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Eclipse Scientific

Eddy Current Testing Technology

1st Edition

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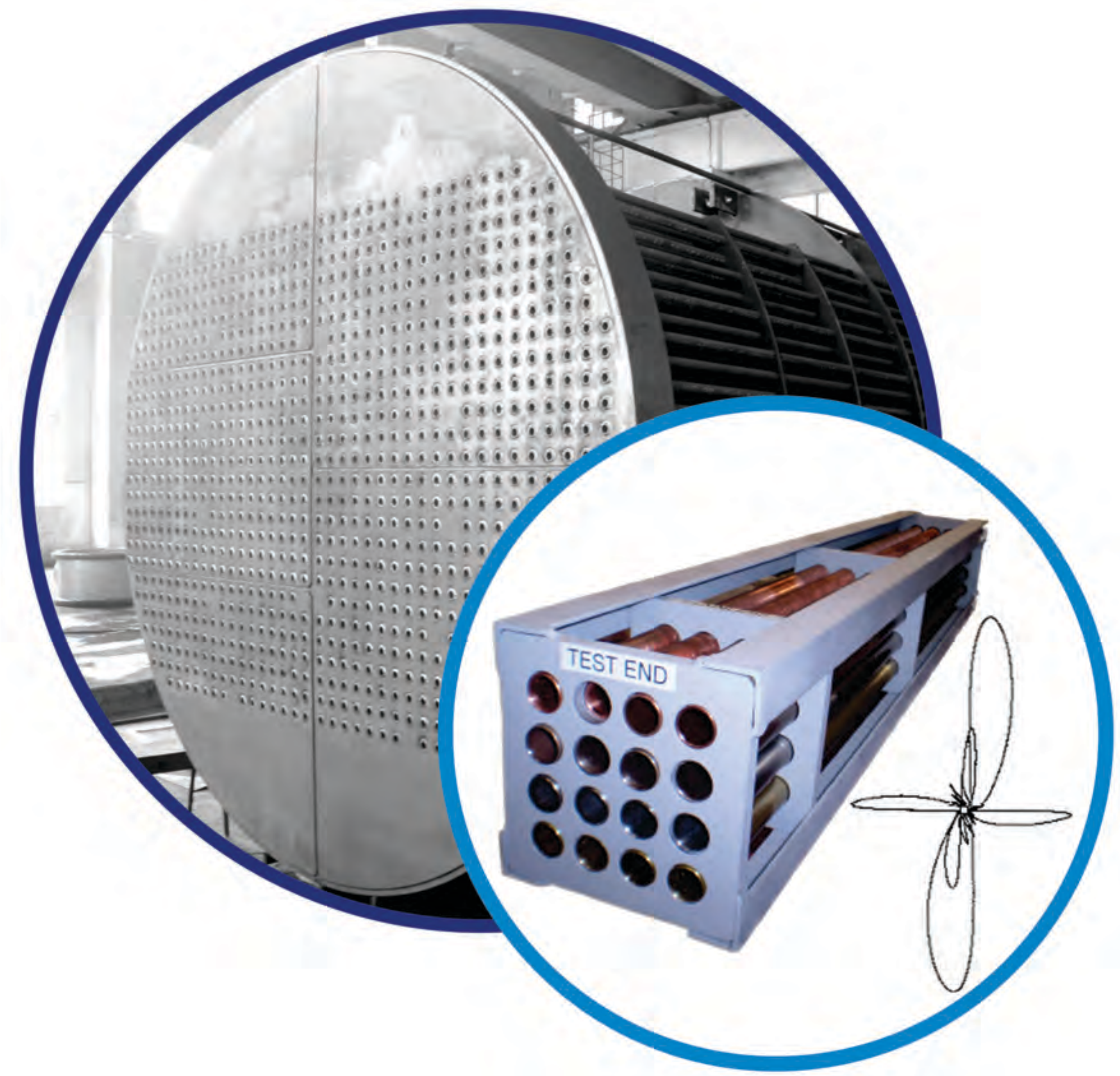

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CHAPTER (5): TYPES OF SENSING ELEMENTS

5.1 INTRODUCTION TO SEMI-CONDUCTOR DETECTING DEVICES

Semi-conductor detecting devices are not used very extensively in Eddy Current testing, but there has been a lot of research and development with semi-conductor devices. The principle behind a semi-conductor Eddy Current sensor is called the Hall Effect. The Hall Effect was discovered by Edwin Hall in 1879.

