Module 6

Eddy Current Testing (ECT)

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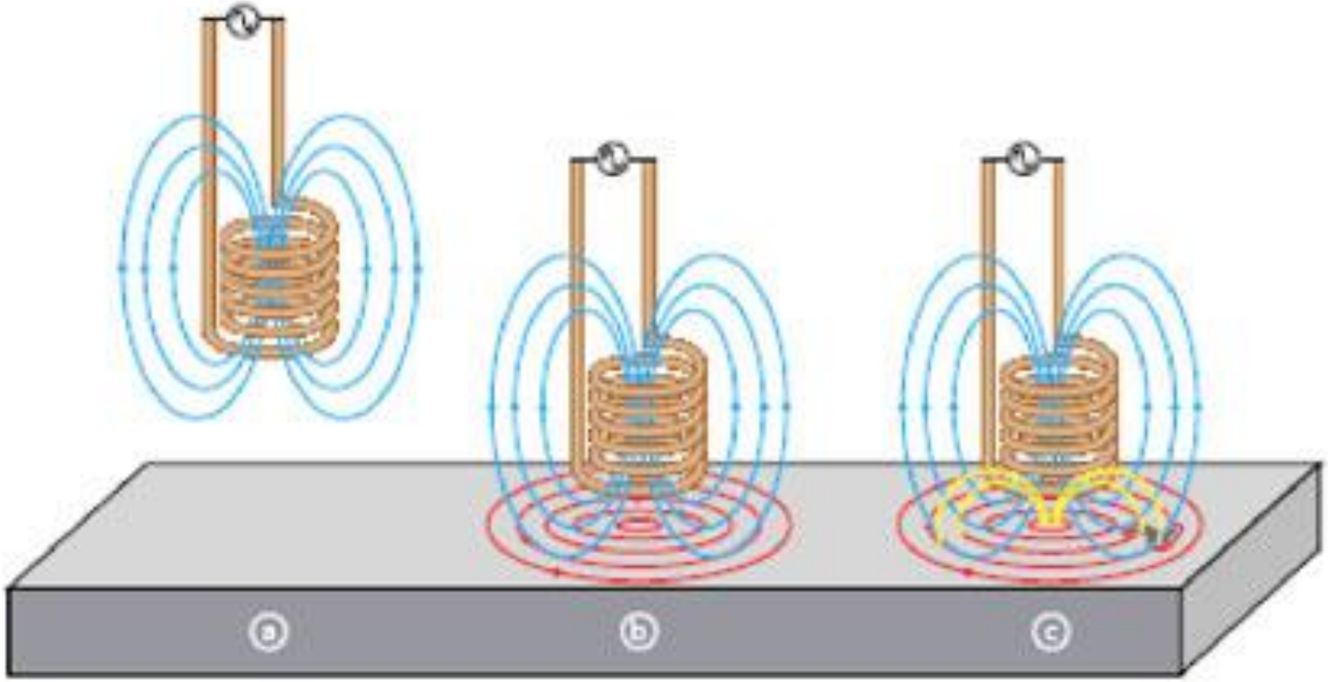
Eddy Current Testing
History and development

- Discovery of law of electromagnetic induction by Faraday in 1832.
- Faraday's law: "when a magnetic field cuts a conductor or when a conductor cuts a magnetic field, an electric current will flow through the conductor if a closed path is provided over which the current can circulate".
- Christian Oersted's discovery: "A magnetic field exists around a coil carrying current proportional to the number of turns in the coil and the current".
- Eddy currents are defined as oscillating electrical currents induced in a conductive material by an alternating magnetic field, due to electromagnetic induction.
- ECT is used for sorting materials, measurement and control of dimensions of tubes, sheets and rods and for pre-service and in-service examination of heat exchanger tubes

Principle

- In ECT an AC (1 kHz – 2 MHz) is made to flow in a coil (probe) which in turn produces a magnetic field around it.
- This coil when brought close to the electrically conducting surface of a metallic material to be inspected, induces an eddy current flow due to electromagnetic induction.
- The presence of any defect in the material disturbs the eddy current flow.
- This generates an alternating magnetic field (in opposite direction) which may be detected as a voltage across a second coil or by the deviation of impedance of original coil.



a—The alternating current flowing through the coil at a chosen frequency generates a magnetic field around the coil.

b—When the coil is placed close to an electrically conductive material, eddy current is induced in the material.

c—If a flaw in the conductive material disturbs the eddy current circulation, the magnetic coupling with the probe is changed and a defect signal can be read by measuring the coil impedance variation.

Physics aspects of ECT

- ***<u>Conductivity</u>***
- Conductivity is defined as the ability of a material to conduct electric current.
- It is denoted by σ. The unit of conductivity is mho per meter.
- The conductivity of a conductor decreases with the increase in the temperature.
- Each element has a unique value of conductivity.
- Copper, silver and gold have high conductivities where as, carbon has a very low conductivity.
- An eddy current is a flow of electrons. The amount of electron flow through an electrically conductive material is directly related to the conductivity of the material.
- If the conductivity increases, the flow of eddy current increases.

