Chapter 4

Eddy Current

4.1 Physics

- Current in a coil, produces magnetic field, $\vec{H}$ along axis.
- $\vec{H}$ creates a magnetic flux, ϕ_p.
- If coil is placed near a metallic (conducting but not necessarily ferromagnetic) specimen, and coil movement is allowed, ϕ_m, flux inside metal, changes with time.
- Faraday's law of induction: ϕ_m creates a secondary *circular* current within specimen. This is the *Eddy Current.*
- This eddy current creates a secondary flux, ϕ_s, around coil.
- Net flux in coil $= \phi_e = \phi_p - \phi_s$, minus sign due to fact that two fields oppose each other.
- If coil is far away from specimen: $\phi_e = \phi_p$, no change.
- If sample is not ferromagnetic: $\phi_s < \phi_p$ and the net flux drops in value.
- If sample is ferromagnetic: $\phi_s >> \phi_p$ and net flux increases in value.
- If secondary coil is used, the voltage across this coil is:

$$V_s = -N_s \frac{d\phi_s}{dt} \tag{4.1}$$

where N_s is the number of coils is the secondary coil.

- AC current is used to enable ϕ_p to change with time:

$$I_p = N_p I_0 \sin \omega t \tag{4.2}$$

where I_p is the primary current, N_p is the number of coils in the primary coil, I_0 is the magnitude of the AC current and $\omega = 2\pi f$, where f is the AC frequency (50 Hz to 50 kHz).

- The eddy current density, J, in the specimen is governed by the diffusion equation:

$$\nabla^2 = \sigma\mu \frac{\partial J}{\partial t} \tag{4.3}$$

where σ is the metal's conductivity and μ is its magnetic permeability.

- In a semi-infinite medium:

$$J(x) = J_0 \exp[\omega t - x/d] \tag{4.4}$$

where x is the distance in the medium measured from the surface J_0 is the current density at the surface and d is the skin depth, i.e. depth at which J drops to $1/e = 0.368$:

$$d = \sqrt{\pi f \mu \sigma} \tag{4.5}$$

$$d(\mathrm{m}) = \sqrt{\pi f(\mathrm{Hz})\mu_0(\mathrm{Henry/m})\mu_0\sigma(\mathrm{Siemens/m})} \tag{4.6}$$

$$d(\mathrm{mm}) = 50\sqrt{\frac{\rho(\mu\mathrm{ohm\text{-}cm})}{f(\mathrm{Hz})\mu_r}} \tag{4.7}$$

$$d(\mathrm{inches}) = 1980\sqrt{\frac{\rho(\mathrm{ohm\text{-}cm})}{f(\mathrm{Hz})\mu}} \tag{4.8}$$

where f is the excitation frequency, σ is conductivity, ρ is resistivity and μ_r is taken as unity for diamagnetic and paramagnetic materials and for ferromagnetic materials an average over the local B-H curve scanned by the exciting coil is used.

- The phase lag of J is given by:

$$\beta = \frac{x}{\pi d} \text{ in radian } = 57.3\frac{x}{d} \text{ in degrees} \tag{4.9}$$

β is proportional to the thickness.

- Above equation indicates that the eddy current decays exponentially in medium and its phase shift also changes with distance.

- J being dependant of σ and μ, discontinuities directly affect J, and the corresponding secondary field is generated in coil.

4.2 General

Source: Primary current, producing primary flux.

Modification: change in eddy current density and distribution by discontinuities and inclusions.

Sensors: Same primary coil, secondary coil, or flux detector (Hall transistors can provide very localized sensing or array of sensing elements).

Indication: ϕ_s, $\phi_p - \phi_s$, impedance (resistance of AC flow) of exciting coil changes, meter deflection or digital readout, oscilloscope presentation, strip chart recording, alarm or operational control actuation.

Interpretation: may be difficult.

4.2.1 Affecting Parameters

- Frequency of primary current.
- Conductivity, σ and change in σ, of inspected part.
- Magnetic permeability of inspected part, μ and change in μ.
- Radius of the excitation (primary) coil.
- Radius of sensing coil.
- Number of turns in coils.
- Proximity of excitation coil to part.
- Proximity of sensing coil to part.
- Part dimensions.
- Proximity to edge or physical changes in part.

Above parameters need to be optimized to obtain best response. Other affecting parameters include: grain size, surface treatment, coating thickness, hardness, cracks, inclusions, dents, holes, and composition.

4.2.2 Advantages

Rapid, can give information on many parameters, can be automated, no specimen contact, can give permanent record.

4.2.3 Limitations

Manual inspection is very slow, needs an electrically conducting material, requires complex electronics, sensitive to many parameters, small depth of penetration (6 to 12 mm), interpretation may be difficult.

4.3 Coils

4.3.1 Absolute Coils

- A single coil is usually used both as an excitor and as a sensor.
- The impedance of the coil is directly monitored.
- Called absolute since measurement is not compared to anything else.
- Simplest arrangement is to measure the impedance change in coil in an impedance bridge.
- A large variety of configurations is available to accommodate different applications: pancake or flat oil, encircling coil, robbin coil.

4.3.2 Differential coils

- Two coils that oppose each other are used.
- Typically the sensing coil is smaller, placed closer to specimen and oriented differently from the primary coil.
- A single measurement of the combined two windings is usually monitored.
- Produces better sensitivity since independent parts of the specimen are compared, with a signal produced only when the part of the specimen near one coil is different from that near the other.
- Some configurations: encircling coil, centre tipped, end-on or flat coil, bobbin coil.
- Localized pits and small cracks are well-defined by differential coils.
- Not very sensitive to gradual changes in specimen and are suited for thickness measurements.

4.3.3 Combined Coils

- Excitor (primary coil) and sensor (secondary coil) are separated.
- Both the primary and the secondary coil may be wound as differential coils.
- A variety of arrangements are possible.

4.3.4 Frequency

Primary coil frequency affects:

- Depth of penetration (decreases with frequency).
- Skin effect limits the depth of penetration.
- Skin depth is usually used to indicate the "standard depth".
- Very high frequency is used to measure the distance between the specimen and the probe.
- Multiple simultaneous frequencies are used to minimize the effect of unwanted interference, such as effect of support structures, elimination of effect of holes and pitting in thickness measurements.

4.4 Special Effects

4.4.1 Edge Effect

- Distortions of magnetic field at the end or edge of specimen.
- Occurs when inspection at less than 3 mm from the edge of a nonmagnetic material or 150 mm of the edge of a magnetic material. Overcome by:
  - Using a small coil.
  - Enclosing coil in a magnetic shield (e.g. mu metal).

4.4.2 Fill Factor

Gap between a circular and an encircling coil affects field:

$$\text{Fill Factor} = \frac{\text{Diameter of Specimen}}{\text{Inside Diameter of Coil}} \tag{4.10}$$

Fill factor should approach one for best sensitivity.

4.4.3 Lift Off

- Gap between probe and surface of specimen affect sensitivity.
- Field of coil is strongest close to the coil.
- Attempt to maintain a constant and minimum gap (spring loading is often used).
- This "lift-off" effect is used to measure the thickness of a nonconductive coating on a conductive material, or a nonmagnetic metal plating on a magnetic substrate.

4.5 Analysis and Indication

4.5.1 Inductance

A coil has an inductance L and resistance R:

$$R = \frac{\rho \ell}{A} \tag{4.11}$$

$$L(\text{Henry}) = \frac{N\phi(\text{Weber})}{I(\text{amp})} = \text{Constant} \propto \frac{N^2 A}{\ell} \tag{4.12}$$

where ρ is the resistivity (ohm-m), N is the number of turns in coil, ϕ is magnetic flux, I is current in coil, A is the planar surface area of coil, ℓ is the length of coil and the Constant depend on the geometry of the coil.

$$X_L = 2\pi f = \omega L \tag{4.13}$$

X_L is called the reactance and has units of ohm.

