraphs summarize how major test variables affect performance.

1. *Conductivity.* The greater the conductivity of the test material, the greater the sensitivity to surface discontinuities, but the less the penetration of eddy currents into the material. Initially, this reduced penetration may seem contradictory, but is actually quite logical. As the coil's flux field expands, voltage is induced first on the surface and then at increasing depths in the test material. In high-conductivity materials, a considerable eddy current flow and thus a strong secondary flux are 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.

2. *Permeability.* This variable applies only to ferromagnetic materials. As material permeability increases, noise signals resulting from permeability variations increasingly mask eddy current signal variations. This effect becomes more pronounced with increased depth. Permeability thus limits effective penetration of eddy currents. The problem can be eliminated by magnetically saturating the material. However, the opportunity to saturate is limited by coil/test material geometry.

3. *Frequency.* Eddy current testing is performed within a frequency range of approximately 50 Hz to 10 MHz, although most applications are performed well within the extremes of that range. As test frequency is increased, sensitivity to surface discontinuities increases, permitting increasingly smaller surface discontinuities to be detected. As fre-

TABLE 8-1 Typical Depths of Penetration

	Conductivity			36.8% Depth of penetration					
Metal	% IACS	Resistivity	Permeability	1 KHz	4 KHz	16 KHz	64 KHz	256 KHz	1 MHz
Copper	100	1.7	1	0.082	0.041	0.021	0.010	0.005	0.0026
6061 T-6	42	4.1	1	0.126	0.063	0.032	0.016	0.008	0.004
7075 T-6	32	5.3	1	0.144	0.072	0.036	0.018	0.009	0.0046
Magnesium	37	4.6	1	0.134	0.067	0.034	0.017	0.008	0.0042
Lead	7.8	22	1	0.292	0.146	0.073	0.37	0.018	0.0092
Uranium	6.0	29	1	0.334	0.167	0.084	0.042	0.021	0.0106
Zirconium	3.4	70	1.02	0.516	0.258	0.129	0.065	0.032	0.0164
Steel	2.9	60	750	0.019	0.0095	0.0048	0.0024	0.0012	0.0006
Cast steel	10.7	16	175	0.018	0.0089	0.0044	0.0022	0.0011	0.0006

quency is decreased, eddy current penetration into the material increases. In addition, as frequency is decreased, the speed of coil motion must be decreased in order to obtain full coverage.

The test frequency for obtaining adequate penetration in a given material can be estimated using the skin depth equation or by using a penetration chart plotted from the skin depth equation for various conductive materials. Table 8-1 shows skin depths obtained at various frequencies for a selection of materials. However, because of the number of variables affecting eddy current behavior, this frequency should only be used as a starting point. The optimum frequency is best determined by experimentation.

4. *Coil Design.* Penetration and sensitivity are affected by conflicting requirements for coil geometry. Sensitivity to small surface discontinuities requires that the eddy current field be sufficiently compact so that it will be adequately distorted by the discontinuity. Conversely, penetration requires that the eddy current field extend to the required depth in the test specimen. The rules of thumb are that eddy current penetration is limited to a depth equivalent to coil diameter while sufficient sensitivity requires that coil diameter be limited to the minimum length of discontinuity to be detected.

5. *Lift-off.* Since flux density decreases exponentially with distance from the test coil, the amount of lift-off, or separation between the coil and test specimen, has a significant impact on sensitivity. The closer the coupling between coil and test specimen, the denser the eddy current field that can be developed, and thus the more sensitive the test to any material variable. Conversely, close coupling increases sensitivity to lift-off noise due to causes such as probe wobble.

8.5 TEST EQUIPMENT

Basic eddy current hardware includes instruments, coils and coil fixtures, coil/test specimen transport equipment, recording devices, and reference standards. Test instruments can be either general purpose or designed for a specific application. Coils are usually designed for a particular category of application.

8.5.1 Eddy Current Instruments

A broad variety of eddy current instruments is 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.

In addition to a power supply, all eddy current instruments require at least three circuit elements: AC generator, coil circuit, and processing/display circuitry. The level of flexibility designed into each of these elements generally determines how eddy current instruments differ from each other.

- *AC generators* provide the voltage that drives the coil. They can operate at a single fixed frequency, provide a selection of switchable frequencies, be continuously variable, or even provide multiple frequencies simultaneously. In some instruments, there is adjustment for amplitude of the voltage applied to the coil.
- *Coil circuits* range from designs intended to work with only a single specific coil, a limited range of specified coils, or with virtually any coil configuration available.
- *Displays* can range from single LED and meter readouts to multifrequency presentations on multicolor display screens.

Dedicated Instruments

Dedicated instruments are designed for a specific application and are usually able to perform that application more efficiently than general-purpose instruments. Examples of dedicated instruments are crack detectors, coating thickness gauges, and conductivity meters. Conductivity meters, for example, can give direct readout of conductivity in IACS values. In addition, some crack detection instruments provide lift-off suppression to prevent noise signals caused by variations in coil to test material spacing. When there is sufficient work in a given application to justify investment in a single-purpose instrument, it is likely to be the best choice. However, one must be careful using eddy current meter-type instruments. Because they do not provide the quantity of information available from an impedance plane display, meter-type instruments can mislead less-qualified users. Since meter instruments can display only upscale or downscale deflections, they must be operated so that only one material variable is displayed. However, with impedance plane display instruments, each type of material condition deflects the display dot in a characteristic manner, facilitating separation of variables and interpretation of signals.

Standard Impedance Plane Display Instruments

The AC generator of a standard impedance plane display instrument drives the test coil at only one frequency, which is usually selectable from a wide range of frequencies. These general-purpose instruments can perform an extensive variety of eddy current applications. The ability to view actual impedance plane signals provides the knowledgeable user a great deal of valuable information. Some newer impedance plane instruments have flat displays, offering enhanced portability, such as the unit shown in Figure 8-23. However, test-system-type instruments (Figure 8-24) do not provide portability, but may be expected to operate 24 hours a day to accommodate continuous production at tubing, pipe, rod, or wire mills.