- ***Resistivity***
- Resistivity is reciprocal of the conductivity.
- Therefore the materials that have high resistivity have poor conductivity and vice versa.
- The resistivity is denoted by ρ and is defined as the 'ratio of electrical intensity (emf) to the current per unit cross-section area.'
- Mathematically it can be written as $\rho = E / I / A$ *or* $\rho = EA / I$
- ρ = resistivity, E = emf, A = area
- The unit of resistivity is Ohm-meter.
- Resistivity of a material changes with the change in temperature.

- ***Magnetic Permeability***
- Magnetic permeability is an intrinsic property of a material.
- It is the ability of a material to concentrate magnetic lines.
- It is denoted by the Greek letter μ.
- Any material that is easily magnetized, such as soft iron, concentrate the magnetic flux.
- This is the main feature separating magnetic materials from nonmagnetic materials.
- The magnetic permeability is equal to the induced magnetic flux density B divided by external magnetic field intensity (magnetizing force) H.
- $\mu = B/H$,
- Where μ = magnetic permeability, B = flux density (tesla), H = magnetizing force (amperes/metre)

- For air, vacuum, and non-magnetic materials the μ is constant.
- The numerical values of μ for different materials are assigned in comparison with air or vacuum.
- This is called the relative permeability and is defined as $\mu_r = \mu / \mu_0$
- Where μ_r = relative permeability, μ = permeability, μ_0 = permeability in vacuum

- ***Inductance***
- Inductance is the property of a conductor by which a change in current flowing through it induces a voltage (electromotive force) in both the conductor itself (self-inductance) and in any nearby conductors (mutual inductance).
- It is customary to use the symbol *L* for inductance.
- In the SI system the measurement unit for inductance is the henry (H).
- **Inductive Reactance** (X_L), is the property in an AC circuit which opposes the change in the current.

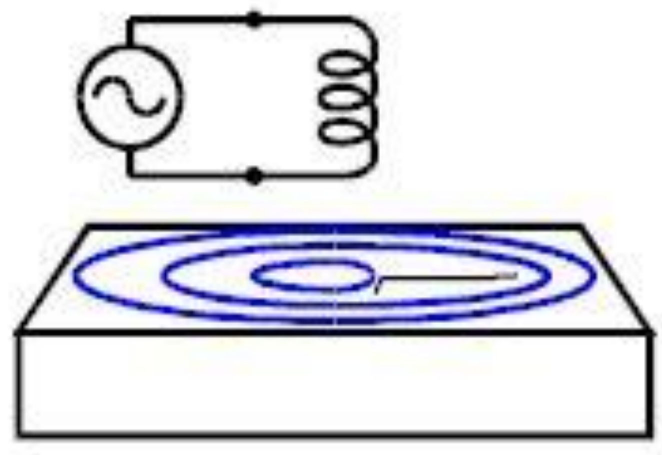
- ***<u>Impedance</u>***
- Electrical **impedance** is the measure of the opposition that a circuit presents to a current when a voltage is applied.
- In quantitative terms, it is the complex ratio of the voltage to the current in an alternating current (AC) circuit.

Basic Eddy Current Testing

- **<u>Simple Coil above a metal surface</u>**
- When an AC current flows in a coil in close proximity to a conducting surface the magnetic field of the coil will induce circulating (eddy) currents in that surface.
- The magnitude and phase of the eddy currents will affect the loading on the coil and thus its impedance.

•As an example, assume that there is a deep crack in the surface immediately underneath the coil.

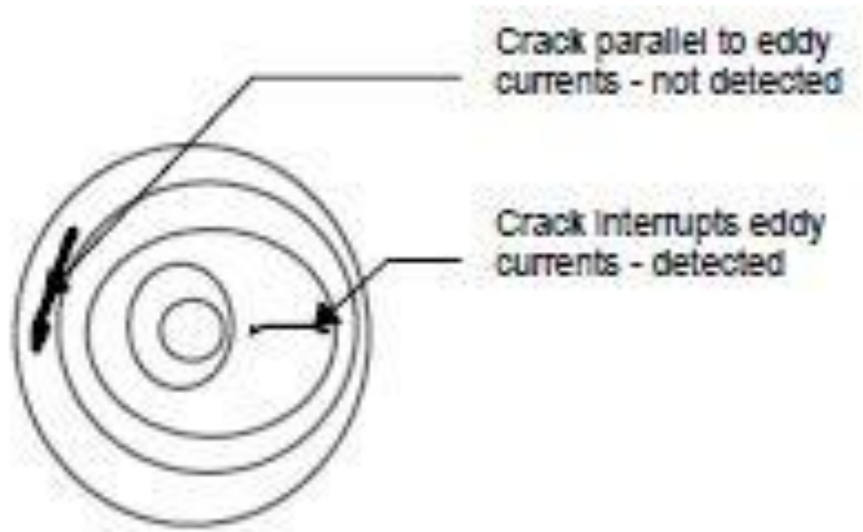
•This will interrupt or reduce the eddy current flow, thus decreasing the loading on the coil and increasing its effective impedance.



