EDDY CURRENT TEST

6. EDDY CURRENT TEST

6.1. PRINCIPLE OF EDDY CURRENT

When magnetic flux through a conductor changes, induced currents are set up in closed paths on the surface of the conductor. These currents are in a direction perpendicular to the magnetic flux and are called *eddy currents*.

Figure 6.1 illustrates the eddy current.

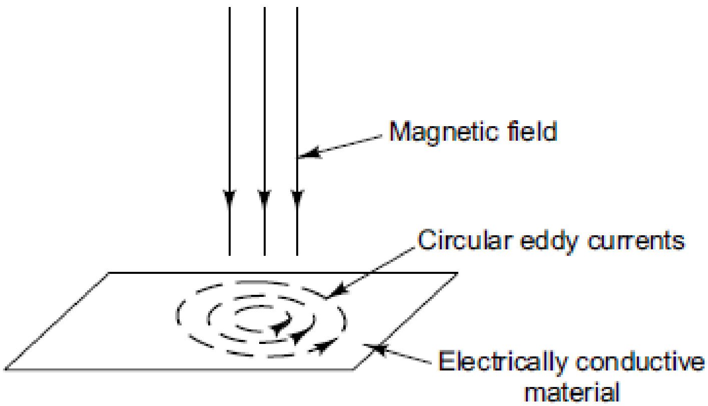

Figure 6.1. Eddy Current

The basic arrangement for producing eddy currents in a conducting material is shown in Fig. 6.2.

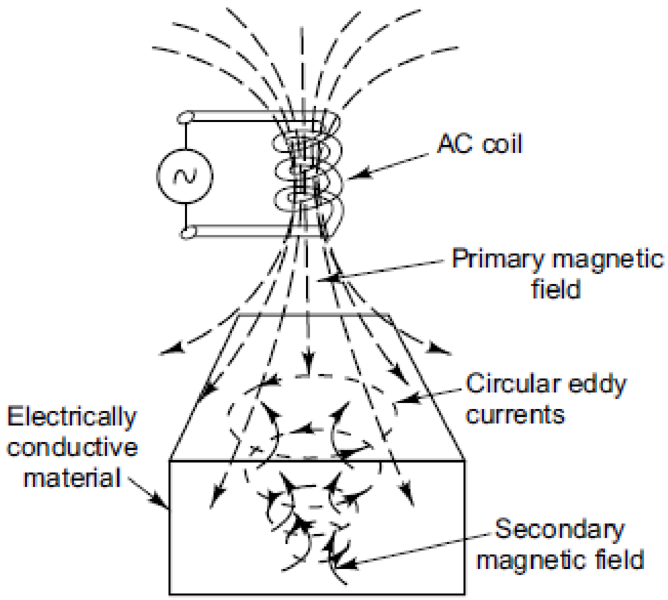

Figure 6.2. Generation of Eddy Current

When an alternating current is passed through a coil, a magnetic field is set up around it. The direction of the magnetic field changes with each cycle of alternating current. If a conductor is brought near this field, eddy currents are induced in it. The direction of the eddy current changes with a change in the direction of the magnetic field during the cycles of alternating current.

The induced eddy current produces its own magnetic field in a direction opposite to the inducing primary magnetic field. The secondary magnetic field due to the eddy current interacts with the primary magnetic field and changes the overall magnetic field and the magnitude of the current flowing through the coil. This means that the impedance of the coil is altered due to the influence of the eddy current.

During non-destructive testing, changes in impedance are displayed either on a meter or on a CRT screen.

6.1.1. Factors Affecting Eddy Currents

The magnitude and distribution of eddy currents in a given conductor is influenced by the conductivity, the magnitude of the primary magnetic field, the permeability of the conductor, geometrical variations, magnetic coupling, in-homogeneity, discontinuity, the test frequency and skin effect.

In non-magnetic materials, the distribution of eddy currents is strongly influenced by their conductivity. In materials of high conductivity, strong eddy currents are generated on the surface of the conductor. This results in a strong secondary magnetic field, opposing the primary magnetic field. This restricts the penetration of the primary magnetic field into the depth of the material. This means that the depth penetration of eddy currents in good conducting materials is limited. But in poor conducting materials, the depth penetration of eddy currents is comparatively larger as shown in Fig. 6.3.

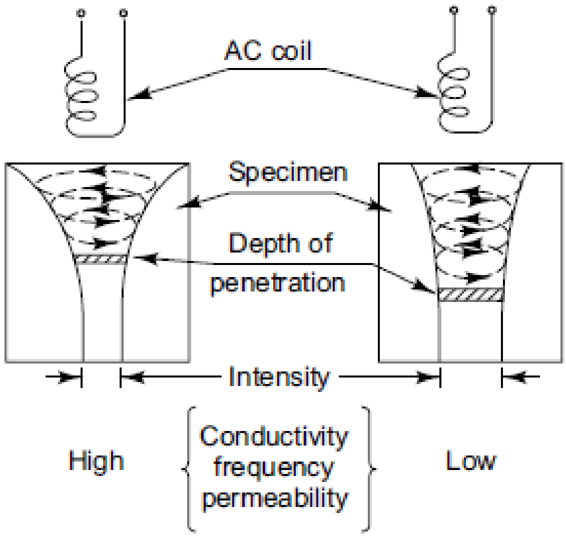

Figure 6.3. Depth of Eddy Current Penetration

The primary magnetic field determines the strength of the induced eddy current as well as the depth of penetration of the eddy current into the material. The effect of magnetic permeability on the eddy current is similar to that of conductivity. Geometrical variations like shape, thickness and the presence of conducting materials in close proximity affects the distribution of eddy currents and the associated magnetic field.

Edges, corners and radii obstruct the circular pattern of the eddy current. This is called the edge effect. It limits the volume distribution of the eddy current and its associated magnetic field as shown in Fig. 6.4.