Impedance plane display instruments show variation of both inductive reactance and resistance during testing. Control functions of impedance plane instruments can include, but are not limited to, the following:

- *Frequency:* Adjusts the frequency at which the AC generator drives the test coil
- *Gain (Sensitivity, dB):* Adjusts amplification of the bridge output signal for display (see Mode of Operation)
- *Horizontal/Vertical Dot Position:* Adjusts dot position on the display
- *Phase Rotation:* Rotates the direction of dot deflection
- *Balance (Null, Zero):* Adjusts impedance to be identical on both sides of the bridge

FIGURE 8-23 Portable impedance plane display instrument.

- *Erase (Clear):* Erases the display
- *Gate:* Sensitizes some portion of the display to trigger an alarm
- *Filters:* Prevent display of signal above and/or below a certain frequency range
- *Probe Drive:* Adjusts voltage amplitude applied to the test coil
- *Horizontal and Vertical Display Amplification:* Allows one axis of the display to be expanded relative to the other for signal enhancement

Multifrequency Instruments

Development of multifrequency instruments was one of the most significant advances in the evolution of eddy current testing hardware. These instruments practically eliminate what had been one of the most severe limitations of the method, the fact that signals

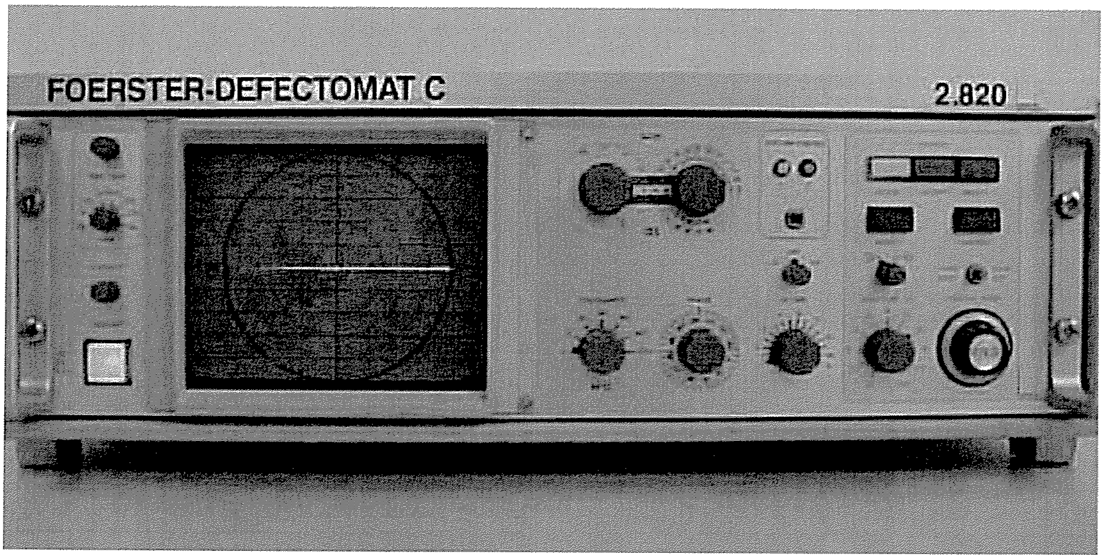


FIGURE 8-24 Production line system instrument.

caused by different material variables can vector into a combined signal that becomes difficult to interpret. In addition, they offer potential for substantial enhancement of performance. Driving the test coil at more than one frequency, multifrequency instruments can not only display the test activity at each frequency separately, but can also show a so-called "mixed output" of different frequency signals subtracted from each other. These capabilities result in the following four advantages:

1. *Suppression of Undesired Variables.* The ability to subtract signals from each other and display the difference as mixed output permits elimination of undesired signals on the display. This feature is the reason why multifrequency instruments were originally developed: to suppress signals from steel supports during inspection of nonferromagnetic tubes, as well as reduce lift-off noise due to probe wobble. A two-frequency instrument can eliminate one source of unwanted signal. Each additional frequency enables the mixing out of an additional type of signal.
2. *Optimization of Normally Contradictory Test Variables.* Use of multiple frequencies allows more than one frequency-dependent performance variable to be optimized simultaneously. For example, during in-service tube inspection using internal coils, a higher frequency provides sensitivity to inner diameter discontinuities, while a lower frequency provides the penetration needed to detect outer diameter discontinuities.
3. *Signal Identification by Pattern Recognition.* A given signal deflection could be caused by a number of detectable conditions. However, each condition exhibits a unique pattern of behavior when viewed over a wide range of frequencies. Multifrequency instruments display this behavior, enhancing the likelihood of identifying the true nature of the signal.
4. *Simultaneous Absolute/Differential Operation.* Some multifrequency instruments have the advantage of allowing a single dual coil assembly to be operated simultaneously in both absolute and differential mode (see Mode of Operation, below), cutting in half the required testing time when the inspection is required to be performed using both of these techniques.

Two types of multifrequency instruments are available: multiplexed and multichannel. Multiplexed equipment operates at only one frequency at a given instant, rapidly switching among the available frequencies. Thus, the test is not being performed simultaneously at all frequencies, although the display gives the illusion that this is the case. Multichannel equipment is the equivalent of having more than one eddy current instrument sharing a single display screen. Early multifrequency instruments required that signal mixing be performed manually by the technician. Recent designs, such as the unit shown in Figure 8-25, perform the mixing automatically.

8.5.2 Test Coils

Eddy current techniques are often classified according to the mode of operation and basic configuration of the test coil assembly. *Mode of operation* determines how the instrument interfaces with the test specimen, such as whether it is comparing coil input from the test specimen to a reference coil (absolute operation) or whether it is comparing coil input from two adjacent portions of the test specimen to each other (differential operation). *Basic configuration* determines how coils are physically packaged to "fit" the test object; that is, whether the coil approaches a portion of the test surface in a probe-like fashion (surface coil), whether it fully encircles the outer circumference of the test object (encircling coil), or whether it passes through the inside of tubular product (internal coil). Coil design, as well as magnitude and frequency of the applied current, all affect the electromagnetic field developed by the coil.