•This is the basis of eddy current testing, by monitoring the voltage across the coil in such an arrangement we can detect changes in the material of interest.

•Note that cracks must interrupt the surface eddy current flow to be detected.

•Cracks lying parallel to the current path will not cause any significant interruption and may not be detected.



Factors affecting eddy current response

- Test parameters
  - (i) Frequency
  - (ii) Type and geometry of test coil
  - (iii) Lift off or Fill factor
- Test object
  - (i) Electrical conductivity
  - (ii) Magnetic permeability
  - (iii) Dimension
  - (iv) Temperature

- **Effect of test frequency**
- The importance of test frequency is that it determines the depth of penetration.
- The eddy current density decreases exponentially from the material surface.
- The rate of decrease depends on test frequency, electrical conductivity and magnetic permeability of test material.
- Although higher frequencies are suitable for achieving higher inspection speeds and better sensitivity to defects,
- they mainly increase the noise due to lift-off or fill factor to such an extent that masking the signals due to defects.
- Lower frequencies yield reduced noise, but at the cost of sensitivity.
- Hence enough care should be taken while selecting test frequency.

- <u>Depth of penetration and frequency</u>
- Depth of penetration is a critical factor.
- In the case of tube inspection, if the eddy currents do not penetrate the wall thickness of the tube, the defects may be missed.
- Depth of penetration (in mm), $\delta = 500/ (\sigma\mu f)^{1/2}$
- σ = conductivity, μ = relative permeability, f = inspection frequency.
- The standard depth of penetration is generally taken to be that depth at which the eddy current field intensity 37% of the intensity at the surface of the conductor.
- Higher the frequency, lower the depth of penetration.
- Thus a frequency must be chosen which permits penetration to the depth up to which defects are to be found.

- Higher the permeability, lower is the depth of penetration.
- As relative permeabilities of ferromagnetic materials are less, eddy currents in these materials are concentrated at the surface.
- Hence subsurface defects are not detectable.

- **Effect of lift-off**
- For probe over a metallic plate being inspected, the distance between the probe and the plate is called lift-off (in case of inside coils for inspecting tubes, it is termed as fill factor).
- The lift-off causes impedance change that occurs when there is variation in the distance between the inspection coil probe and the test piece
- As lift off increases, the eddy current density in the material, in turn, the impedance change in the probe decreases.
- For better sensitivity, lift-off should be as minimum as possible.
- In many applications, eddy current measurements are adversely affected by lift-off.
- Lift-off is considered a noise source and it is undesirable in defect detection.
- Therefore, the distance between the probe and metal must be as constant as possible in order to avoid lift-off effect.
- Lift-off is a function of coil diameter, bigger the diameter of the probe, smaller the lift-off.

- **<u>Effect of conductivity</u>**
- The material in which eddy currents can be induced should be of conductive in nature.
- The conductivity of a material has a very direct effect on the eddy current flow: the greater the conductivity of a material the greater the flow of eddy currents on the surface.
- Different factors affecting conductivity are material composition, heat treatment, temperature, work hardening etc.

- **<u>Effect of Magnetic permeability</u>**
- This may be described as the ease with which a material can be magnetized.
- In a material with a high permeability a larger density of magnetic lines will be created for a given source and the lines will tend to concentrate in the material.
- This has two effects; firstly a large amount of magnetic energy can be stored in the material which increase inductance,
- Secondly plenty of eddy currents are generated which increases the lift-off.
- The tendency of lines of force to concentrate in the material causes very little penetration.

- **<u>Effect of geometry</u>**
- In a real part, for example one which is not flat or of infinite size, Geometrical features such as curvature, edges, grooves etc. will exist and will effect the eddy current response.
- A curved piece of metal will have a different lift-off response compared to a flat one, and the edge effect can distort the eddy current field and produces a signal lag.
- Where the material thickness is less than the effective depth of penetration this will also effect the eddy current response.