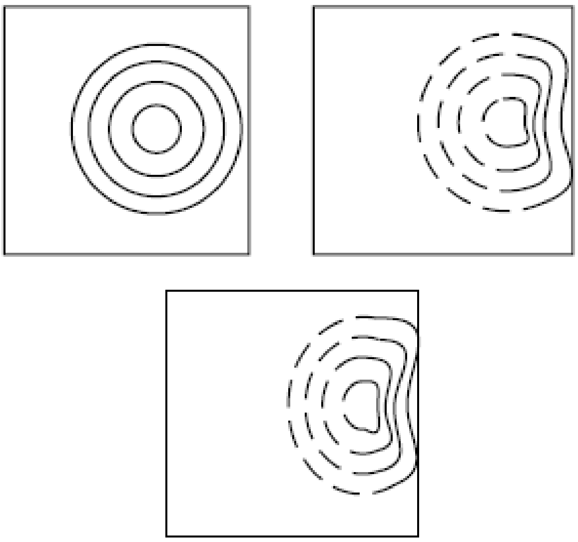

Figure 6.4. Distribution of Eddy Current Due to Edge Effect

In-homogeneities and discontinuities like cracks, inclusions, voids, etc. in conducting materials also affect the circular pattern of eddy currents and the associated magnetic field. Figure 6.5 illustrates the distortion in eddy current distribution due to a discontinuity.

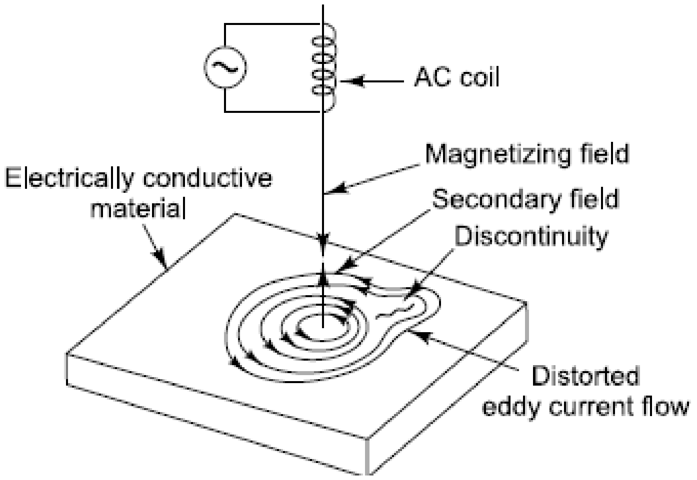

Figure 6.5. Effect of Discontinuity on Eddy Current Distribution

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6.1.2. Coupling

Magnetic coupling refers to the interaction of the varying magnetic field of the test coil with the test object. The effect of the primary magnetic field of the coil in inducing an eddy current on the surface of a conductor is strongly influenced by the distance of the coil from its surface. A small distance of separation ensures good coupling.

However, coupling is influenced by such factors as configuration, geometry, surface condition and coating on the surface of the test object. Coupling is of two types: Lift-off and Fill-Factors. Lift-off indicates the effect of separation of the test coil and the test surface. Fill-factor indicates the effect of magnetic coupling when the encircling coil is used to test a cylindrical object. Fill-factor is given by the ratio of the cross-sectional area of the specimen to the effective cross-sectional area of the encircling coil as shown in Fig. 6.6.

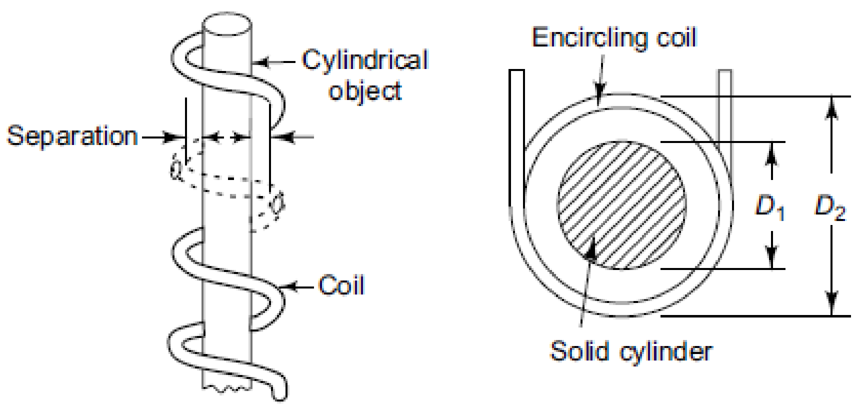

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Figure 6.6. Fill-factor Encircling the Coil Surrounding the Cylindrical Test Object

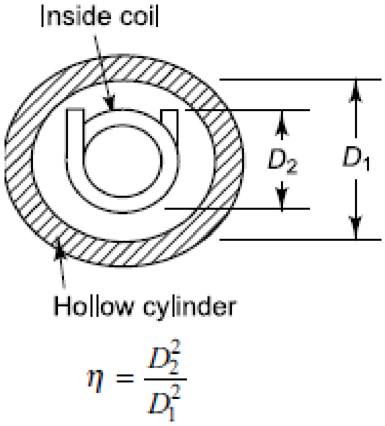

Figure 6.7. Fill-factor for a Hollow Cylinder with an Inside Coil

Thus,

$$\text{Fill-factor } \eta = \frac{\pi D_1^2}{\pi D_2^2} = D_1^2 / D_2^2$$

where

D_1 = Diameter of the cylindrical object

D_2 = Inner diameter of the encircling coil

If the coil is used inside a hollow cylinder, the fill-factor is given by the expression

$$\text{Fill-factor } \eta = D_2^2 / D_1^2$$

where

D_1 = Internal diameter of the hollow cylinder

D_2 = External diameter of the coil

The magnitude of the induced eddy current in an object increases with the frequency of the inducing magnetic field. However, its depth of penetration is low in materials of high conductivity and high magnetic permeability. Eddy current concentration is greater at the surface of the conductor as the depth increases. The depth at which eddy current intensity is reduced to 37% of its intensity on the surface is called *standard depth of penetration* and is given by:

$$\text{Standard depth of penetration} = 1 \Big/ \sqrt{\pi f \mu_r \sigma}$$

where

f = Frequency

μ_r = Relative permeability

σ = Electrical conductivity

Figure 6.8 illustrates the relationship between the depth of penetration and the frequency for various materials.