Mode of Operation

With most eddy current instruments, the coil assembly is connected to the instrument via a bridge circuit, as illustrated in Figure 8-26. Bridges are capable of detecting very small

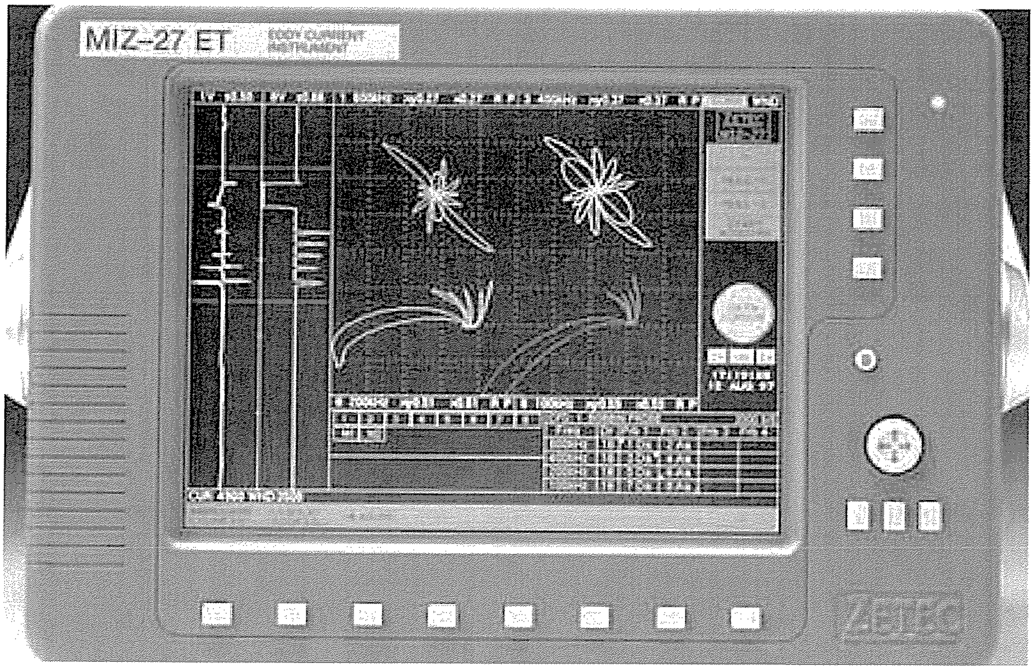


FIGURE 8-25 Multifrequency instrument.

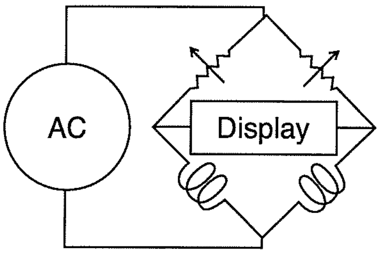


FIGURE 8-26 Bridge circuit.

impedance variations. At the start of the test, the instrument operator balances the bridge to provide a reference signal. During testing, the display provides a readout of bridge imbalance caused by interaction of the coil with the test material.

Absolute coil configurations (Figure 8-27) place a single coil on the test material and employ a second coil, called a *balance load,* remote from the test material to balance the bridge. Absolute coils detect any condition that affects eddy current flow. Although this means that they are capable of detecting any type of condition to which the eddy current method is sensitive, it also means that they are sensitive to potentially unwanted signals such as lift-off and material temperature variations.

Differential coil configurations (Figure 8-28) use a matched pair of coils to perform a comparison. Both coils are coupled to the test material, with one portion of the test material being compared to another. Conditions sensed by both coils are not detected, whereas conditions sensed by only one coil are detected. This has the advantage of suppressing temperature and lift-off variations. Suppression of lift-off helps small discontinuities to be distinguished from lift-off noise. The downside to differential coils is that they provide no signal when a defect condition is simultaneously detected by both coils. Thus, differential coils will only display the ends of long discontinuities; they are not sensitive to gradual discontinuity variations and could ignore a long discontinuity entirely if its ends are very narrow. Differential coil signals are also difficult to interpret: the displayed signal represents the *difference* between two coils' impedances, rather than the impedance of a single coil's interaction with the test material.

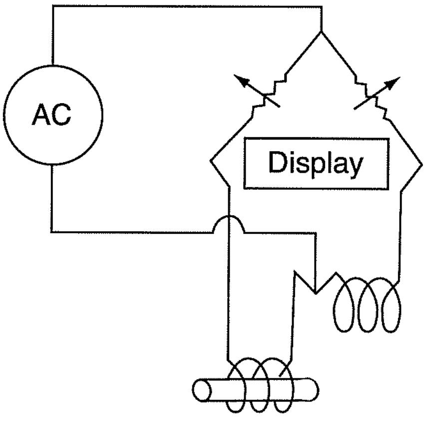


FIGURE 8-27 Absolute coil configuration.

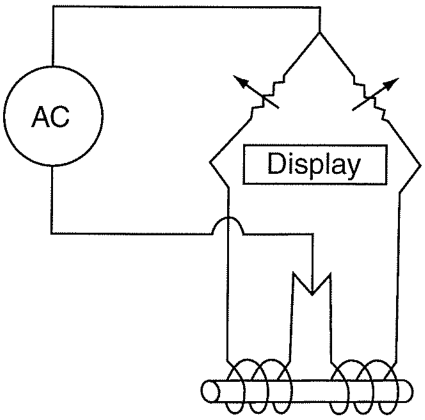


FIGURE 8-28 Differential coil configuration.

External Reference coil configurations (Figure 8-29) combine features of both the absolute and differential modes, placing one coil in contact with the test material and the other coil coupled to a reference standard. This technique provides an indication whenever the test material differs from the standard.

Basic Configurations

Surface Coils. Surface coils are usually designed to be hand-held and are encased in probe-type housings for scanning material surfaces. Surface coils are available in different shapes and sizes to meet different application needs. There is vastly more variety in surface coil design than with encircling and internal coils. Some of them are astonishingly small, wound with wire finer than human hair. Some surface coils can perform a variety of applications, whereas others have been configured to fit a specific size and shape of test specimen. For example, surface probes have been fitted with guides to enable tracing the coil along the edge of turbine blades.