Edge Effect

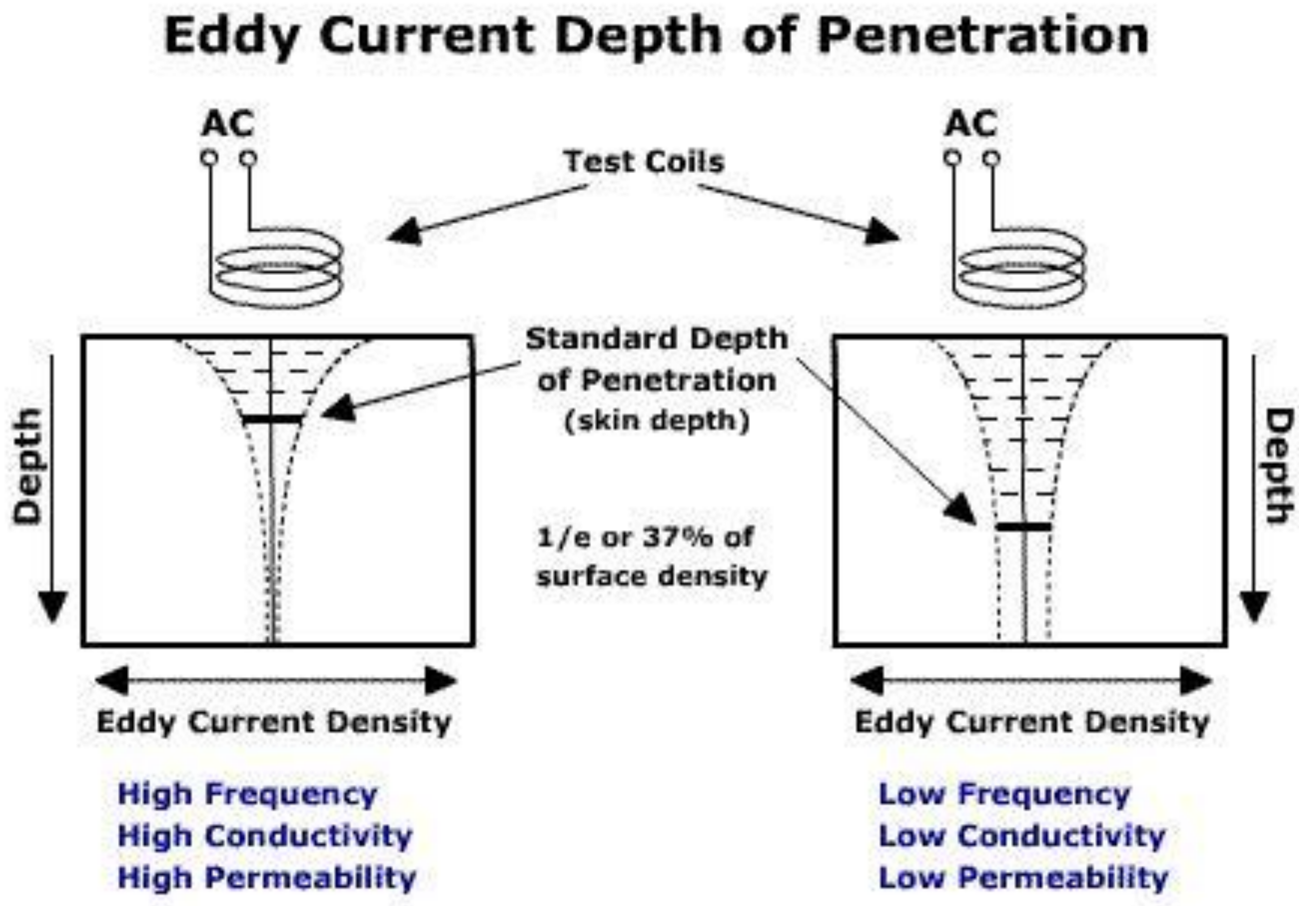
- Edge effect is a phenomenon that occurs when an inspection coil is at the end of the test piece.
- In these instances, eddy current flow is distorted as currents cannot flow at the edge.
- So, in order to avoid the confusion with flaws, inspection is limited near edges.
- The distance where the edge effect is present is from approximately one to three times the diameter of the inspection coil in the case of encircling probes.
- So a reduction in coil size reduces the edge effect, although there is a limit, as the diameter of external encircling coils must be higher than that of the inspected materials.

Depth of Penetration & Current Density

- Eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux.
- They normally travel parallel to the coil's winding and flow is limited to the area of the inducing magnetic field.
- Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil.
- Eddy current density decreases exponentially with depth. This phenomenon is known as the ***skin effect***.

- The skin effect arises when the eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing the net magnetic flux and causing a decrease in current flow as the depth increases.
- Alternatively, eddy currents near the surface can be viewed as shielding the coil's magnetic field, thereby weakening the magnetic field at greater depths and reducing induced currents.