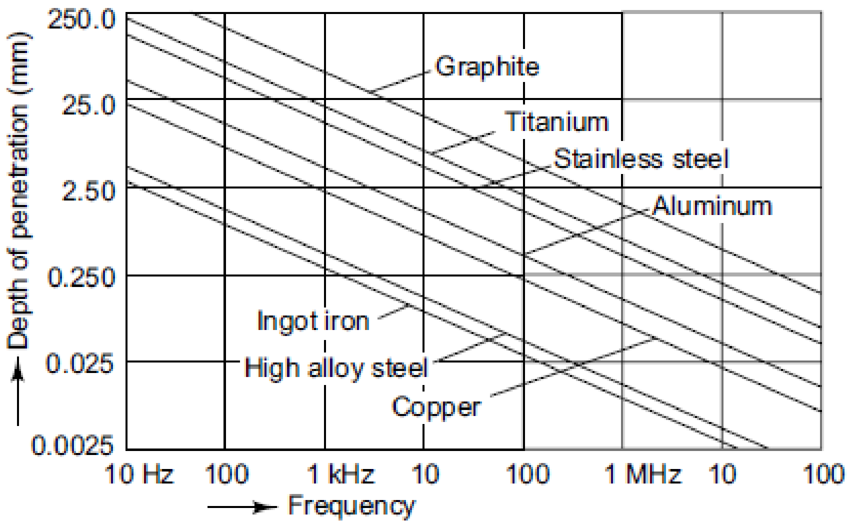

Figure 6.8. Depth of Penetration at Various Frequencies in Various Materials

6.1.3. Impedance Diagram

An impedance diagram is a graphical representation of the effect of eddy current variables on the test coil impedance. The variables are electrical conductivity, dimensional variations and the magnetic permeability of the part. In addition to these, frequencies, discontinuities and coupling factors also influence the impedance of the coil.

The *x*-axis of the impedance diagram represents the resistive component of the coil's impedance, while the *y*-axis represents the inductive component of the coil's impedance. Impedance diagrams are prepared for each of the variables mentioned.

To eliminate the effect of construction or geometry of the coil, the impedance diagrams are normalized. This is done by using the ratio of the inductance of the coil L with the specimen, and L_0 without the specimen (L/L_0). This procedure makes the presentation of information independent of the physical parameters of the coil. In a normalized impedance diagram, the *x*-axis represents the ratio

$(R—R_0)/\omega L_0$ and the *y*-axis represents the ratio $\omega L/\omega L_0$

where

R_0 = Resistance of the coil without the test specimen

R = Resistance of the coil with the test specimen

L_0 = Inductance of the coil without the test specimen

L = Inductance of the coil with the test specimen

ω = Angular frequency of the applied AC

Further, in order to make the impedance diagram independent of the conductivity, permeability and diameter of the test piece, impedance diagrams are plotted for the ratio f/f_c instead of the existing frequency '*f*'. Here, f_c is called limiting frequency and is defined as

$$f_c = \frac{2}{\pi\sigma\mu d^2}$$

where

σ = Electrical conductivity

μ = Magnetic permeability

d = Diameter of the test piece

The estimated value of f_c is given as $5066/\mu\sigma d^2$.

6.1.4. Effect of Coupling on Impedance Diagram

6.1.4.1. Effect of Lift-off

It has been explained earlier that the separation between the test object surface and the test coil is a measure of the lift-off. A large distance of separation (large lift-off) leads to a weak induction of the eddy current, resulting in small changes in the impedance of the coil. A small separation (small lift-off) leads to a strong induction of the eddy current, resulting in large changes in the impedance of the coil.

Other variables remaining constant, a variation in lift-off produces a significant variation in the impedance of the test coil. This effect may mask the variation in impedance of the test coil due to property variation or due to the presence of a defect in the text material. It is necessary, therefore, from the viewpoint of the practical application of eddy currents for nondestructive testing, to know the effect of the lift-off on the impedance of the coil. Figure 6.9 shows an impedance diagram for different values of lift-off.

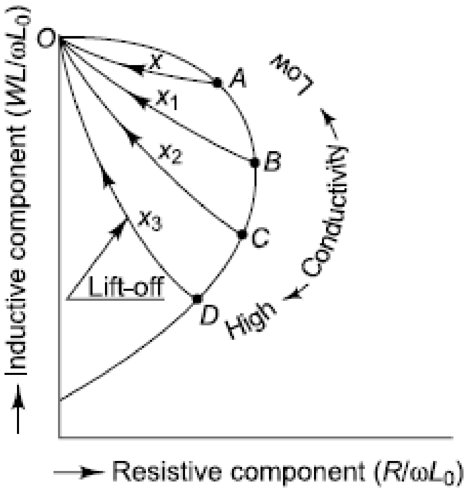

Figure 6.9. Effect of Lift-off on the Impedance of the Coil

In the figure, *O* represents the impedance of the coil when it is in the air, a good distance away from the test specimen. As the coil approaches the test object with conductivity *A*, the impedance locus is *OAX*. Similarly, for materials of conductivity *B, C, D*, etc. the loci are OX_1B, OX_2C, OX_3D, etc. for various values of lift-off. When the coil touches the part, the point of intersection with the impedance locus of the variable under consideration (conductivity in the present case), namely points *A, B, C, D*, etc. gives the impedance of the test coil-test piece combination.

6.1.4.2. Effect of Fill-factor

The impedance diagram is plotted in a similar manner for different values of fill-factor (η) as Fig. 6.10 illustrates.