4.5.2 Impedance

Resistance to AC current, with $j = \sqrt{-1}$:

$$Z = R + jX_L \tag{4.14}$$

$$|Z| = \sqrt{R^2 + X_L^2} \tag{4.15}$$

$$\text{Phase Angle} = \frac{X_L}{R} \tag{4.16}$$

- Impedance Diagram: graphics display of R, X_L and Z.

- R and X_L can be measured by the inspection coil circle and fed to the x-plates and y-plates of an oscilloscope to display points on the impedance diagram.
- In air (absence of specimen), Z_0, is represented by a point on the oscilloscope's display.
- In the presence of a conducting material, the eddy current changes the impedance from Z_0 to say Z_1.
- Indication: line connecting Z_1 to Z_0, with length indicating magnitude of change and orientation indicating phase angle of change.
- Change in magnetic flux, ϕ, affects L, X_L and consequently Z, $|Z|$ and Phase shift.
- Phase change may be caused by changes in conductivity, permeability or dimensions of specimen.
- If conductivity changes produces a phase lag, then permeability and dimension changes will produce a phase lead.
- Electronics can make phase change due to one variable be at a certain angle, say 90 degrees from the other.

4.5.3 Voltage and Current

- A current, I flowing through a coil produces voltages:

$$V_R = RI \tag{4.17}$$

$$V_L = X_L I \tag{4.18}$$

$$V_T = V_R + jX_L \tag{4.19}$$

$$V_T = I_0 \left[\sin(\omega t + 0) + j\omega L \sin(\omega t + \frac{\pi}{2})\right] \tag{4.20}$$

- Phasor Diagram: graphic display of voltage phasors (V_R, V_L and V_T). Measurement of V_R and V_T or V_L facilitate therefore the measurement of R, Z_R and $|Z|$ and phase angle.

4.5.4 Testing Methods

Impedance Method

- Amplitude of impedance is measured with no information on phase change.
- Balanced Bridge method is set up so that no signal through meter is produced when coil is placed against a specimen (or part of specimen) in good condition.
- Dislocations, bridge unbalanced results in a voltage difference across meter.

Phasor Testing

- Z_0 is air is measured and point seen on oscilloscope.
- Z_1 is measured and corresponding point is noted.
- Change from Z_0 to Z_1 is calibrated using specimen of know behaviour, to know effect of a surface crack, surface scratch, sub-surface discontinuity, etc.

Differential Testing

- Two inspection coils are linked electrically in opposition, resulting in a signal only when one of the coils crosses a discontinuity.
- Reference point on oscilloscope will then correspond to Z_0.
- As one coil approaches a discontinuity, point will move in one direction, as the second probe come closer to discontinuity point will change direction.
- When two probes are exactly at same distance (but at opposite direction) from the discontinuity, the point on the oscilloscope returns to the reference point at Z_0, due to the cancellation effect.
- As probes traverses the dislocation in the other direction, another loop is creates on the display, with the impedance point return to the Z_0 location when the two probes are far away from the dislocation.
- The above movement creates a loop (figure of eight) know as Lissajous figure.

- Other variations of this technique are available.

Elliptical Testing

- A phase shifter is used to create an ellipse, corresponding to a reference point.
- Phase change in coil alters shape of ellipse, via a processing unit.
- Changes in dimension results in changes in tilt angle.
- Changes in conductivity create change in opening of ellipse.
- Other oscilloscope references are also used.

4.6 Remote-Field Testing

- In above applications, both source and sensor were in the same proximity, this is called close-field inspection.
- When excitor and separator are far way from each other.
- Eddy current then reaches sensor by diffusion with medium.
- Technique used is limited to a tubular products.

4.6.1 Schmidt Experiment

- Low-frequency (30 - 120 Hz) excitor coil placed inside tube.
- Sensing coil is placed inside or outside tube.
- As sensing coil moves away from excitor, the sensor moves from the direct coupling zone (DCZ), to the remote field zone (RFZ), with the separation at about 1.9 pipe diameters from excitor col.
- In DCZ, inner-sensor amplitude, voltage, drops off rapidly, until it reaches RFZ and the degree of drop weakens.
- Outer-sensor amplitude is about 10 times higher than that of inner sensor and is less affected by transition to from DCZ to RFZ.
- Phase difference between excitor and inner-sensor shows a large jump when passing through the transition zone.

- Isolation by conducting material between excitor and sensor coils does not produce a significant change in above behaviour, must be a tube-wall effect.
- Current in excitor produces a circumferential eddy current in tube, pipe wall being in effect a shorted single turn.
- Eddy current diffuses through wall and eventually re-diffuses back.
- At the transition zone, the dip is caused by the interaction of the two signals that have about the same amplitude but different phases.
- Phase lag is found to be linearly proportional to wall thickness (36 degrees per mm or 0.92 degrees per 0.001 inch of wall).

4.7 Work Problems

1. The skin depth is expressed in these notes in three different systems of units. Using each of then, calculate the standard depth for a non-ferromagnetic stainless steel of resistivity 72 μohm-cm at 150 kHz and calculate the phase lag at 2 m depth.
2. Consider stainless steel tubing of wall thickness of 4 mm; resistivity of 1.5×10^6 Siemens/m, $\mu = 1.3 \times 10^{-6}$ Henry/m.
3. Design a differential pickup probe system for finding:
   (a) Thinning in ferromagnetic tubes.
   (b) Localized wall loss over a 500 mm^2 area.
4. Explain briefly how eddy current is used for:
   (a) Examination of steam generator tubes in the presence of support plates.
   (b) Measurement of electrical conductivity.
   (c) Metal sorting (according to material type).
   (d) Thickness of coatings. How do you differentiate between a coating and a discontinuity?
   (e) Surface conditions (corrosion, heat damping and hardness).