Most surface coils are "bobbin wound" like a spool of thread (Figure 8-30a) and are

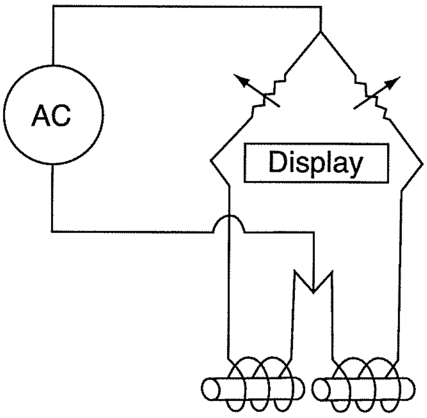


FIGURE 8-29 External reference coil configuration.

designed so the axis of the coil is perpendicular to the surface of the test specimen. Such coils are sensitive to surface cracks and discontinuities that are oriented perpendicular to the test surface; they are generally insensitive to planar subsurface discontinuities. Planar discontinuities can be detected using so-called "horseshoe" or "gap" probes (Figure 8-30b). These probes employ a pair of coils wound on each end of a U-shaped ferrite form so that the flux field flows from one pole of the "horseshoe" to the other and therefore parallel to the test surface. The eddy current field thus flows perpendicular to the test surface, providing sensitivity to planar discontinuities.

Wide surface coils permit rapid scanning and deeper penetration but are less effective at pinpointing the location of small discontinuities. They are often selected for conductivity testing 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. Surface coils are made in numerous configurations to meet specific application needs. Typical surface coil configurations include the following:

Pencil Probe (Figure 8-31a): Shaped, as its name implies, to be held between the fingers and drawn across the test specimen.

90° Probe (Figure 8-31b): Similar in function to a pencil probe, except that the coil is at a right angle to the probe housing for use where access is limited

Bolt Hole Probe (Figure 8-31c): Designed to fit inside bolt holes with the coil axis perpendicular to the wall of the hole. Manual bolt hole probes are often fitted with retainers so that they can be rotated at a certain depth in the hole and may be fork-shaped to ensure a snug fit. Motorized bolt hole probes are also available. Their output is generally shown on a time base display, allowing the user to determine circumferential position of discontinuities.

Fastener (Doughnut) Probe (Figure 8-31d): A probe designed to fit above the fastener (rivet) holes of an aircraft fuselage. It is used to inspect for cracks around the hole and can be fitted with a clear plastic sight to aid in aligning the probe with the hole.

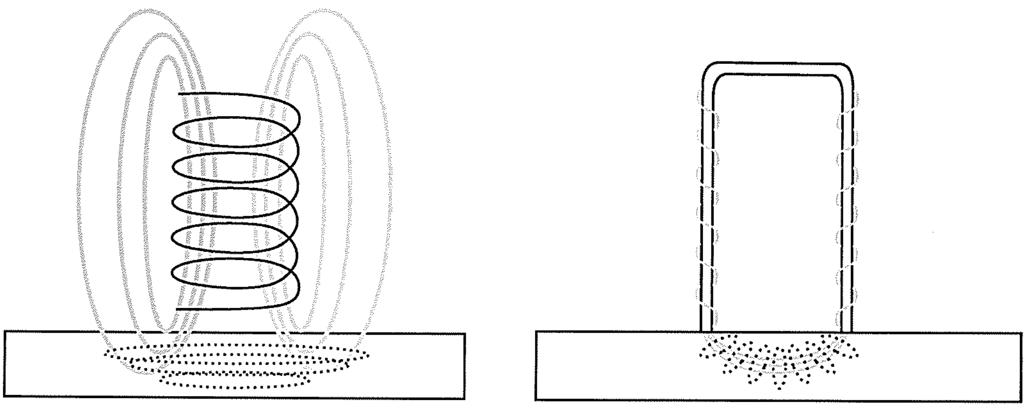

(a) (a)

FIGURE 8-30 Surface coils: (a) bobbin-wound, (b) horseshoe probe.