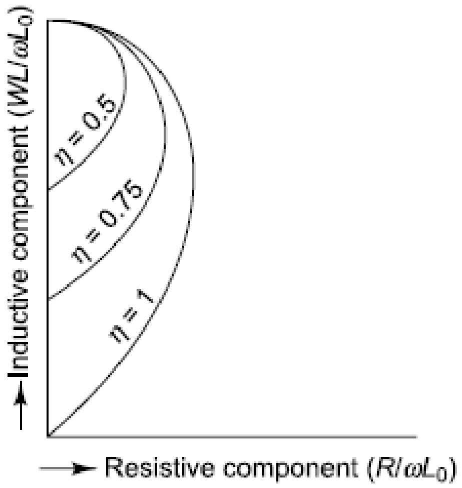

Figure 6.10. Impedance Diagram for Different Values of Fill-factor

6.1.5. Effect of Magnetic Permeability on Impedance Diagram

The current in a test coil induces magnetic flux in a conductive material present near it. The distribution of magnetic induction is uneven along the cross-section of the material. This uneven distribution of magnetic induction leads to an uneven distribution of the eddy current, resulting in the charge of impedance of the test coil. If no conducting material is present near the coil, the flux density is given by:

$$B_0 = \mu_0 H_0$$

where

H_0 is the field due to the coil

μ_0 is the permeability of free space

B_0 is the flux density

If a conducting material is present, the flux density in the material changes to B_1 (say) and is no longer constant over the cross-section due to non-uniformity of eddy current density within the material. The changed flux density B_1 is given by:

$B_1 = \mu_{eff}.\ B_0$, where μ_{eff} is the changed permeability due to presence of the conducting material.

Figure 6.11 shows the effect of changes in permeability on the impedance diagram.

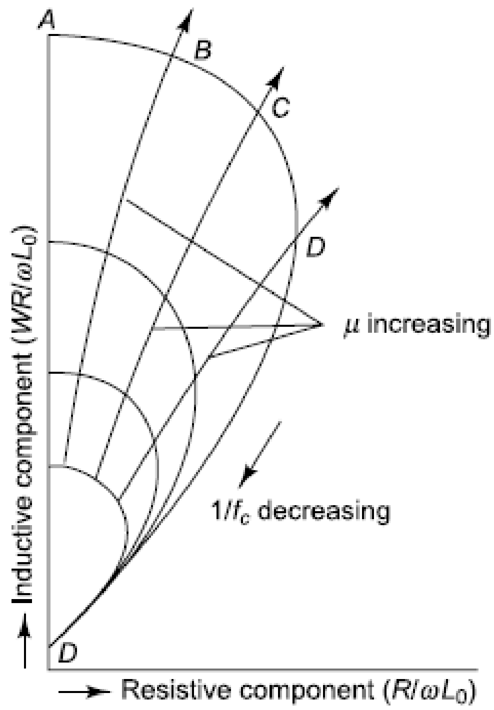

Figure 6.11. Effect of Permeability on Impedance Diagram

The test frequencies are expressed as ratio f/f_c = 1, 2, 3, 4….

The curve *ABCD* represents various f/f_c values, *f* being the frequency of the existing current.

6.1.6. Effect of Crack on the Impedance Diagram

The effect of crack depth from the test surface on the impedance diagram is shown in Fig. 6.12.

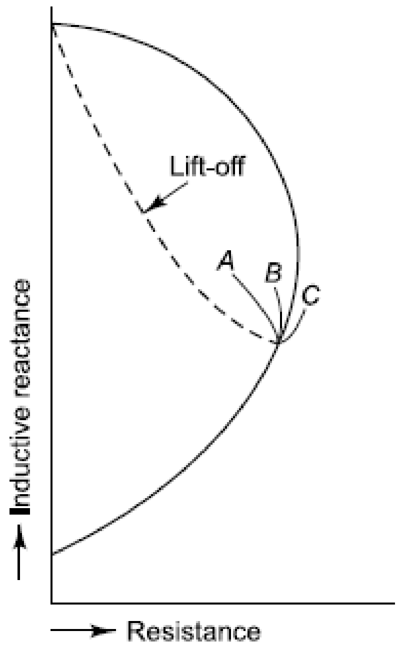

Figure 6.12. Effect of Crack Depth from the Surface on the Impedance Diagram

With increasing depth of crack from the test surface, the impedance loci are *A, B, C*: *A* being a crack near the surface and *C* being a crack at greater depth.

Note that a change in impedance includes a change in magnitude as well as phase.

From the viewpoint of the test, it is necessary to keep all the eddy current variables constant, except the one of interest, and study the change in magnitude as well as phase.

Phase studies help to separate the eddy current responses of specific variables like permeability, cracks, thickness, conductivity or magnetic coupling from others.

6.2. EDDY CURRENT TEST SYSTEM

Any eddy current test system consists of:

- An oscillator to provide the alternating current for exciting the test coil
- A combination of a test coil and a test object to generate information in the form of an electrical signal. Varying the property of the test object modulates the impedance magnitude of the coil
- Signal processing and display

Figure 6.13 gives the block diagram of an eddy current test system.