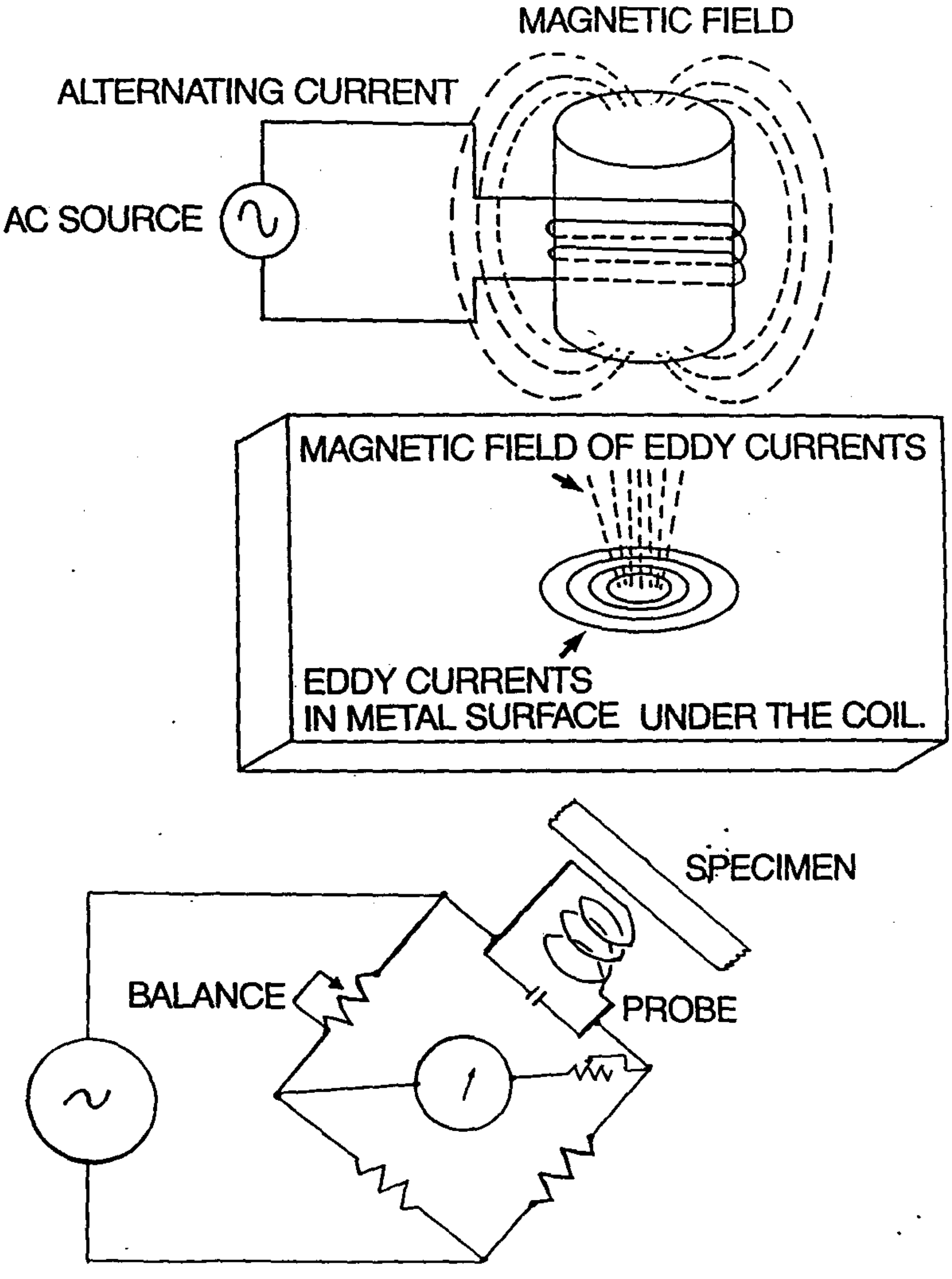


Figure 4.1: Eddy Current

4.8 Graphs

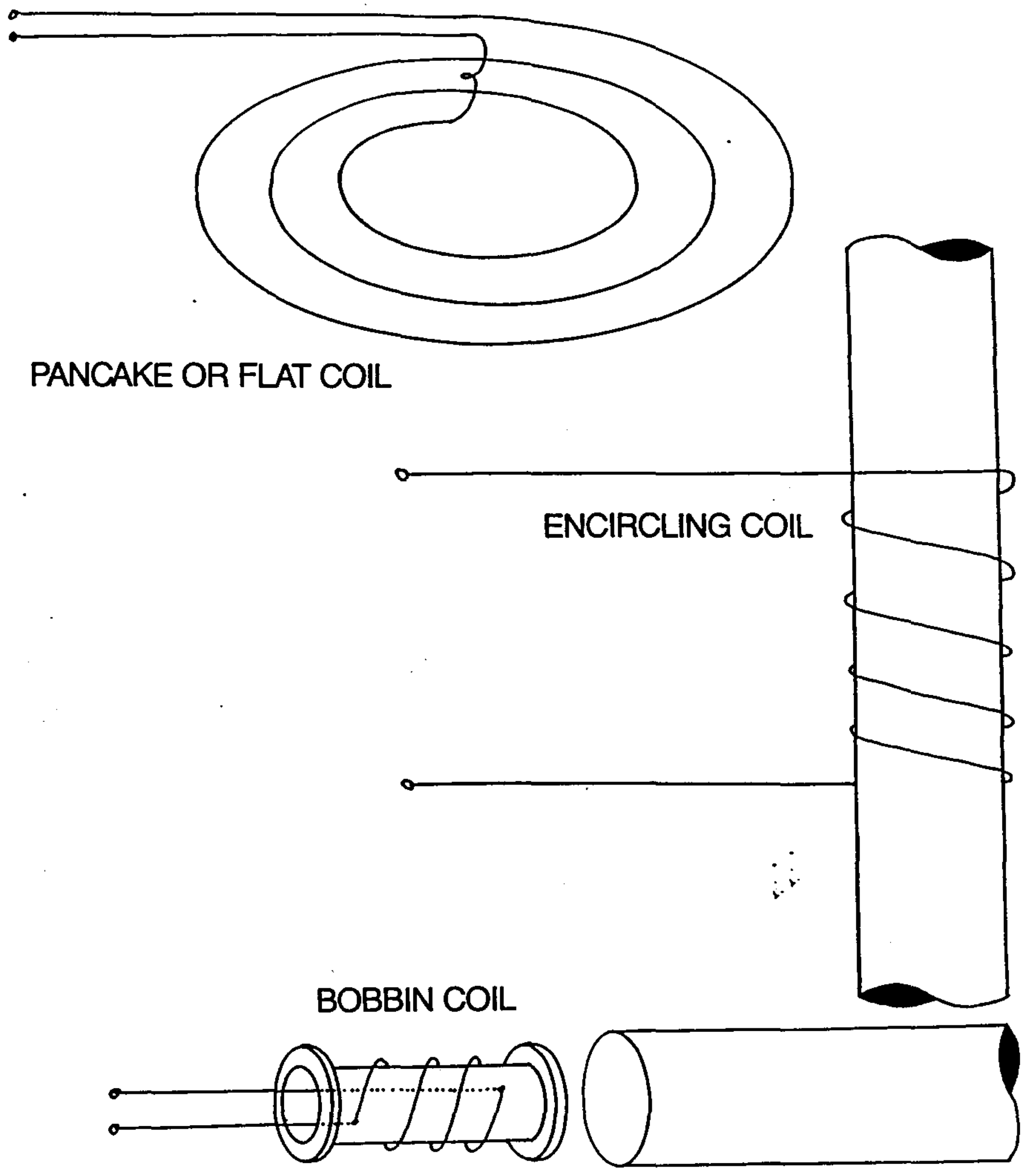


Figure 4.2: Single Coils