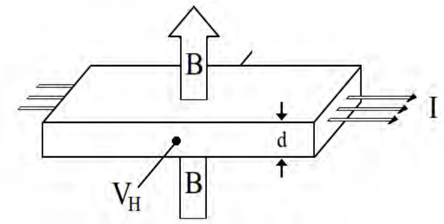

Figure 5.1 Current flowing through a conductor in the presence of a perpendicular magnetic field

The movement of electrical charges is referred to as electromigration. Current can consist of electrons, ions, holes or missing electrons (or all three). When current (movement of charges) passes through a conductor in the presence of a perpendicular magnetic field they experience a force. This force is called the Lorentz force and is written as:

$$F = q[E + (v \times B)] \tag{5.1}$$

F is the force, q is the charge of the particle, E is the electric field, v is the instantaneous velocity of the particle, and B is the magnetic field. F, E, and B are vectors and the x is the vector cross product operator.

When there is no magnetic field present the charges move in relatively straight lines. When the charges move in the presence of a perpendicular magnetic field the charges move in curved paths between collisions. These curved paths cause an accumulation on one face of the material. This leaves a buildup of opposite charges on the parallel face; as there are less of the moving charges. This creates an asymmetric distribution of charge density across the Hall element that is perpendicular to the path of the current.

For a metal that has only electrons as the charge carrier, the Hall voltage V_H is:

$$V_H = -\frac{IB}{ned} \tag{5.2}$$

I is the current, *B* is the magnetic field, *d* is the thickness of the plate, *e* is the electron charge, and *n* is the charge carrier density of the carrier electrons.

The Hall coefficient is a material property value like conductivity and resistivity. It is defined as the ratio of the induced electric field to the product of the current density and the applied magnetic field. Different materials will be able to create or build up more Hall Effect or Hall voltage.

The Hall coefficient is defined as:

$$R_H = \frac{E_y}{j_x B} \qquad (5.3) \qquad\qquad R_H = \frac{E_y}{j_x B} = \frac{dV_H}{IB} = \frac{-1}{ne} \qquad (5.4)$$

Where j is the current density of the carrier electrons, and E_y is the induced electric field.

The Hall Effect is a very useful tool for measuring either the carrier density or the magnetic field. Most Hall Effect sensors used in Eddy Current testing are used to detect changes in magnetic fields.

Figure 5.2 Hall effect sensors are usually just IC's

Figure 5.3 TRESCAN Hall element array probe (2)

5.2 PHYSICAL CONFIGURATIONS

Eddy Current probes are all simple types of coils. There are different coil geometries, coil arrangements and operating modes. The simplest probes are called pancake probes. Pancake probes can be as simple as a coil with a single layer.

Figure 5.4 Pancake probe coils

The coils can vary from around a centimetre to a millimetre in diameter. The diameter, number of turns and wire gauge used, is very specific for the design or purpose of the probe.

Coils can come in many different geometrical shapes and configurations. In the Figure 5.5, the first row shows various pancake type coils with different diameters and core sizes. The second row shows square coils of different sizes with the last coil showing a square pair of coils. The third row shows rectangular coils, with the last coil on the right being a set of two rectangular coils. The bottom row shows cubic coils of different sizes.

Figure 5.5 Probe coils with various geometrical configurations

Figure 5.6 Coil with some core material, and types of coil shielding

Each coil can be wrapped around a core material or have no core (air core). The core material can be made from ferromagnetic material to help with penetration in the test material. Adding a ferromagnetic core also increases the inductance of the coil. There are many different types of core/shielding material. Coils can be shielded to help eliminate outside noise, or to help focus the magnetic field into the test material. Some probe coils are shielded with a cup type core or with a shield and core material.