- The depth that eddy currents penetrate into a material is affected by the frequency of the excitation current and the electrical conductivity and magnetic permeability of the specimen.
- The depth of penetration decreases with increasing frequency and increasing conductivity and magnetic permeability.
- The depth at which eddy current density has decreased to 1/e, or about 37% of the surface density, is called the standard depth of penetration (d).
- The word 'standard' denotes plane wave electromagnetic field excitation within the test sample (conditions which are rarely achieved in practice).
- Although eddy currents penetrate deeper than one standard depth of penetration, they decrease rapidly with depth.
- At two standard depths of penetration (2d), eddy current density has decreased to 1/e squared or 13.5% of the surface density.
- At three depths (3d), the eddy current density is down to only 5% of the surface density.


Eddy Current Depth of Penetration
AC
Test Coils
AC
Standard Depth
of Penetration
(skin depth)
Depth
Depth
1/e or 37% of
surface density
Eddy Current Density
Eddy Current Density
High Frequency
High Conductivity
High Permeability
Low Frequency
Low Conductivity
Low Permeability

- Since the sensitivity of an eddy current inspection depends on the eddy current density at the defect location, it is important to know the strength of the eddy currents at this location.
- When attempting to locate flaws, a frequency is often selected which places the expected flaw depth within one standard depth of penetration.
- This helps to assure that the strength of the eddy currents will be sufficient to produce a flaw indication.
- Alternately, when using eddy currents to measure the electrical conductivity of a material, the frequency is often set so that it produces three standard depths of penetration within the material.
- This helps to assure that the eddy currents will be so weak at the back side of the material that changes in the material thickness will not affect the eddy current measurements.

Relation between depth of penetration and frequency

- The depth of penetration of eddy currents in a material is a critical factor.
- For example, in tube inspection, if eddy currents do not penetrate the wall thickness of the tube, then it is possible to miss the defects.
- The depth of penetration of eddy currents can be found by the relation
- d = $\frac{500}{\sqrt{\sigma \mu f}}$
- Where d = standard depth of penetration (mm), σ = conductivity, μ = relative permeability, f = inspection frequency

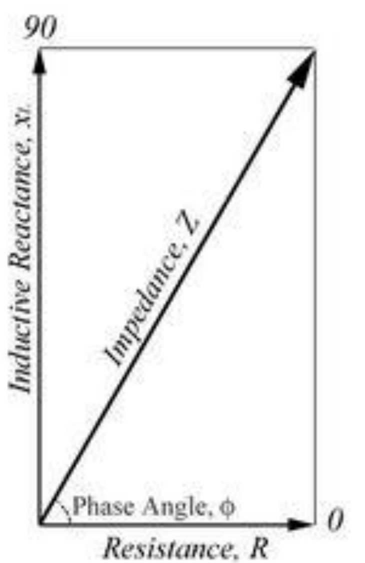
- Higher the frequency, lower the depth of penetration.
- Thus a frequency must be chosen which permits penetration to the depth up to which defects are to be found.
- For general tube inspection, the frequency used is often the frequency at which the standard depth of penetration is equal to the wall thickness of the tube.
- This is given by, $$f = \frac{250}{\sigma r^2}$$
- Where r = wall thickness of tube in mm.

Impedance Plane Diagram

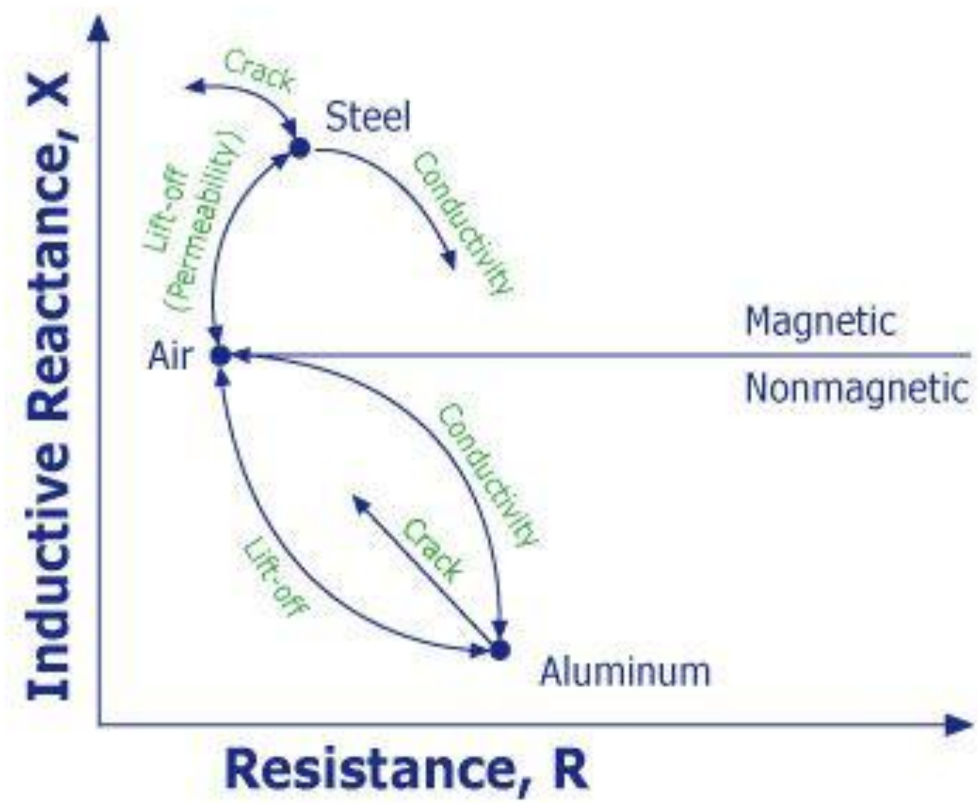
- Electrical **Impedance (Z)**, is the total opposition that a circuit presents to an alternating current.
- Impedance, measured in ohms, may include resistance (R), inductive reactance (X_L), and capacitive reactance (X_C).
- Eddy current circuits usually have only R and (X_L) components.
- The resistance component and the reactance component are not in phase, so vector addition must be used to relate them with impedance.
- For an eddy current circuit with resistance and inductive reactance components, the total impedance is calculated using the following equation.