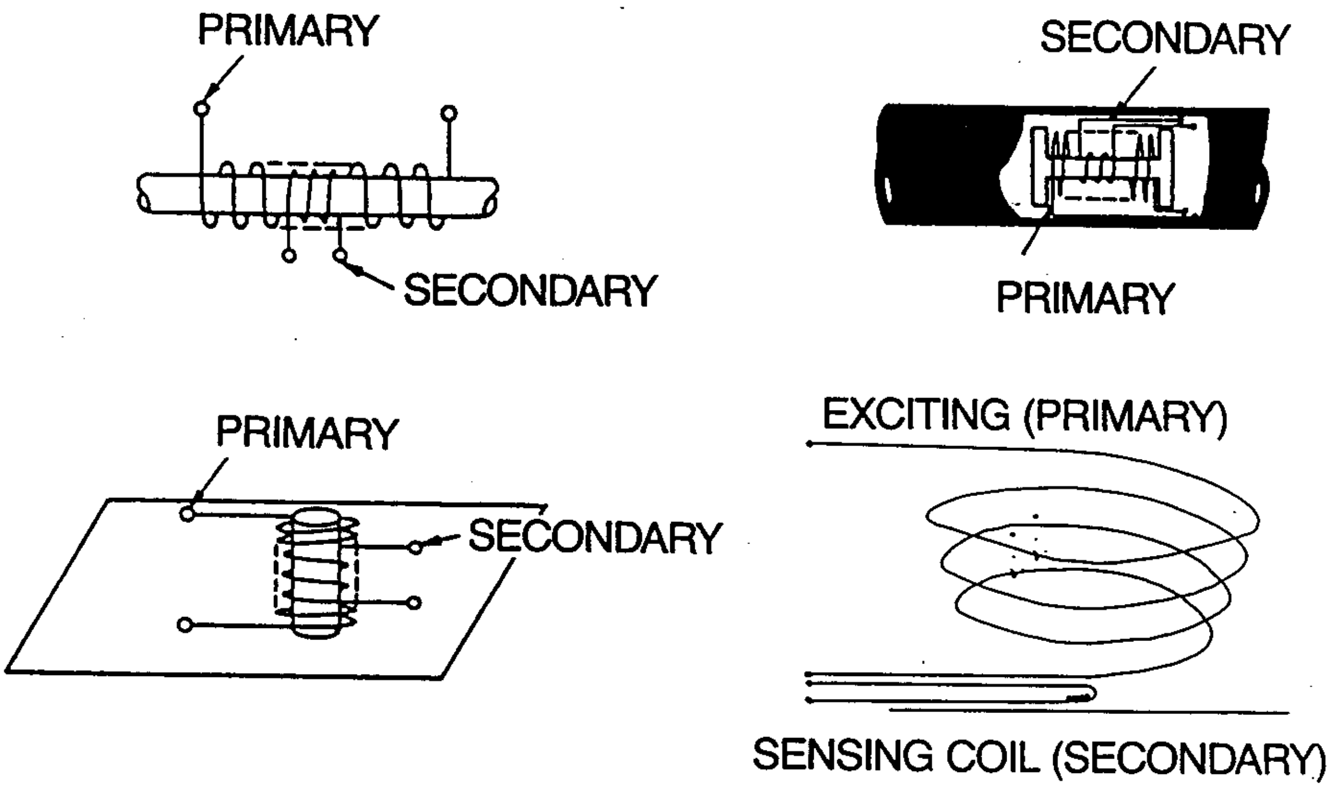


Figure 4.3: Dual Coils

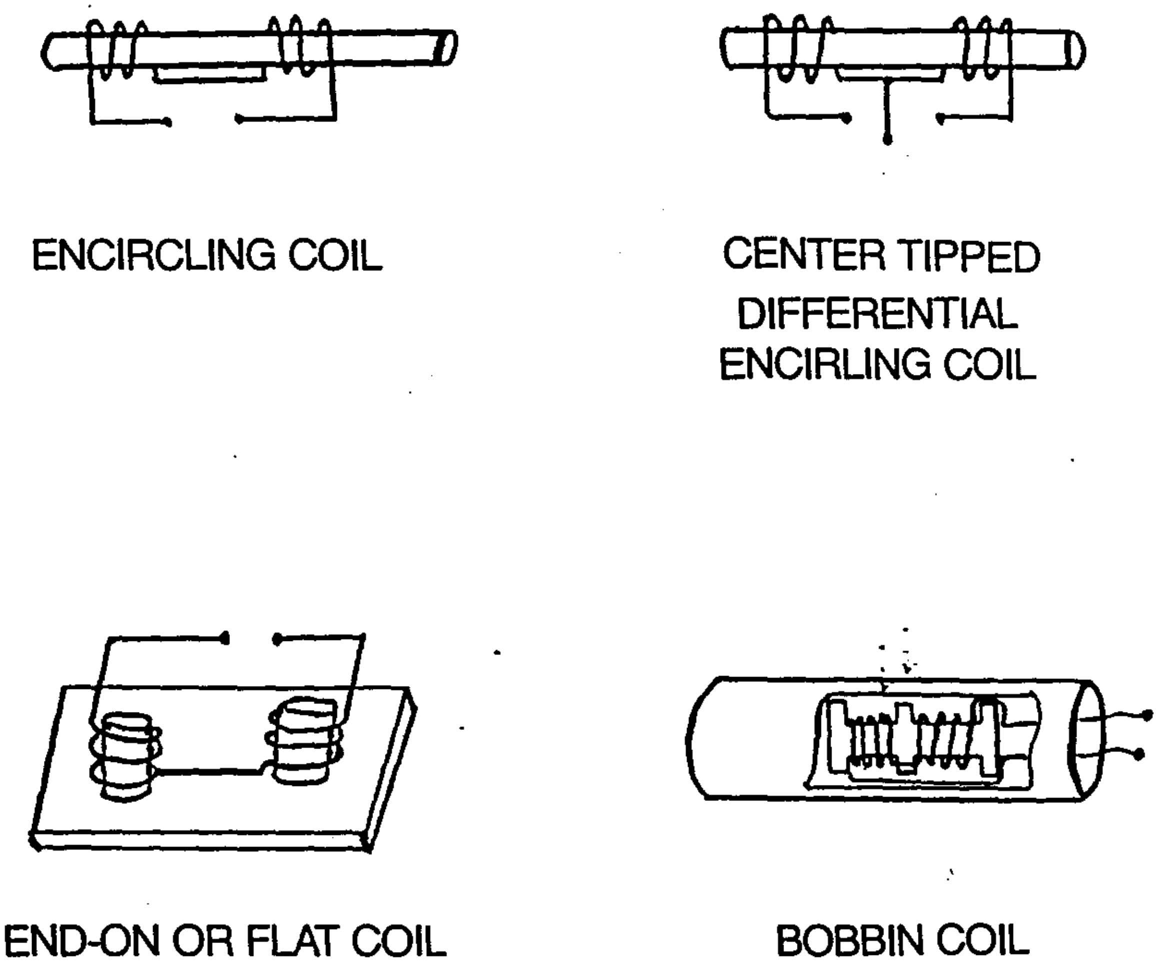


Figure 4.4: Differntial Coils