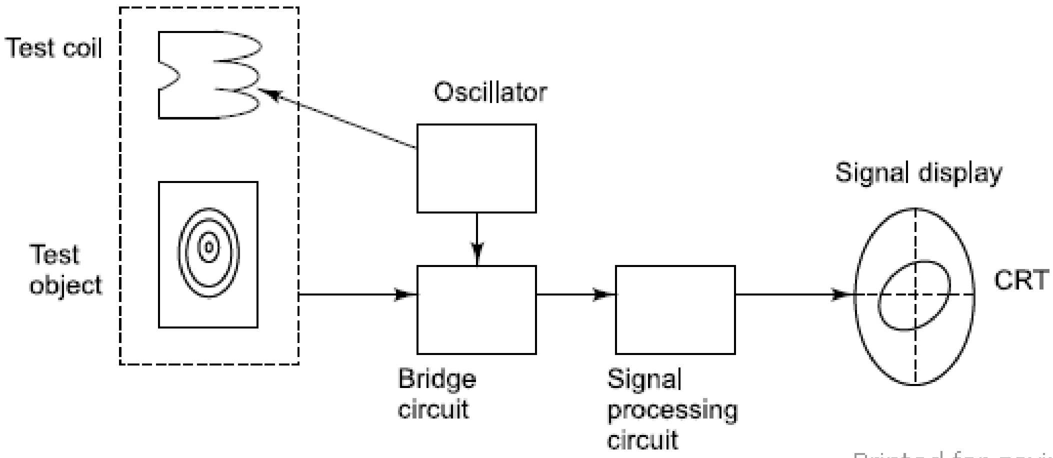

Figure 6.13. Block Diagram of Eddy Current Test System

The oscillator provides an alternating current of the required frequency to the test coil, which generates an eddy current in the test object. Test object variables like conductivity, permeability or discontinuities modulate the test coil impedance. The modulated impedance signal is processed and displayed over a readout mechanism like meters, CRT, relays, recorders, etc.

There are four basic types of eddy current instruments that carry out the following measurements:

- Measurement of the change in magnitude of the total impedance of the test coil, regardless of phase
- Phase-sensitive measurement, which separates the resistive and reactive components of the test coil impedance
- Measurement of the resistive component of the test coil impedance
- Measurement of the inductive component of the test coil impedance
- Measurement of the total impedance of the test coil, regardless of phase

6.2.1. Sensing Element and Test Arrangements

The sensing element (also called the test coil) serves as the main link between the test instrument and the test object. It establishes a varying electromagnetic field, which induces the eddy current in the test object and increases the magnetic effect in magnetic materials. It also senses the current flow and magnetic effect within the test object and feeds the information to the signal analysis system.

The test coils are essentially of three types as discussed next.

6.2.1.1. Encircling Coil

The test coil is in the form of a solenoid into which the test part is placed as shown in Fig. 6.14.

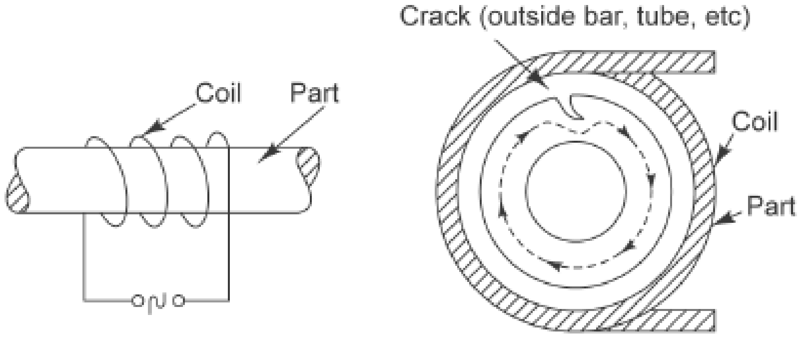

Figure 6.14. Encircling Coil

Test objects in the form of rods and tubes are examined conveniently. The entire exterior circumferential surface of the test object covered by the coil is scanned. This arrangement also helps high-speed testing. However, it is not possible to exactly locate the defect on the circumference.

6.2.1.2. Coil Inside the Test Object

Here the test coil is in the form of a winding over a bobbin. The coil, thus wound, passes through test objects like tubes, bolt holes, etc. and scans the inner circumferential surface of the test object as illustrated in Fig. 6.15.

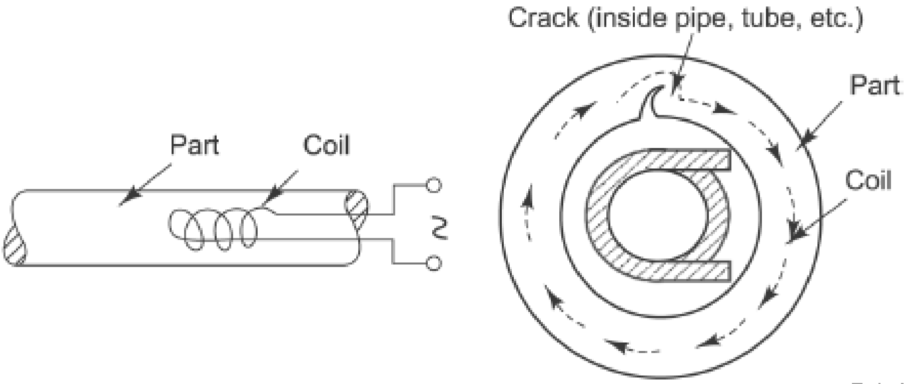

Figure 6.15. Coil Inside the Test Object

This arrangement evaluates the entire internal circumferential surface at a time, which is not accessible to any other optical method of inspection. However, it is not possible to exactly locate the defect over the circumference examined.

6.2.1.3. Surface Coil

Here, the test coil is in the form of a spring-mounted flat probe or a pointed pencil-type probe, which scans the surface of the selected location of the test object. The arrangement is shown in Fig. 6.16.

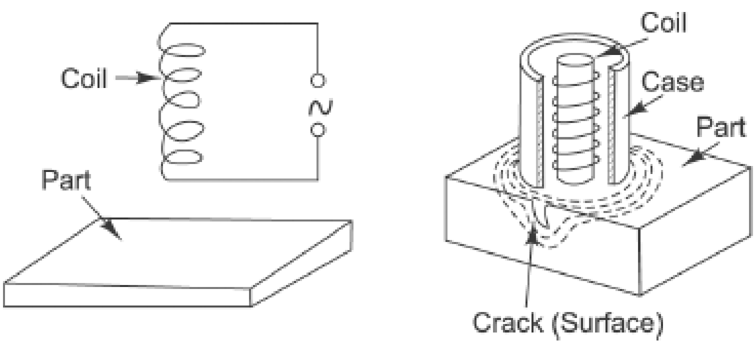

Figure 6.16. Surface Coil

The advantage of this arrangement is that it is possible to pin-point the defect.