Common shields will be made of:

- *Ferrite* (like a ceramic made of iron oxides): a superior shield, as it has poor conductivity which will concentrate the field within its area.
- *Mu-metal:* a thin material used sparingly in pencil probes but does not provide the same advantages as ferrite.
- *Mild steel:* used primarily in spot and ring probes. As mild steel is easy to be machined it can be used when ferrite is not available in a particular shape or size. A disadvantage is that mild steel will reduce the field strength due to loss of field strength in the core.

Shielding Advantages:

- Reduces geometry changes, such as edge effect
- Allows for inspection closer to ferrous fastener heads and rivets
- Smaller defects can be located due to the field concentration induced by the shielding
- Reduces the possibility of irrelevant indications

Although all combinations of core and shield are made, the shielded style coils are very rare for most array probes. The shielding can interfere with the transmit-receive mode of operation.

Every coil type can be wired to operate in different modes. The differential mode and the transmit-receive mode involve more than one coil while the absolute mode can function with only one coil.

5.3 SIGNAL RESPONSES

5.3.1 ABSOLUTE MODE

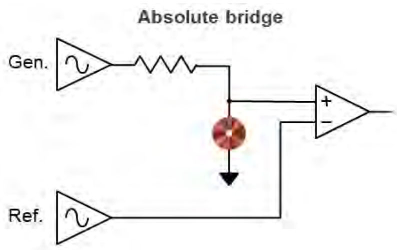

Figure 5.7 Wiring diagram for an absolute probe coil

Applications:

Absolute probes or mode is commonly used in many applications. Bobbin tube probes have a coil pair that operates as both an absolute probe and a differential probe. Single element surface probes are commonly absolute probes. Many array probes are made from adding several absolute mode coils to scan larger areas. Absolute mode coils work well for crack detection, corrosion mapping, and material sorting.

Advantages:

Absolute mode is sensitive to abrupt and long slow changes in material. Most absolute mode probes are inexpensive to manufacture.

Limitations:

Absolute mode is very sensitive to lift-off variations. Some setups with absolute probes will require a reference probe. This mode is more sensitive to temperature variations between test and reference probes.

5.3.2 DIFFERENTIAL MODE

Figure 5.8 shows the wiring diagram for two coils connected with a different bridge. This mode has two coils where one is wired to each pole of the bridge.

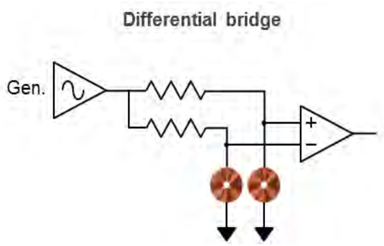

Figure 5.8 Coils – bridge wiring diagram

Applications:

Differential mode is primarily used in bobbin probes for tube inspections. This mode is common in some array probes and even with some transmit-receive coil arrangements.

Advantages:

Differential mode does not require a reference probe. This mode is less sensitive to lift-off/probe wobble variations. This mode is very good at identifying and sizing very short flaws. Since there is no required reference probe, temperature variations have less impact on the Eddy Current signals.

Limitations:

- Differential mode is not good at detecting very long or gradual material variations
- Detects only the start and end of a long flaw
- Indications may be difficult to interpret

5.3.3 TRANSMIT-RECEIVE MODE (REFLECTION)

Figure 5.9 shows the wiring diagram for a transmit-receive coil pair connected with absolute mode and differential mode. Reflection probes are types of transmit receive coil arrangements.