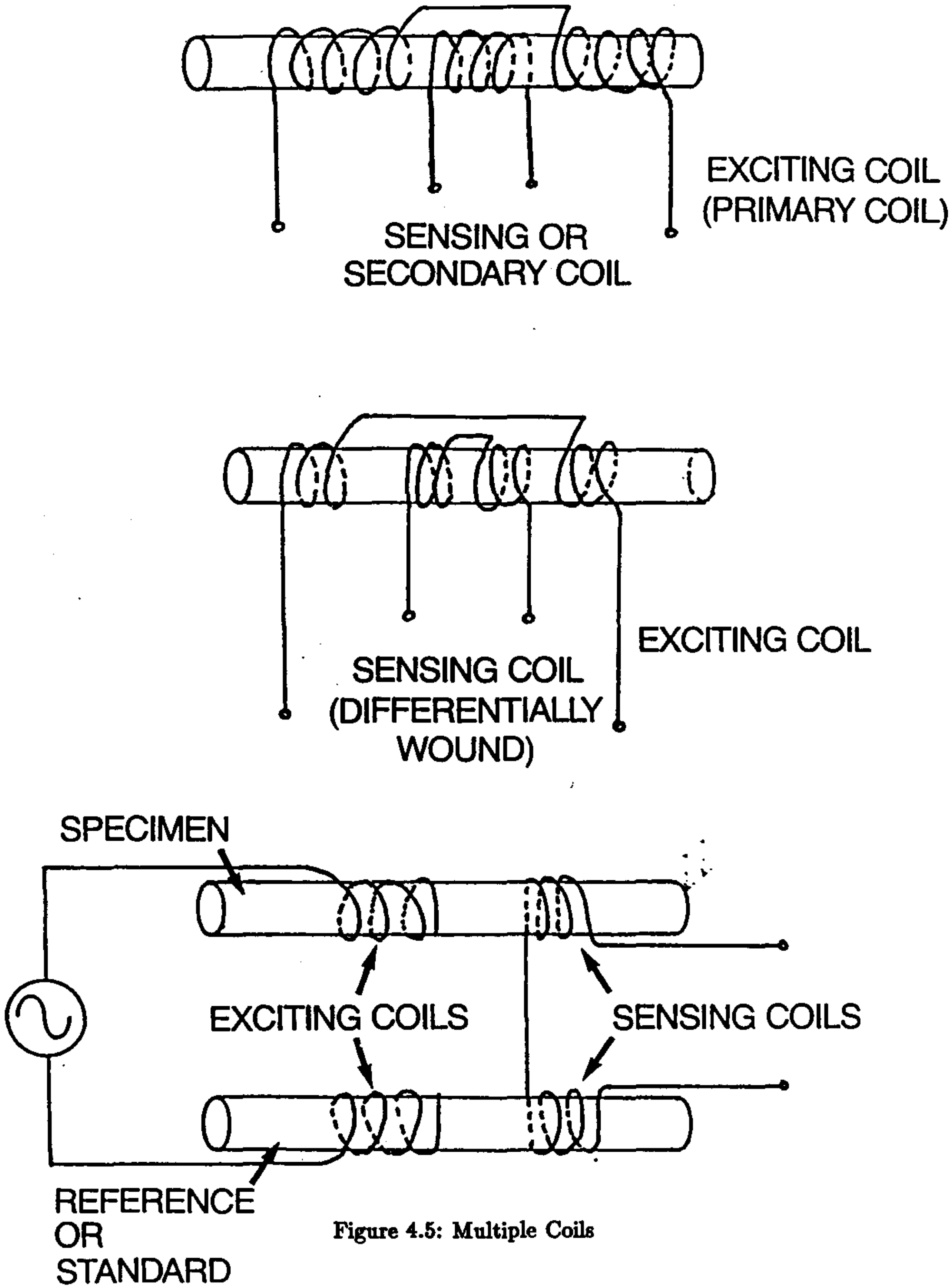


Figure 4.5: Multiple Coils

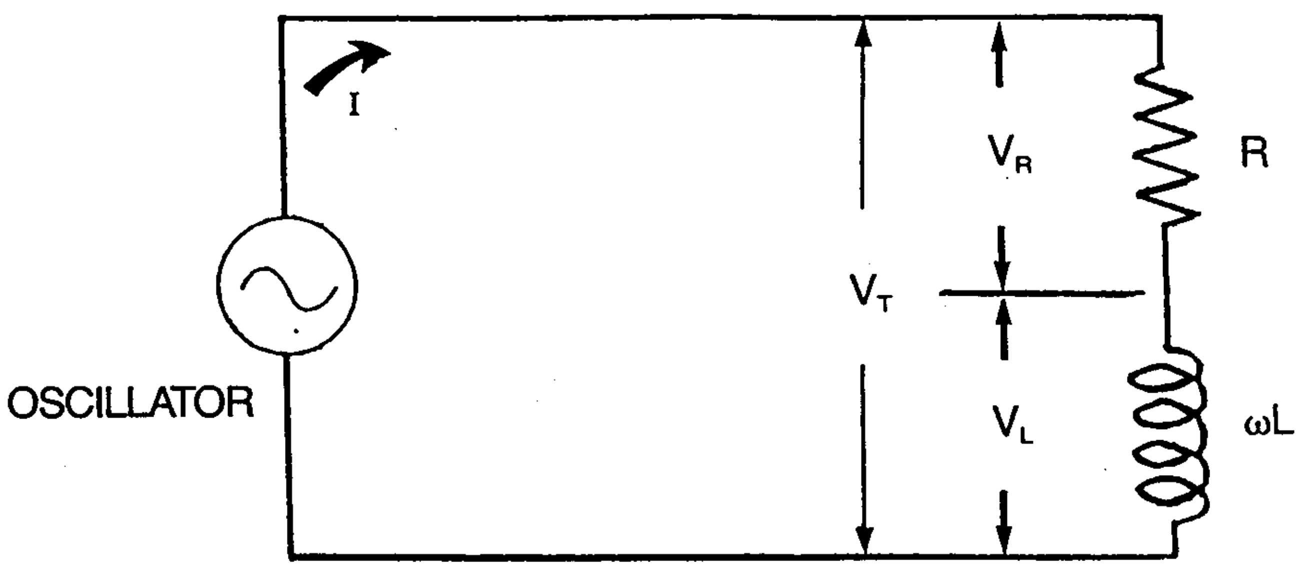
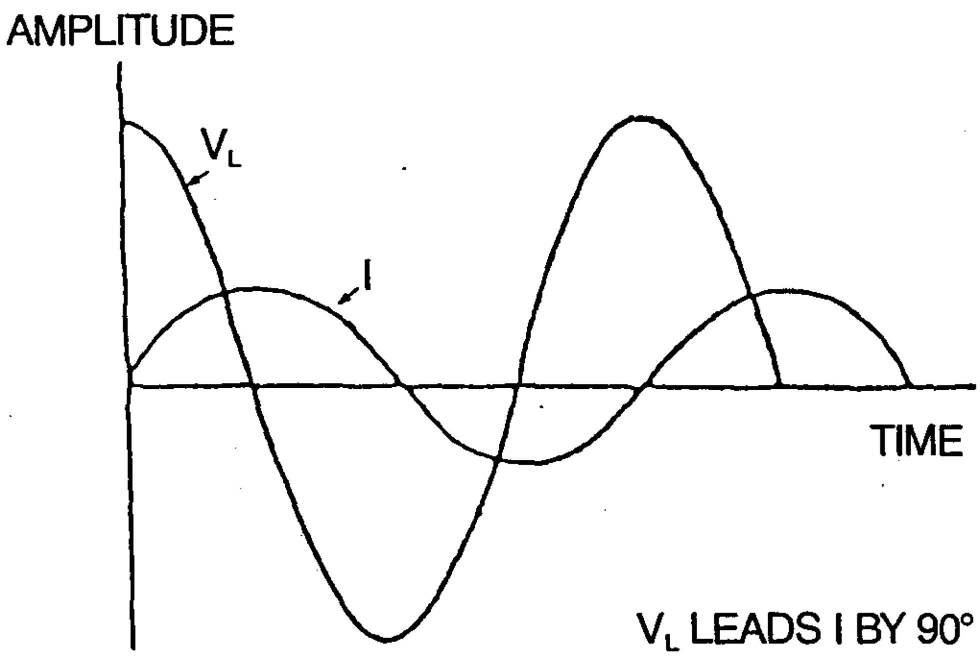