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

- This can be graphically displayed using the impedance plane diagram as shown.



- The impedance plane diagram is a very useful way of displaying eddy current data.
- As shown in the fig., the strength of the eddy currents and the magnetic permeability of the test material cause the eddy current signal on the impedance plane to react in a variety of different ways.



- If the eddy current circuit is balanced in air and then placed on a piece of aluminum, the resistance component will increase (eddy currents are being generated in the aluminum and this takes energy away from the coil, which shows up as resistance) and the inductive reactance of the coil decreases (the magnetic field created by the eddy currents opposes the coil's magnetic field and the net effect is a weaker magnetic field to produce inductance).
- If a crack is present in the material, fewer eddy currents will be able to form and the resistance will go back down and the inductive reactance will go back up. Changes in conductivity will cause the eddy current signal to change in a different way.

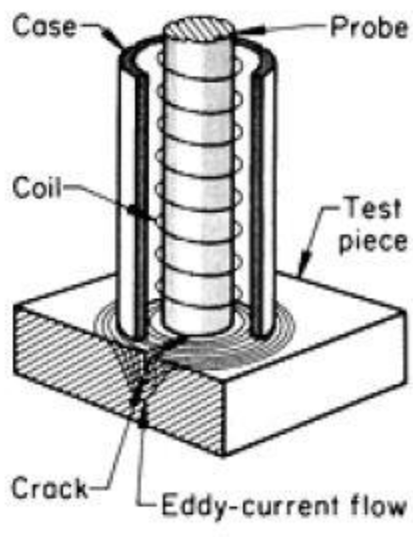
- When a probe is placed on a magnetic material such as steel, something different happens.
- Just like with aluminum (conductive but not magnetic), eddy currents form, taking energy away from the coil, which shows up as an increase in the coils resistance.
- And, just like with the aluminum, the eddy currents generate their own magnetic field that opposes the coils magnetic field.
- However, you will note for the diagram that the reactance increases.
- This is because the magnetic permeability of the steel concentrates the coil's magnetic field.
- This increase in the magnetic field strength completely overshadows the magnetic field of the eddy currents.
- The presence of a crack or a change in the conductivity will produce a change in the eddy current signal similar to that seen with aluminum.

Inspection Coils

- The inspection coil is an essential part of every eddy current inspection system.
- The shape of the inspection coil depends to a considerable extent on the purpose of the inspection and on the shape of the part being inspected.
- When inspecting for flaws, such as cracks or seams, it is essential that the flow of the eddy currents be as nearly perpendicular to the flaws as possible to obtain a maximum response from the flaws.
- If the eddy current flow is parallel to flaws, there will be little or no distortion of the currents and therefore very little reaction on the inspection coil.

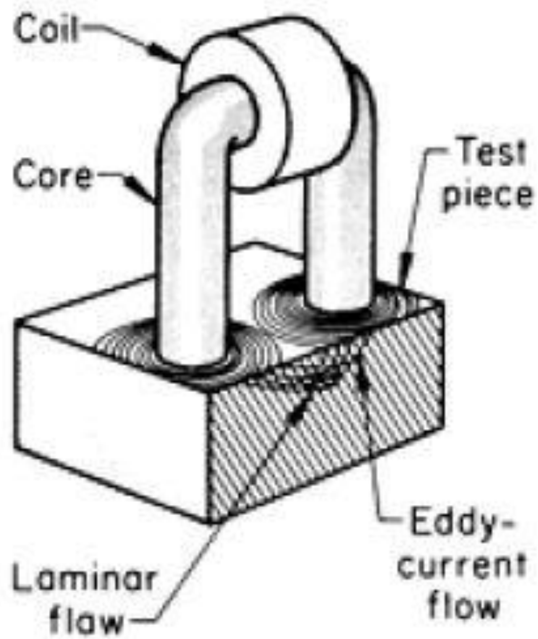
Probe and Encircling Coils.