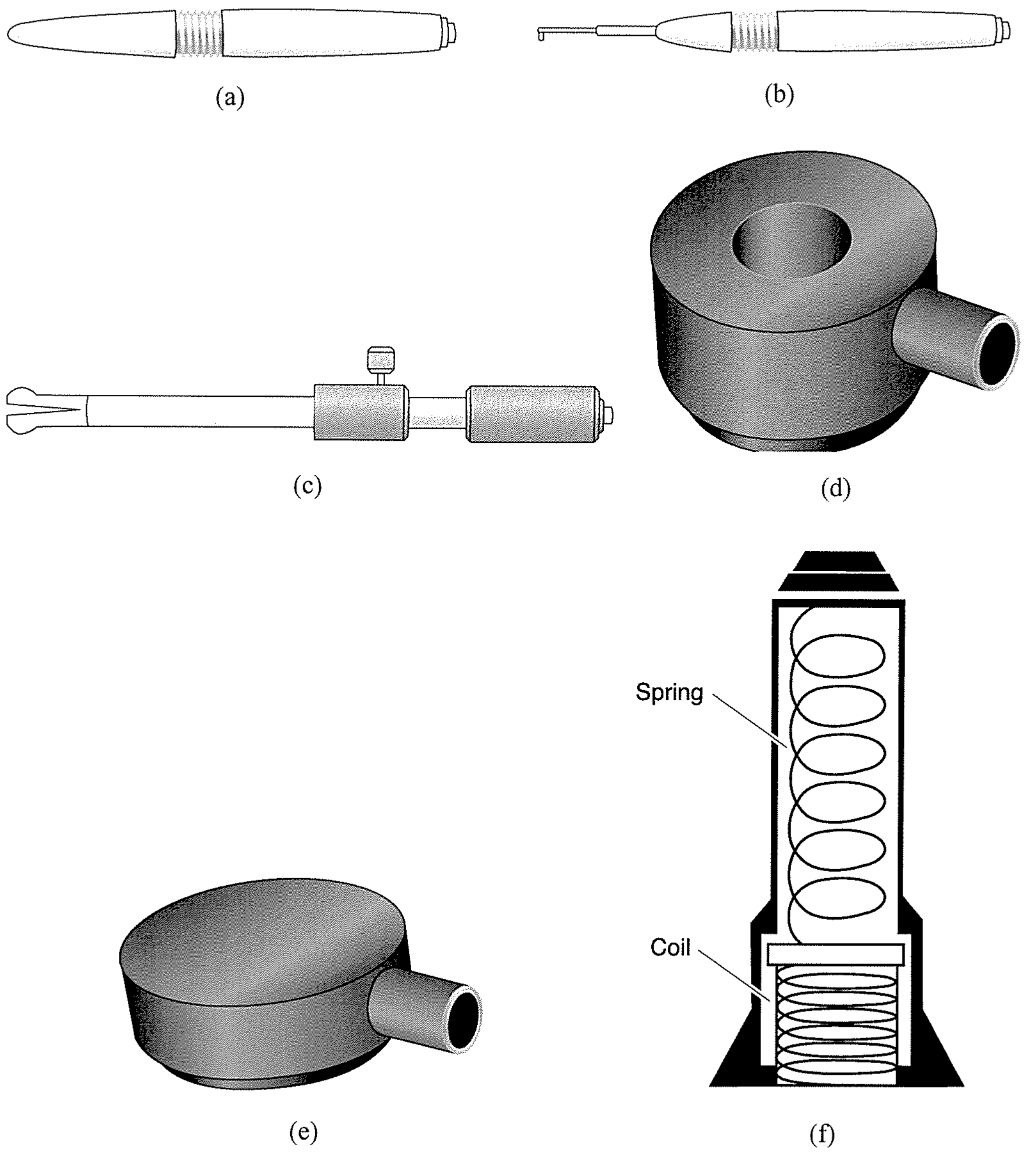


FIGURE 8-31 Typical surface coil configurations: (a) pencil probe, (b) 90° probe, (c) bolt hole probe, (d) fastener (doughnut) probe, (e) pancake probe, (f) spring-loaded surface coil.

Pancake Probe (Figure 8-31e): A low-profile coil generally used for scanning surfaces that have little or no curvature.

Spring Loaded Surface Probe (Figure 8-31f): The coil is mounted like a piston in a cylinder, spring-loaded so that it retracts into an outer housing when pressed against the test surface, thereby minimizing lift-off noise due to probe wobble.

Shielded coils are encased within a cylinder of ferrite, a nonconductive, ferromagnetic material. As shown in Figure 8-32, shielding contains the coil's flux field to prevent interaction with test material boundaries. However, since shielding only operates in the lateral direction, it does not impair penetration.

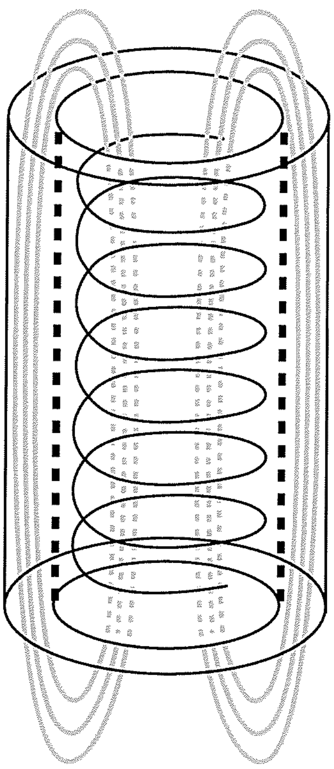


FIGURE 8-32 Shielded coil.

The *cross-axis* coil assembly consists of a pair of adjacent coils interacting with the test material, with the coil axes oriented 90° to each other. Thus, there is sensitivity to defects of all orientations. Cross-axis coils can be placed in a side-by-side configuration as shown in Figure 8-33a, where one coil generates eddy currents parallel to the test surface while the other coil generates eddy currents perpendicular to the test surface. Cross-axis coils can also be wound as a unit with alternate layers wound at 90° angles to each other (x-wound), as shown in Figure 8-33b.

Transmit–receive configurations, such as reflection coils and through-transmission coils, use one coil assembly to induce eddy currents into the test material and a second coil assembly to sense the secondary field.

The *reflection coil* technique, shown schematically in Figure 8-34a, employs two coil assemblies in a single housing, positioned on the same side of the test object. A large single outer coil functions as a transmitter surrounding a pair of smaller, stacked inner coils that form a receiver circuit (Figure 8-34b). The term "reflection" coil results from the fact that the inner coils form a matched pair, wound in opposition. The outer coil induces eddy currents into the test specimen. Secondary flux developed by the eddy currents then induces voltage into the inner coil closest to the test specimen, causing an imbalance in the two-coil receiver circuit, thus providing a signal. Reflection coils have the advantage of being insensitive to temperature drift. They perform well at low frequencies and can function over a broad frequency range.

The *through-transmission* technique (Figure 8-35), positions transmitting and receiving coil assemblies on opposing sides of the test object. It provides a valuable performance advantage in that discontinuities can be detected at greater depths. However, this is

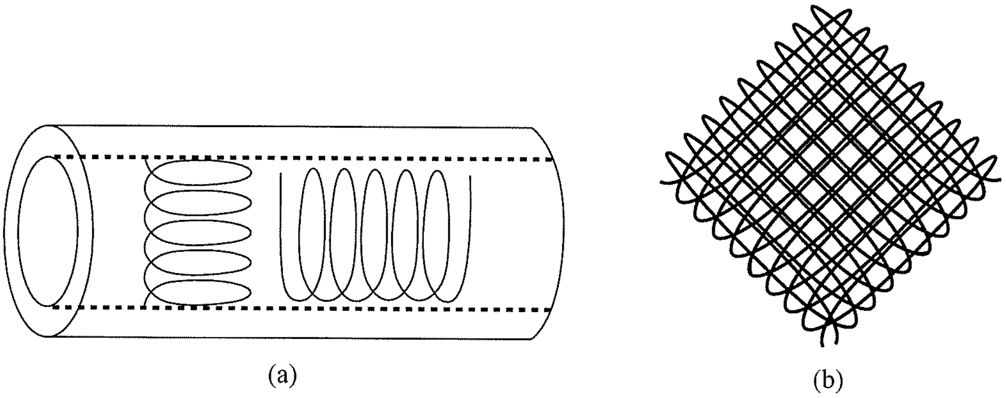

(a) (b)

FIGURE 8-33 Cross-axis coils: (a) side by side, (b) X-wound.

offset by the fact that discontinuity depth cannot be displayed because the technique does not provide phase information.

Hall detector. Another transmit–receive technique employs a coil to provide primary flux for generating eddy currents, but uses a solid-state device called a Hall detector as a receiver. In 1879, E. H. Hall discovered that a small voltage is developed across a current-carrying conductor when an inducing magnetic flux is perpendicular to the direction of current flow. Although the voltage was not significant using typical conductors, certain semiconductors develop voltage of magnitude suitable for eddy current test purposes. An ordinary receiver coil operates according to Faraday's law, with induced voltage proportional to the time rate of change of the inducing flux, and therefore depends on the effects of frequency as well as amplitude, with the result that output decreases as frequency decreases. However, a Hall detector responds only to the instantaneous magnitude of the inducing flux, offering good performance at low frequencies. In addition, a Hall detector can be physically quite small.