Figure 4.6: Equivalent Circuit



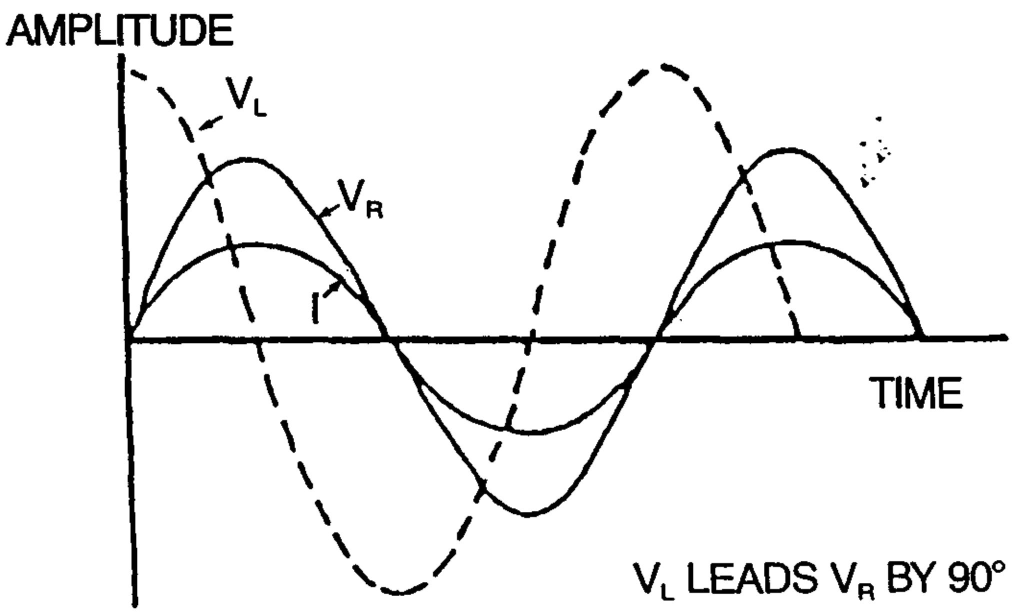


Figure 4.7: Current and Voltage Through Inductance

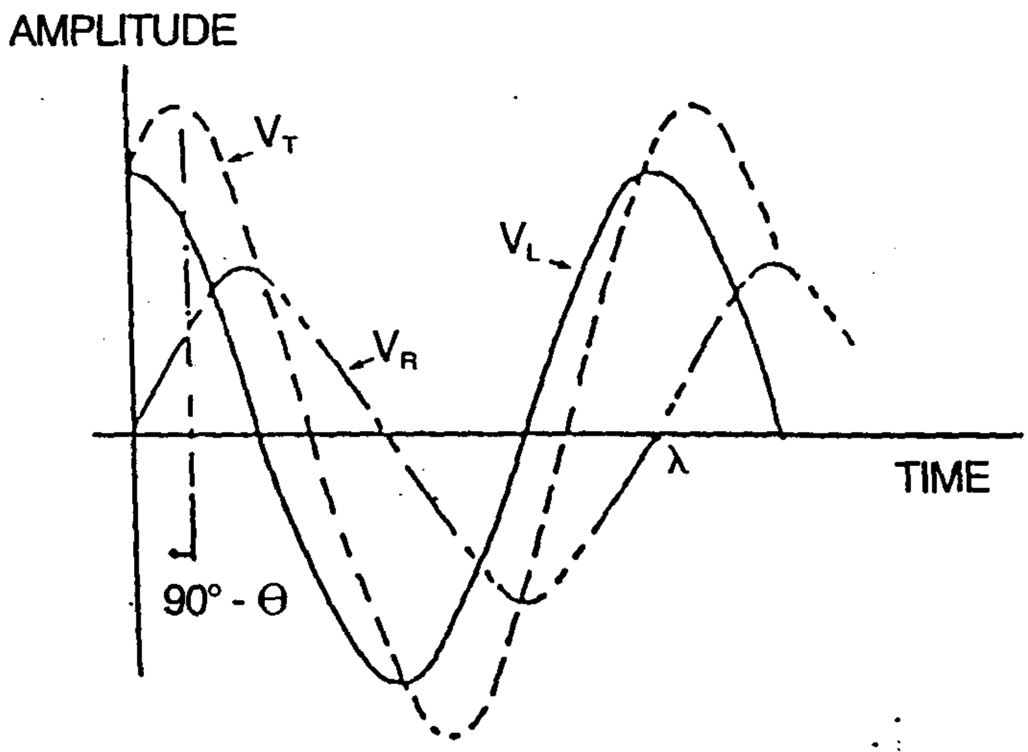


Figure 4.8: Voltage Components in Inductance

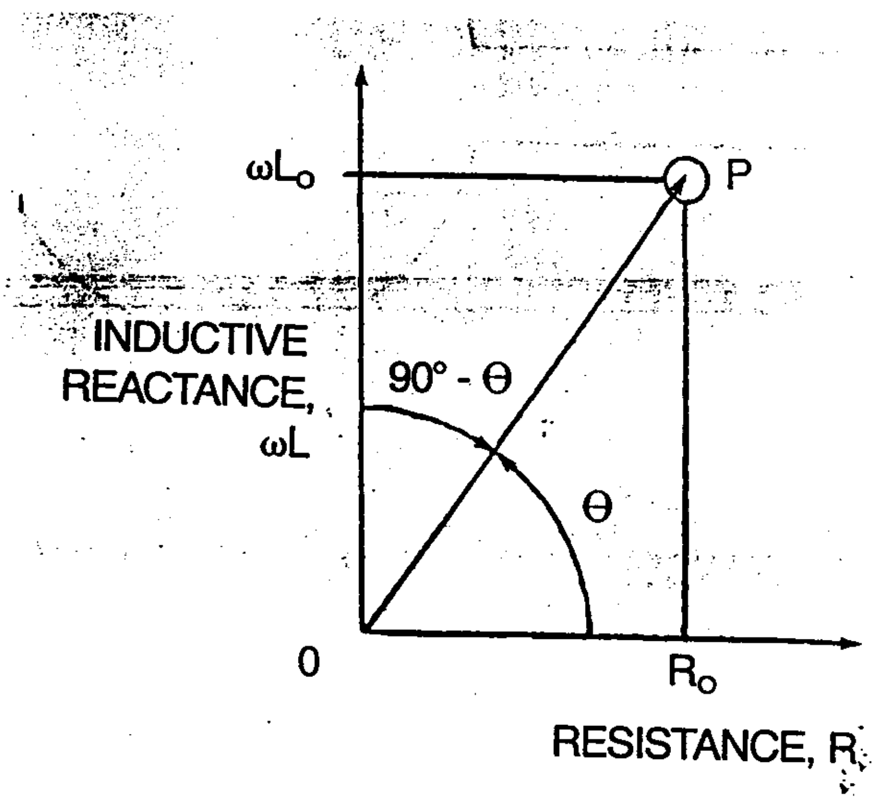


Figure 4.9: Impedance Diagram

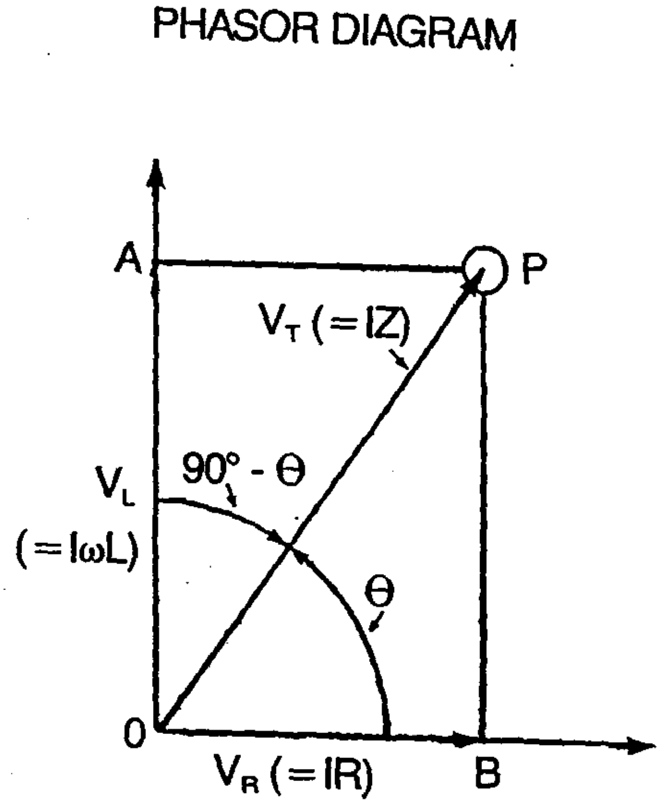
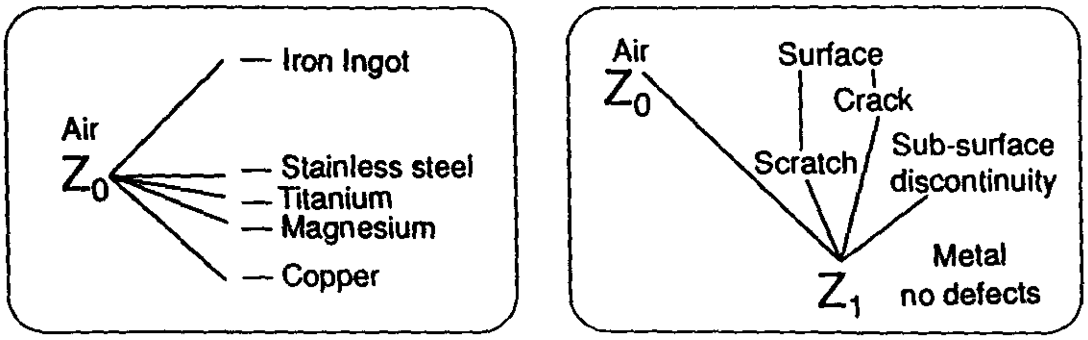