- Of the almost infinite variety of coils employed in eddy current inspection, probe coils and encircling coils are the most commonly used.
- Normally, in the inspection of a flat surface for cracks at an angle to the surface, a probe-type coil would be used because this type of coil induces currents that flow parallel to the surface and therefore across a crack, as shown in Fig.



(a) Probe-type coil

- On the other hand, a probe-type coil would not be suitable for detecting a laminar type of flaw.
- For such a discontinuity, a U-shaped or horseshoe-shaped coil, such as the one shown in Fig. would be satisfactory.



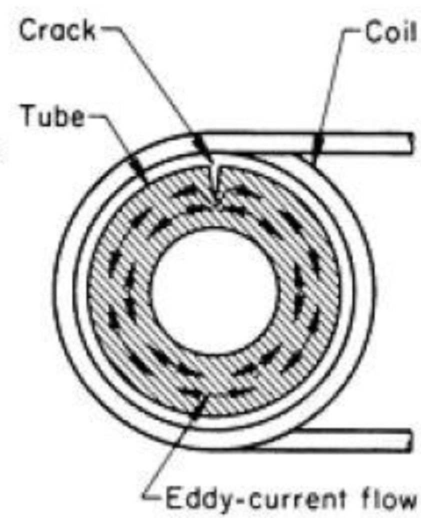
(b) Horseshoe-shape or U-shape coil

• To inspect tubing or bar, an encircling coil (See Fig) is generally used because of complementary configuration and because of the testing speeds that can be obtained with this type of coil.

•However, an encircling coil is sensitive only to discontinuities that are parallel to the axis of the tube or bar.

•The coil is satisfactory for this particular application because as a result of the manufacturing process, most discontinuities in tubing and bar are parallel to the major axis.

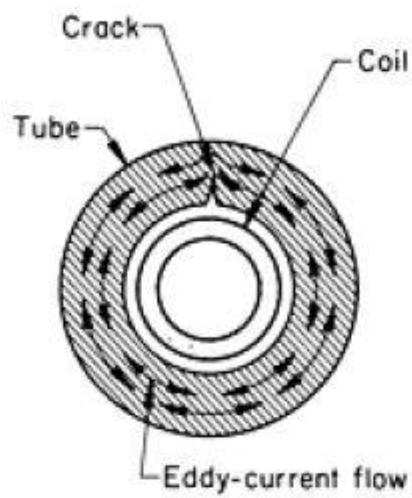
•If it is necessary to locate discontinuities that are not parallel to the axis, a probe coil must be used, and either the coil or the part must be rotated during scanning.



(c) Encircling coil

To detect discontinuities on the inside surface of a tube or when testing installed tubing an internal or bobbin-type coil (Fig.) can be used.

The bobbin-type coil, like the encircling coil, is sensitive to discontinuities that are parallel to the axis of the tube or bar.



(d) Internal or bobbin-type coil

Multiple Coils

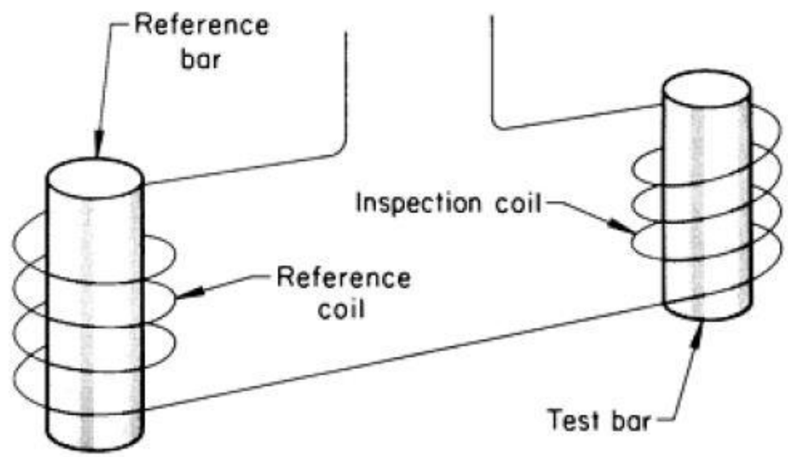
- In many setups for eddy current inspection, two coils are used. The two coils are normally connected to
- separate legs of an alternating current bridge in a series-opposing arrangement so that when their impedances are the same, there is no output from the pair.
- Pairs of coils can be used in either an absolute or a differential arrangement

***Absolute Coil Arrangements*.**

In the absolute arrangement (Fig.), a sample of acceptable material is placed in one coil, and the other coil is used for inspection.

Thus, the coils are comparing an unknown against a standard, with the differences between the two (if any) being indicated by a suitable instrument.