In eddy current testing, the coils are incorporated in a bridge circuit, which can be balanced on any acceptable specimen characteristics. Whenever an impedance change occurs due to the test object parameters of interest, there is an imbalance, which can be seen on a convenient display system. Figure 6.17 shows a simple bridge circuit.

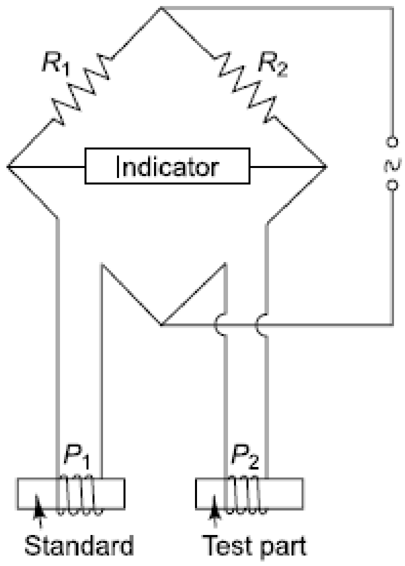

Figure 6.17. Simple Eddy Current Detector

Such testing units are used for material comparison and crack detection.

In more elaborate circuit units, both magnitude and phase of the test coil-impedance change are measured. Phase analysis is based on studying the phase difference between two signals. The current across a resistance is in phase with the applied voltage, whereas the current across an inductor lags behind the voltage. If the coil is empty, the lag is 90°.

If a specimen is passed through the coil, the lag is less than 90°. If the specimen's properties like conductivity, dimension, permeability, etc. change, the phase lag changes accordingly.

If we study the conductivity variation of a number of samples with varying conductivity but same dimensions and permeability, it is seen that measured values of impedance vary with changing conductivity, as shown in Fig. 6.18(a).

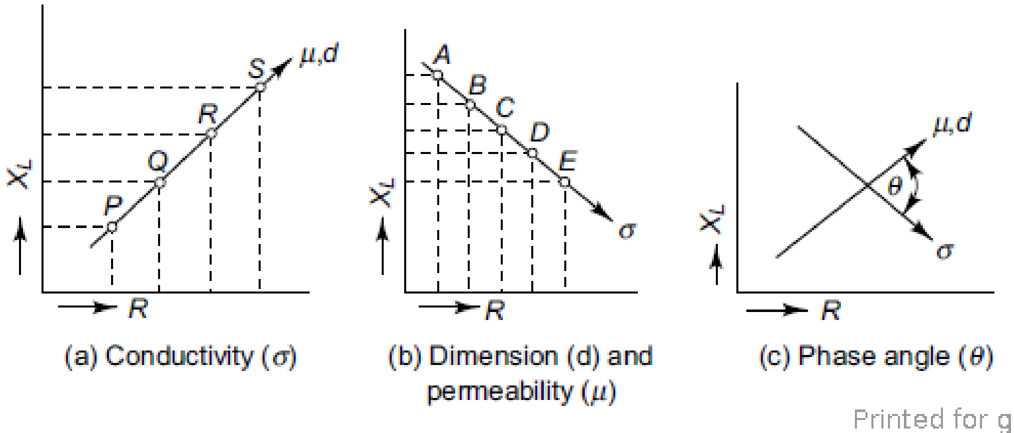

Figure 6.18. Variation in Impedance due to Change in Conductivity, Dimensions or Permeability

Similarly, if conductivity is the same and only dimensions or permeability of the specimen vary, the variation in impedance is as shown in Fig. 6.18(b).

If vectors representing conductivity, dimensions and permeability are superimposed as shown in Fig. 6.18(c), it is clearly seen that the conductivity vector is moving in a direction perpendicular to the vectors of dimensions and permeability. The angle between the two vectors θ is known as the phase angle. Note that the vectors are in two different quadrants.

The vector point displayed on an *X—Y* storage oscilloscope represents the magnitude and phase of the impedance change. If E_1 and E_2 are two voltages, the resultant voltage E_r (by vector addition) is indicated as a point. The position of the point on a CRT depends on the electrical and magnetic variable components E_1 (resistive component of voltage) and E_2 (inductive component of voltage). The movement of the spot during the lift-off of the probe from the surface identifies the permeability axis, whereas the deflection due to defect and conductivity changes, takes place along an axis perpendicular to the permeability axis as shown in Fig. 6.19.

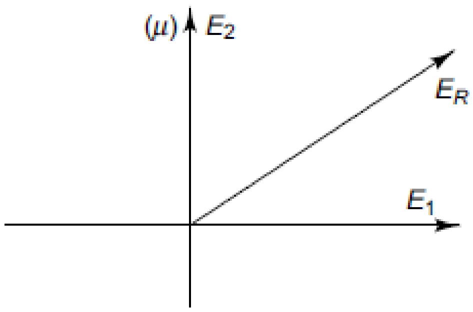

Figure 6.19. CRT Display of Eddy Current Detection

The basic block diagram of a typical vector point method is shown in Fig. 6.20. The oscillator supplies an exciting current to both primary P_1 and P_2. The oppositely wound secondary is connected to a single processor unit, where both resistive and reactive components of voltage are controlled to move the vector point across the CRT screen. In this way the impedance diagram can be produced on a CRT screen.