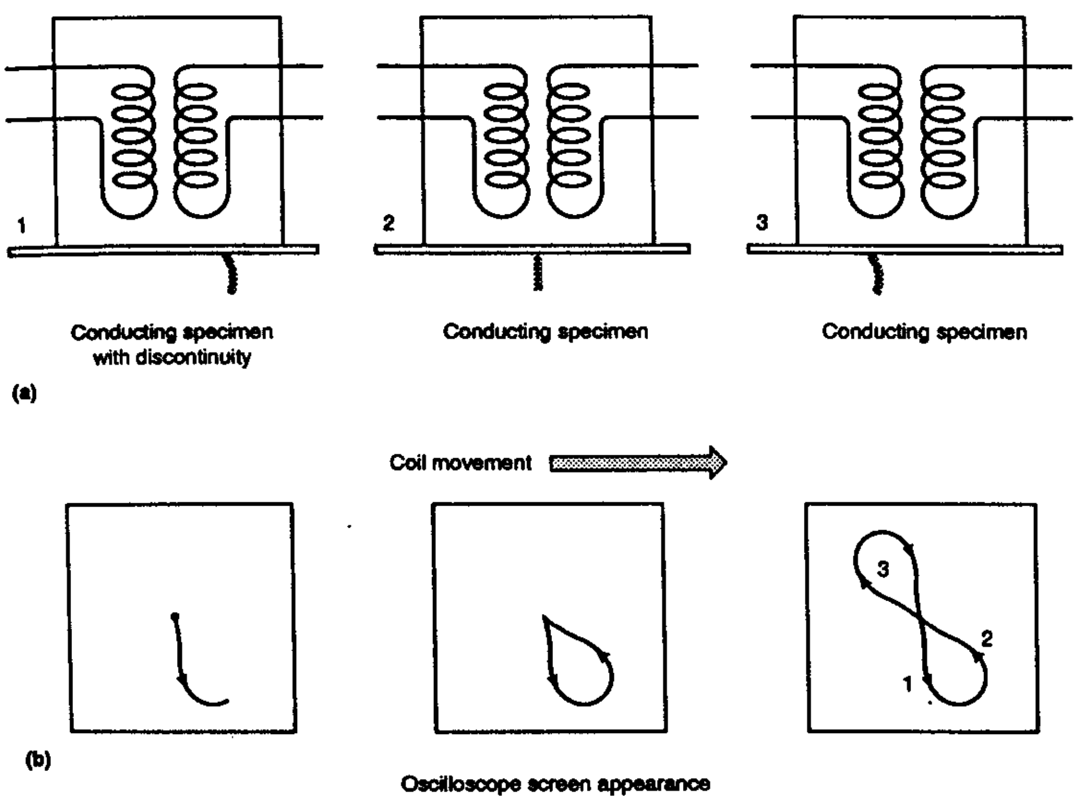
Figure 4.10: Phasor Diagram



(a) (b)

Vector point signal on oscilloscope screen. The changes in the impedance plane can be recognized if one factor only is varying. (a) Electrical conductivity changes in specimen (all other factors constant). The impedance vector point will change as shown. The inspection coil and system needs to be calibrated using metals of known conductivity. (b) Various defects (all other factors constant). The various changes are recognized by experience and by calibration with known defects.

Figure 4.11: Impedance Display on Oscilloscope



Differential testing (impedance plane). The two inspection coils are linked electrically in opposition. The circuit becomes unbalanced if one coil moves opposite a discontinuity. (a) Three different positions, 1, 2, and 3, of the coils as they are moved alongside the specimen with discontinuity; in this case, from left to right. (b) Corresponding view of the oscilloscope screen indicating the direction and manner of the formation of the Lissajous figure (Ref 286).

Figure 4.12: Impedance Plane (Differential Testing)