In addition to the widely known coil types described above, a number of advanced designs have been developed in recent years. A notable contributor in this area is Atomic Energy of Canada, Limited, whose staff has developed a reputation for developing state-of the-art coils for power utility applications.

Encircling coils. Encircling coils (Figure 8-36) completely surround the test material and are normally used for production testing of rod, wire, pipe, tube, and bar stock. Material tested with encircling coils should be centered in the coils by means of guides, so that

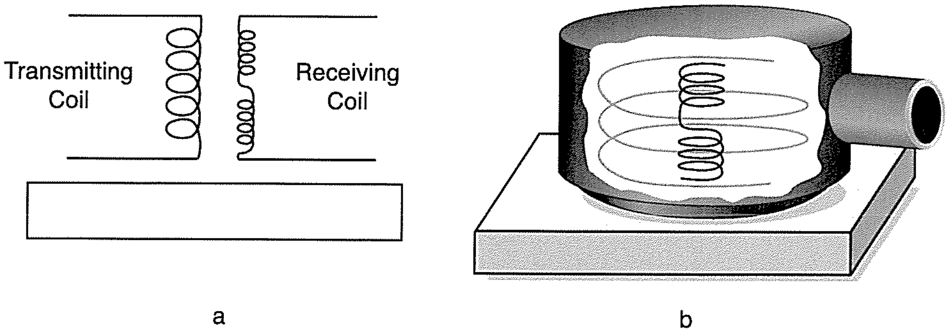


FIGURE 8-34 Reflection coil: (a) schematic diagram, (b) actual configuration.

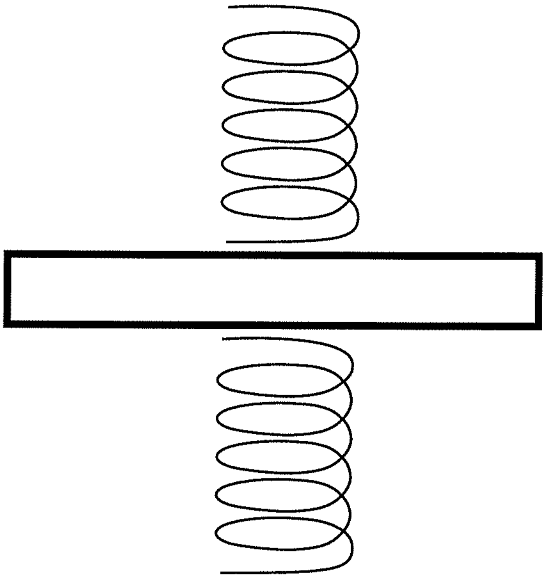


FIGURE 8-35 Through-transmission.

the entire circumference will be tested with equal sensitivity. Production line encircling coils experience more heavy-duty usage than any other type of eddy current coil. Some of them may operate continuously, with product moving through them as fast as 5000 feet per minute. A heavy-duty, production line encircling coil assembly with interchangeable coil size modules is shown in Figure 8-37a. Light-duty, hand-held encircling coil pairs that can be fastened together for differential use or separated for absolute or external reference use are shown in Figure 8-37b.

Because of the "center effect," eddy currents oppose and therefore cancel themselves at the center of solid cylindrical materials tested with encircling coils. Thus, discontinuities located at the center of rods and bar stock cannot be detected with encircling coils. Since encircling coils inspect the entire circumference of the test object, they cannot pinpoint the exact location of a discontinuity along the circumference. So-called *spinning coils* (Figure 8-38), which are actually surface coils that revolve around cylindrical test material, are employed when identification of circumferential location is required in encircling coil applications. Since spinning coils couple to only a limited segment of test material circumference, they are not subject to the center effect. However, spin-

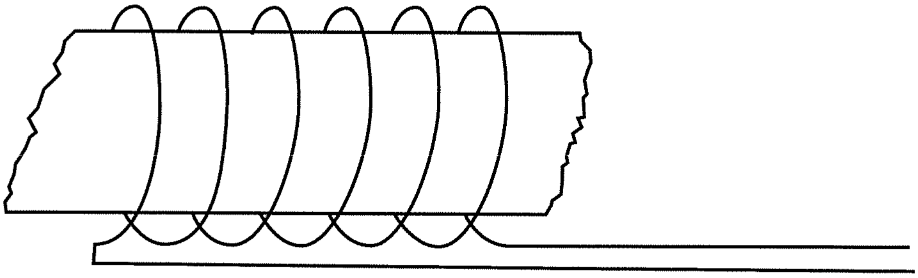
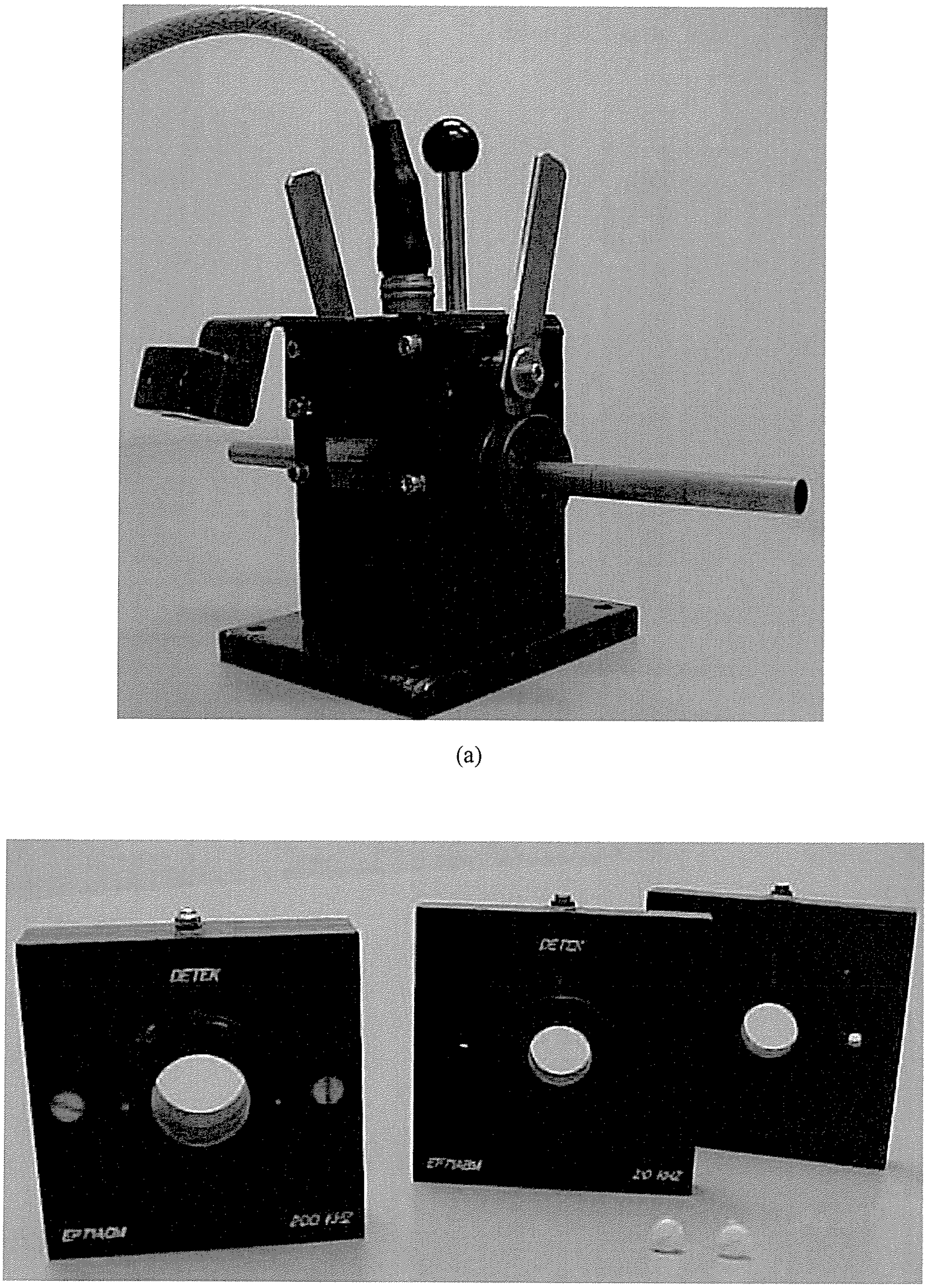