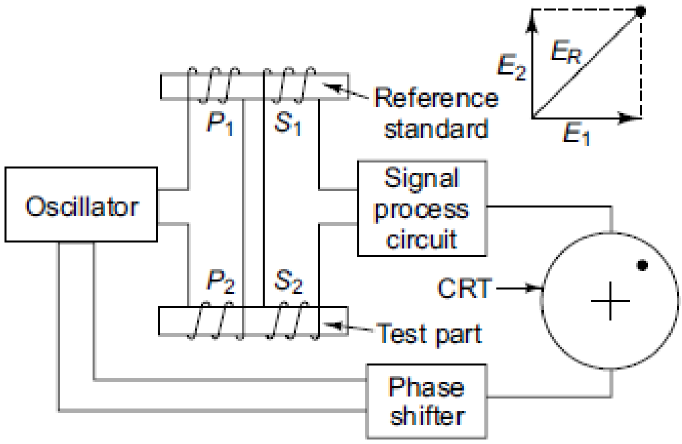

Figure 6.20. Basic Arrangement for Vector Point Method

The processed signal output is driven through a phase shifter. By adjusting the phase shifter, the reference voltage can be changed as desired.

Initially, the adjustment is done with a test part similar to the reference standard. This test object is replaced by a part whose parameter is to be checked; by adjusting the phase shifter, the variables of interest alone can be studied. The test system is also provided with magnetic saturation devices. When the magnetic variable is separated by suitable saturation, the dimensional variation can be studied.

Another example of the use of this method is the ellipse method. Here, the voltage from the primary coil P_1 P_2 is fed to the X-plate of the CRT and the voltage across the secondary S_1S_2 is fed to the Y-plate. Since the two voltages of the same frequency are alternating, the figure on the CRT screen is an ellipse. The shape of the ellipse depends on the phase difference between the voltages. The size and shape of the ellipse can be related to a displacement on the impedance diagram and correlated to a variation in conductivity, dimension or to the presence of defects.

Typical ellipse patterns are shown in Fig. 6.21.

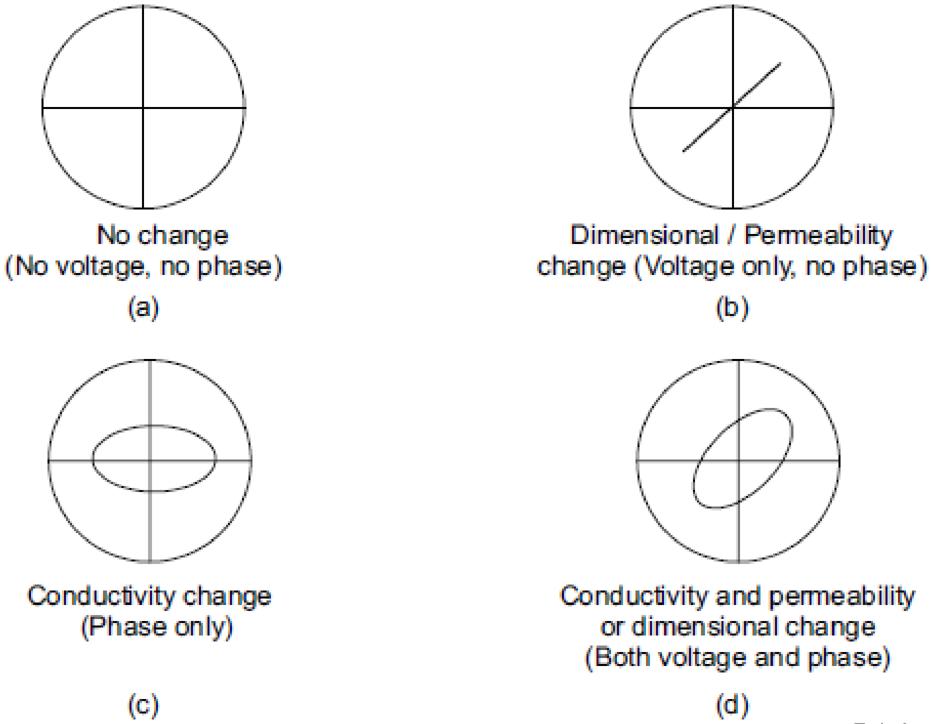

Figure 6.21. Typical Ellipse Patterns

6.2.2. Standardization and Calibration

Eddy current test methods are applied on 'Go/No Go' basis by calibrating the test system against a pre-fabricated standard with known magnitudes of variation of the parameters desired to be measured. The standard test specimen is identical to the test component except in the parameter being measured. Artificially fabricated standards may contain notches, slots, holes, etc.

Reference standards are used to standardize the test system under operating conditions to ensure sensitivity, reproducibility of results and for periodic evaluation of the system.

6.2.2.1. Acceptance Standards

Acceptance standards are used to establish an acceptable level in a test component under standardized conditions. For practical applications, reference standards are employed to establish quality control checks for uniformity of response, which can be related to the minimum size of the crack/defect to be detected.

The following standards, with various types of artificial discontinuities, are widely used in industry.

Defect Measurement: Tubes

Longitudinal notches are made either by milling or by electro discharge machining (EDM) on the outer and inner surfaces of a tube having the same material composition as the tubes under examination. The depth of the notch is specified as a percentage of wall thickness–10%, 12.5%, 20%, etc. The notch width is variable and can be specified. The length of the notch is 6 mm, 12.5 mm, 25 mm, etc. A typical specimen is shown in Fig. 6.22.

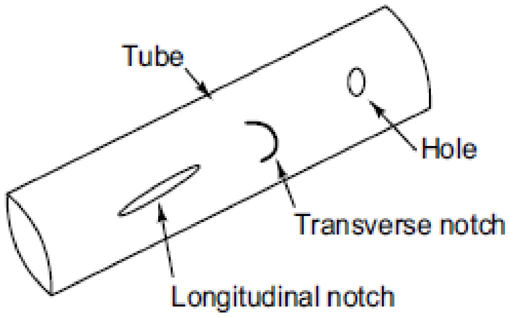

Figure 6.22. Typical Notch Standard

Transverse notch A milled or EDM transverse notch is located at the outer or inner surface or on both surfaces. The notch depth is specified as a percentage of the wall thickness of the tube, the width is variable and is preferably kept below 1.5 mm.