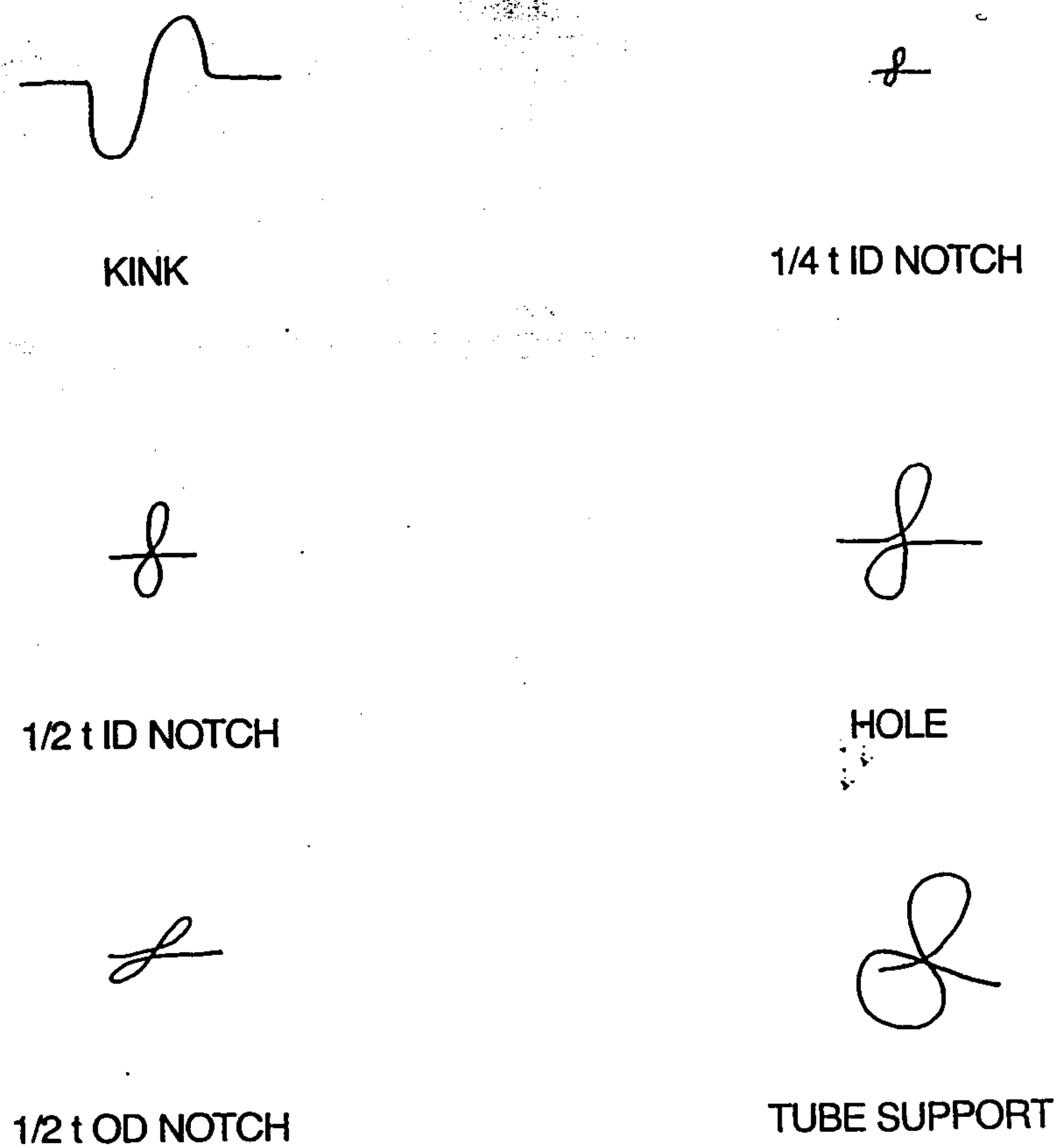
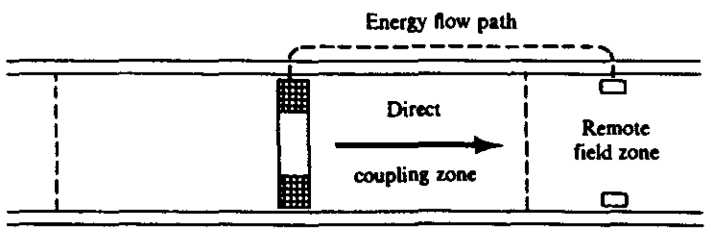
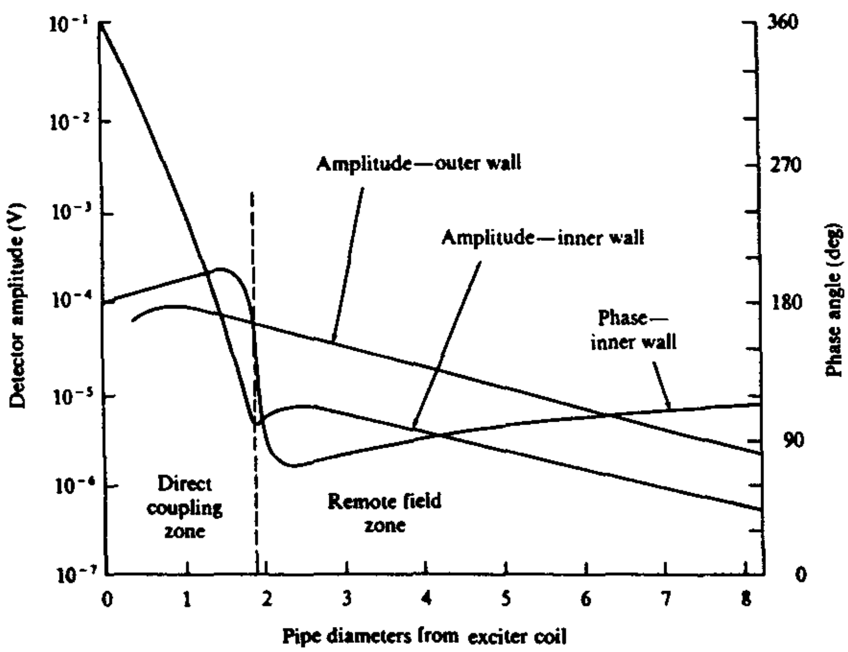


Figure 4.13: Oscilloscope Presentation for Tube Inspection

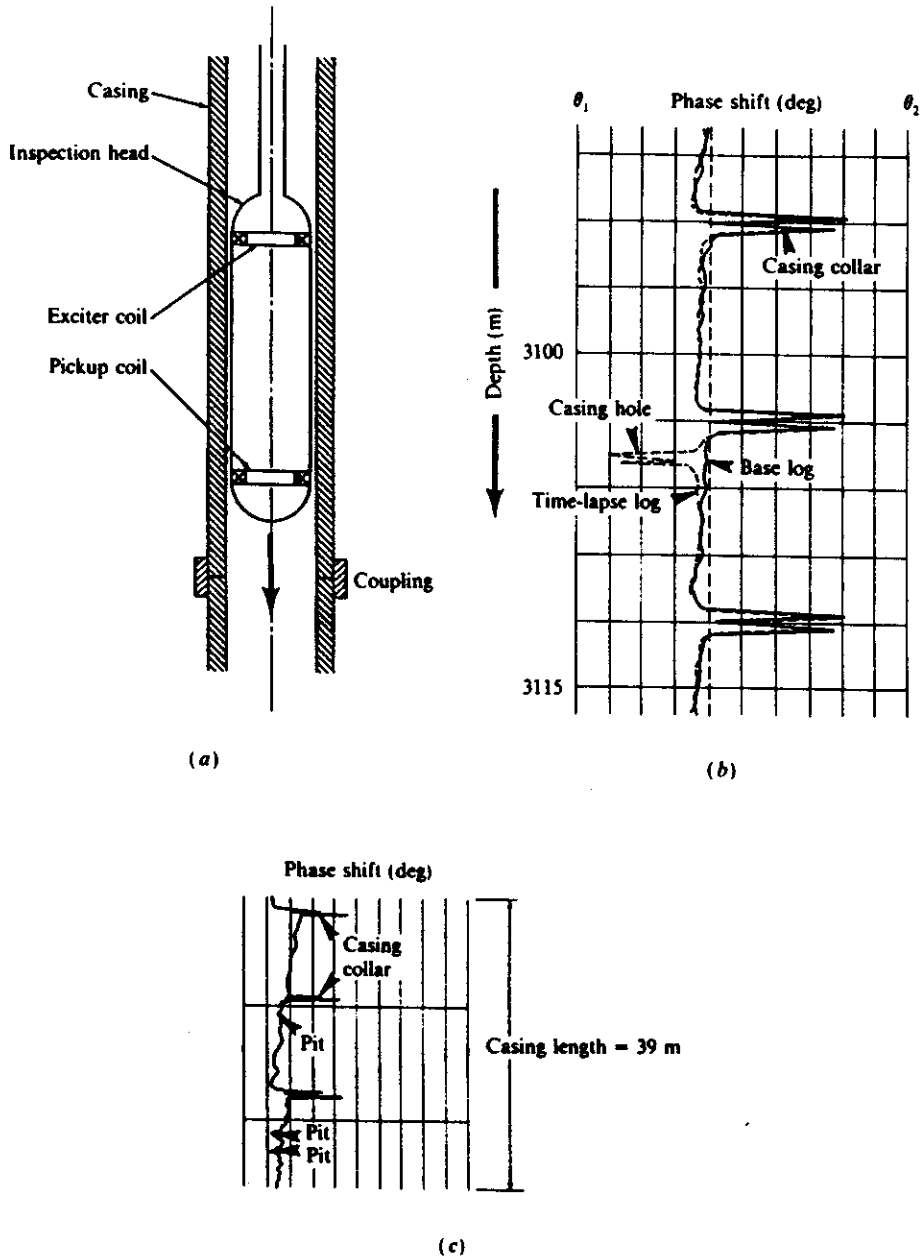


Remote field representation. The energy flow path is indicated. (*After Schmidt* [2].)



Amplitude and phase relation for real and remote field eddy currents in a ferromagnetic tube. (*After Schmidt* [2].)

Figure 4.14: Schmidt's Experiment



(*a*) Simplest RFEC system in well casing. (*b*) Typical data from casing over a period of time. (*c*) Development of pitting.

Figure 4.15: A Remote Field Inspection System