Arrangements of this type are commonly employed in sorting applications.



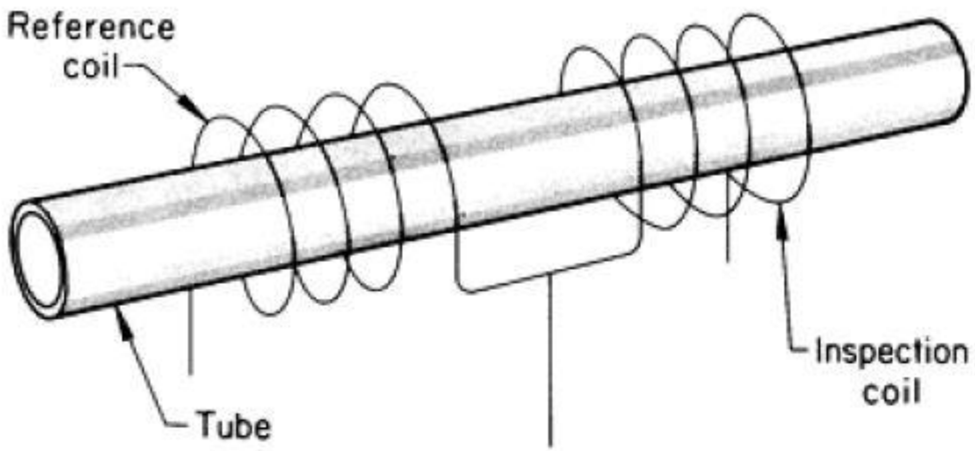
(a) Absolute coil arrangement

Differential Coil Arrangement.

In many applications, an absolute coil arrangement is undesirable. For example, in tubing inspection, an absolute arrangement will indicate dimensional variations in both outside diameter and wall thickness even though such variations may be well within allowable limits.

To avoid this problem, a differential coil arrangement such as that shown in Fig. can be used.

Here, the two coils compare one section of the tube with an adjacent section. When the two sections are the same, there is no output from the pair of coils and therefore no indication on the eddy current instrument.



(b) Differential coil arrangement

Advantages of ECT

- Sensitive to surface and subsurface defects.
- Portability of test equipments.
- Can be easily automated.
- Can inspect complex shape and size
- Little part preparation required
- Can detect through several layers
- Provides immediate results of inspection
- Contact between probe and test specimen is required

Disadvantages

- Susceptible to magnetic permeability changes
- Can inspect conductive materials only
- Insensitive to defects parallel to the surface
- Limited depth of penetration
- Distance between probe and test specimen is to be maintained.
- No permanent record.

Applications of ECT

- **<u>Surface crack detection</u>**
- Normally carried out with pencil probes on ferrous or non-ferrous metals.
- Frequencies from 100 kHz to a few MHz are commonly used.
- Depending on surface condition it is usually possible to find cracks as small as 0.1 mm or so deep.
- Care must be taken to ensure that the orientation of flaws is correct for detection.

- **<u>Non-ferrous metal sorting</u>**
- This is essentially conductivity testing and for dedicated applications a conductivity meter may be a better choice.
- From the impedance plane diagram it will be seen that the indication from a conductivity change is essentially the same as from a crack, and both meter and impedance plane type crack detectors can be successfully used to sort similar metals using a suitable absolute probe.
- It should beremembered that widely different metals may have similar conductivity and that the allowable values for similar alloys my overlap, so conductivity measurement should only be used as an indication that a metal is of correct composition or heat-treatment.

- **<u>Sub-surface crack/corrosion detection</u>**
- Primarily used in Airframe inspection.
- By using a low frequency and a suitable probe eddy currents can penetrate aluminium or similar structures to a depth of 10mm or so, allowing the detection of second and third layer cracking, which is invisible from the surface, or thinning of any of then different layers making up the structure.

- **Ferrous weld inspection**
- The geometry and heat-induced material variations around welds in steel would normally prevent inspection with a conventional eddy current probe, however a special purpose “WeldScan” probe has been developed which allows inspection of welded steel structures for fatigue-induced cracking, the technique is particularly useful as it may be used in adverse conditions, or even underwater, and will operate through paint and other corrosion-prevention coatings.
- Cracks around 1mm deep and 6mm long can be found in typical welds.

- **In-Line inspection of Steel tubing**
- Almost all high-quality steel tubing is eddy current inspected using encircling coils .
- When the tube is made of a magnetic material there are two main problems:
  - Because of the high permeability there is little or no penetration of the eddy current field into the tube at practical test frequencies.
  - Variations in permeability (from many causes) cause eddy current responses which are orders of magnitude greater than those from defects.
- These problems may be overcome by magnetically saturating the tube using a strong DC field. This reduces the effective permeability to a low value, allowing effective testing.

Thank you