Holes Holes are drilled radially through the tube thickness. The diameter of the hole is specified as a percentage of wall thickness or arbitrary sizes may be selected, based on the end use of the test component and its acceptance criteria. Normally, holes of diameters ranging between 20—50% of tube wall thickness are used.

Flat Components

Calibration standard material should have almost the same composition as that of the test component. Milled or EDM slots of depth 0.2 mm, 0.5 mm and 1.0 mm are provided on the standard specimen. The slot width is uniformly maintained at 0.10 mm. A typical flat test standard is shown in Fig. 6.23.

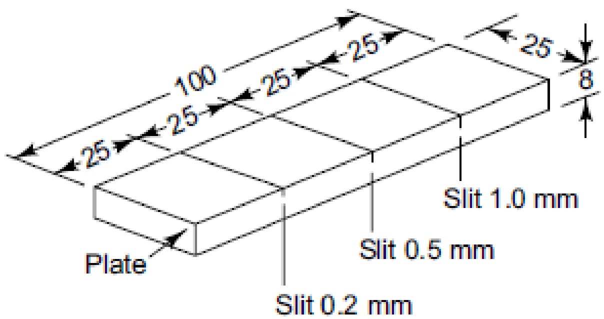

Figure 6.23. Defect Standard for Flat Test Objects

Standards selected for eddy current testing should satisfy: Low cost of fabrication, ease of fabrication, convenience of fieldwork and reproducibility of results.

6.2.3. Test Coil Selection

The selection of a test coil is influenced by the following factors:

- The nature and shape of the specimens to be tested
- The type of information, sensitivity and resolution required
- The volume of tests required

Since the depth of eddy current penetration is a function of frequency, conductivity and permeability, the frequency becomes an important parameter for selecting the test coil for specimens of known conductivity and permeability. High frequency probes are used for the detection of surface and just-below-the-surface defects. Low frequency probes are used to detect corrosion or cracks located deep down in the material. Figure 6.24 gives a general guideline for frequency selection.

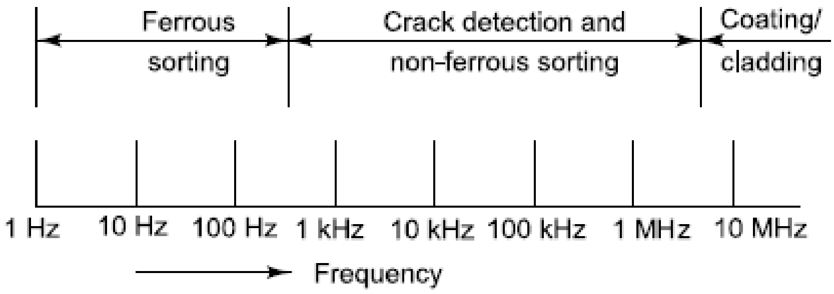

Figure 6.24. Guideline for Selection of Frequency

6.3. APPLICATIONS OF EDDY CURRENT TESTING

Eddy current test methods are put to a variety of applications. Broadly, eddy current applications can be grouped into–conductivity measurement (shorting, hardness, heat treatment, alloy segregation, case depth assessment, etc.), discontinuity testing (cracks, dimensional changes, surface condition, etc.) and thickness measurement (coating, plating, sheet metal gauging).

The electrical conductivity of a material is expressed as a percentage IACS (International Annealed Copper Standard), in which a specific grade of high purity annealed copper is arbitrarily assigned 100% conductivity. All other metals can be identified according to this standard. Many factors like temperature, composition, heat treatment, microstructure, grain size and mechanical properties influence the conductivity of a material. Hence, studying the variation in conductivity helps in indirectly assessing these properties and controlling variables such as composition, heat treatment, metal working, etc. To measure the conductivity of a magnetic material, it is subjected to a strong magnetic field, to its saturation value so that the magnetic characteristics of permeability, hysterisis, etc. do not interfere with conductivity measurement.

In-homogeneities like cracks, inclusions, voids, scamp, laps, etc. appreciably change the normal circular eddy current flow pattern and can be detected by the eddy current test coil.

Further, phase changes are unique for several eddy current inspection parameters. By determining the phase change of an eddy current response, it is possible to isolate the response of specific variables such as conductivity, lift-off, thickness, permeability and cracks.

In so far as coating thickness measurement is concerned, the eddy current system measures the variation in impedance it causes. The basic requirement for this thickness measurement is that the electrical conductivity of the coating should differ significantly from that of the substrate. The accuracy and range of metal thickness that can be measured with the eddy current system depends on the electromagnetic properties of the material and the capability of the test system. Increasing the conductivity and permeability increases the accuracy of measuring a thin specimen but decreases the effective range of measurement and accuracy at greater depths. The main purpose of using an eddy current to measure the total thickness of a metal part is to detect corrosion, erosion, wear out, etc.

6.4. EFFECTIVENESS OF EDDY CURRENT TESTING

Eddy current testing is normally used for the study of surface and sub-surface anomalies in conducting materials. The method is complementary to ultrasonic testing for detecting defects close to the surface. It is also complementary to the liquid penetrant inspection, which cannot reveal sub-surface defects. The method, however, cannot be used on non-conducting materials. Also, local variations in conductivity and permeability of an acceptable nature may interfere with accurate detection of discontinuities. The measurement of metal coating thickness is also difficult unless a substantial difference in conductivity exists between the coating and the substrate under normal operating conditions. It is possible to detect defects of sizes as indicated in Table 6.1. The detectability of defects is, however, influenced considerably by the surface condition, material properties, test equipment capability, the frequency used and the test environment.

Table 6.1. Approximate sizes of detectable defects

Defects	Detectable Size of Defects (mm)	
Surface and sub-surface anomalies	Laboratory condition	0.25
	Production/Processing	1.0
	Service condition	1.0 (fatigue cracks)

At high frequencies (2 MHz or more) and in good conductors, surface cracks of length 15—20 microns can be detected. It is possible to improve limits of detection significantly with improved facilities and techniques.

Citation

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