FIGURE 8-36 Encircling coil.



(a)

(b)

FIGURE 8-37 Typical encircling coil configurations: (a) production line, (b) hand held.

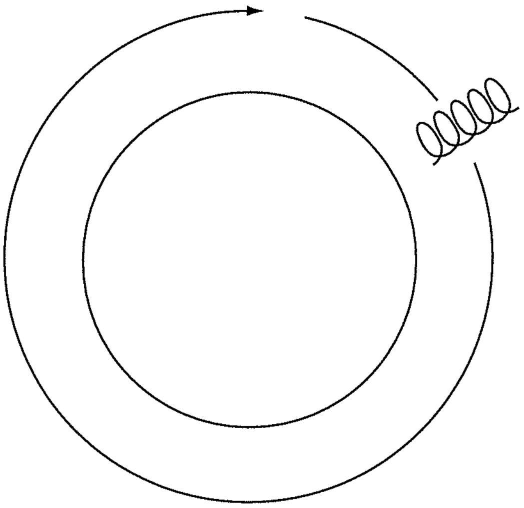


FIGURE 8-38 Spinning coil.

ning coils inspect with a spiral pattern, so their material coverage depends on coil rotation speed versus material transport speed. Care must be taken to ensure adequate coverage.

Internal coils. Internal Coils (Figure 8-39) pass through the core of hollow product and are normally employed for in-service inspection of pipes and tubes. Like encircling coils, standard bobbin-wound internal coils inspect the entire circumference of the test object at one time, but cannot pinpoint the exact location of a discontinuity along the circumference. Again, special designs are available to pinpoint circumferential location of discontinuities. Both manual and automatic means are used to propel internal coils down the length of a long tube. Flexible "u-bend" coil assemblies are available for navigating extreme curvature of tubing. A selection of typical internal coils is shown in Figure 8-40. Inspection of heat exchanger tubing, figure 8-41 is the most common application of internal coils.

8.5.3 Reference Standards

Test calibration or standardization is the process of adjusting the instrument display to represent a known reference standard so that the test can be a comparison between the test

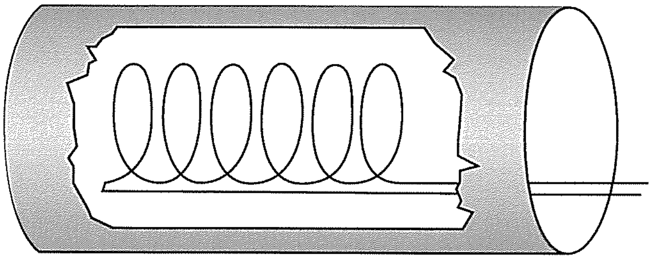


FIGURE 8-39 Internal coil.

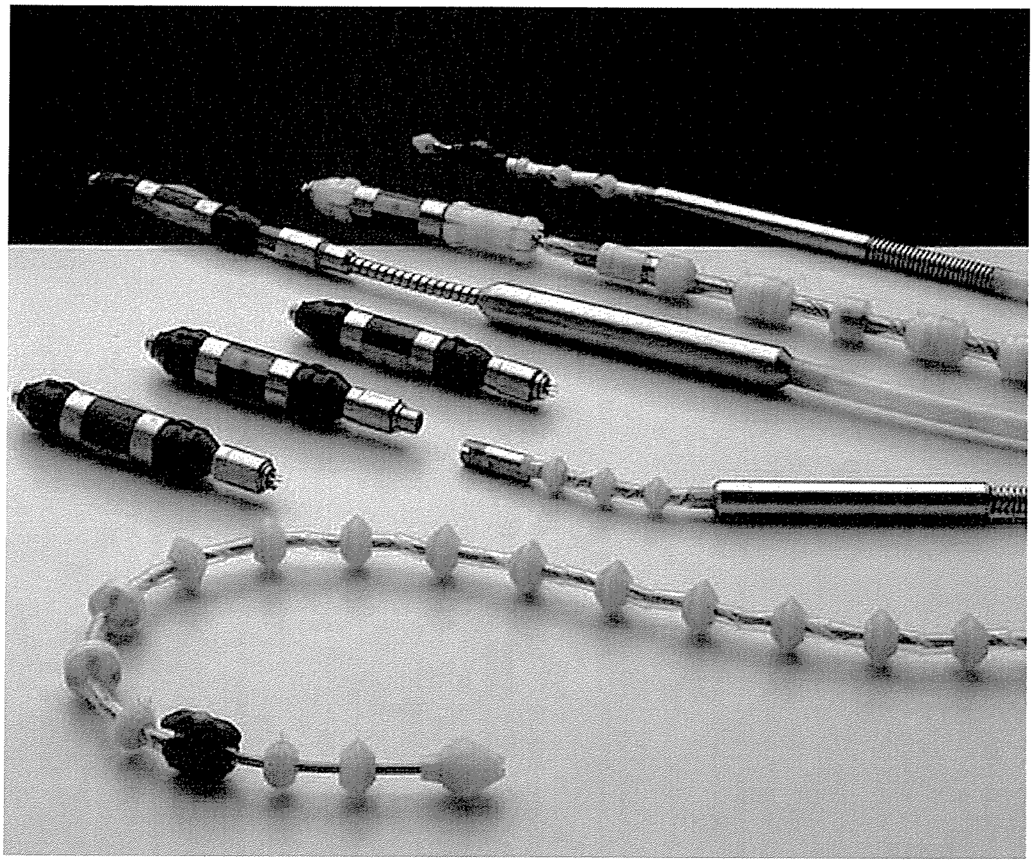


FIGURE 8-40 Typical internal coil configurations.

material and the reference standard. The validity of the test thus depends upon the validity of the reference standard. Moreover, the test system should be checked at regular intervals against the reference standard to ensure that it is operating properly and is still set up correctly for the test being performed. If a variation in instrument performance or setup is discovered, all material tested since the last verification of proper performance and setup should be retested.

Since there is an infinite variety of discontinuity conditions, 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 a test. Testing is therefore not a matter of matching each test 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.

The following rules apply to the selection and fabrication of standards:

1. The test standard should be of the same material, with the same wall thickness and configuration, and receive the same processing as the material to be tested.
2. The artificial discontinuities in the standard should model the natural discontinuities expected in the test material. For example:

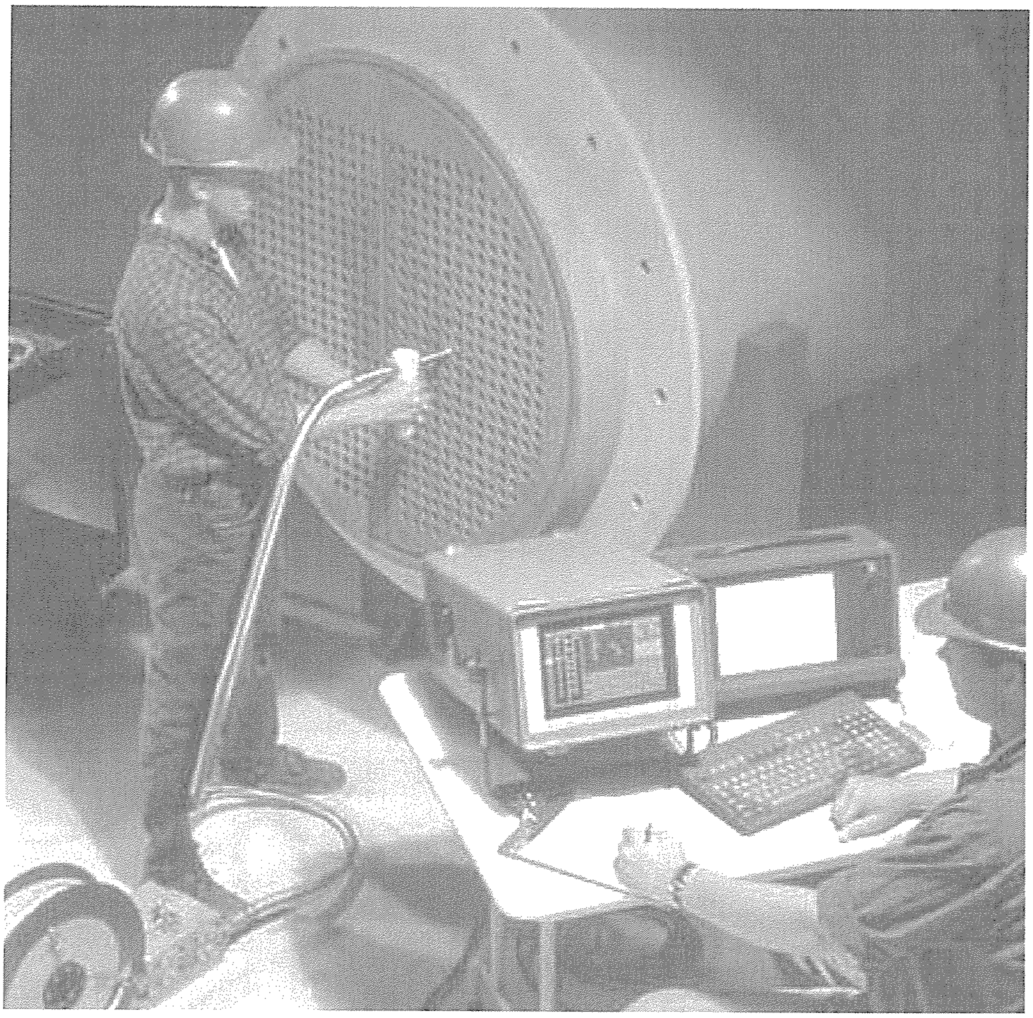


FIGURE 8-41 Inspection of heat exchanger tubing.

a. Drilled holes can simulate pits.
b. EDM notches or saw cuts can simulate cracks.
c. Thickness reduction in tubing can simulate wear.
d. Heat Treatment can simulate a conductivity change.

3. Artificial discontinuities in test standards should be sufficiently separated so that their signals will not interfere with each other.
4. Standards should contain no discontinuities other than those intended to produce reference signals.

Figure 8-42 shows tubing standards as well as standards used to calibrate eddy current instruments for detection and evaluation of cracks in material surfaces and inside bolt holes. To augment standards containing artificial discontinuities, it is helpful to build a library of natural discontinuities by obtaining actual specimens removed from