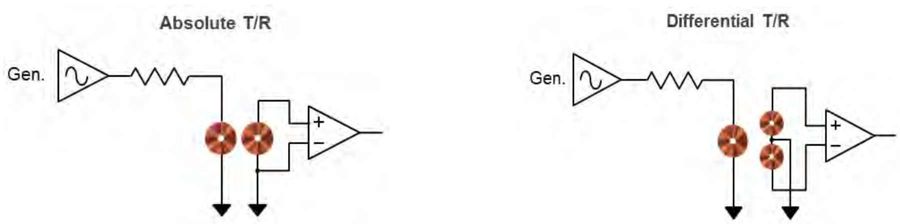

Figure 5.9 Transmit-receive coil pair wiring diagrams

Applications:

Transmit-receive mode is the most common mode used in array probes. Transmit-receive probes are used in rivet testing, corrosion mapping, crack detection and thickness measurements.

Advantages:

Since the coil positions determine the detection area, transmit-receive coils are very direction sensitive. The direction of the T/R unit can be a huge advantage when looking for very specific directional flaws.

Limitations:

Although the directional sensitivity can be a benefit, it can also become a limitation in specific circumstances. There is added complexity to setting up an inspection and in analyzing data. Some coil arrangements will interfere with nearby coils creating crosstalk. Large arrays might need special circuitry (ASIC - Application Specific Integrated Circuits). Equipment becomes increasingly complex with multiple coils in the array.

5.4 COIL ARRANGEMENTS

5.4.1 SINGLE

Single coil arrangements are always absolute mode probes.

Figure 5.10 Single coil arrangement

5.4.2 CONCENTRIC

Figure 5.11 Concentric coil arrangements

Applications:

- This coil configuration is very common in annular or ring style probes
- Very limited number of applications are still using this style of probe coils

Advantages:

Concentric probes are very sensitive to specific geometrical flaws. Concentric differential probes are not very sensitive to lift-off variations.

Limitations:

Concentric differential probes are usually very expensive so they are not very common.

5.4.3 SIDE BY SIDE

Figure 5.12 Side by side coil arrangements

Applications:

These arrangements are the most common in modern Eddy Current testing. All array style probes can be made for either arrangement. The applications vary from crack detection, corrosion mapping, thickness measurements, tube inspections, and even some encircling coils are made from this design.

Advantages:

Very common arrangement in array probes. The arrangement of coils is dependent on flaw orientation. Simple to manufacture so probe cost is improved.

Limitations:

The flaw direction can work against the coil arrangement. This arrangement is sensitive to flaws that are parallel with the coil arrangement. Flaws that are perpendicular to the coil arrangement are more difficult to detect.

5.4.4 THROUGH PROBE COIL TRANSMISSION

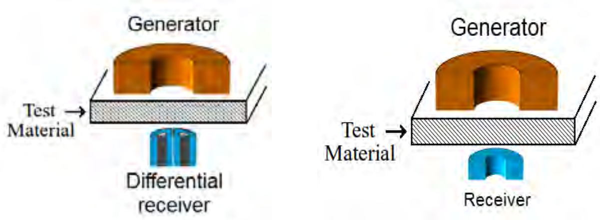

Figure 5.13 Through probe coil arrangement

Applications:

This style of coil arrangement is very rarely used in modern Eddy Current testing. Material consistency and manufacturing processes can still use this type of coil arrangement.

Advantages:

The generator signal has to penetrate 100% of the material to reach the receiver coil. This setup can incorporate very well in a manufacturing assembly line. It is usually configured with an alarm for a pass or fail type criteria, so there is very little analysis required.

Limitations:

The main limitation in a through transmission coil setup is the test material thickness. There are other limitations in physically getting the transmit-receive coils positioned correctly. For example, this type of setup is impossible for the centre of a very large plate or it is impossible if the inspector does not have access to both sides of the test material.

5.5 EC PROBES MODELS

5.5.1 ORTHOGONAL

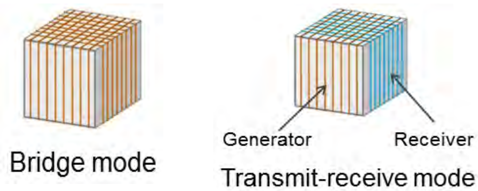

Figure 5.14 Orthogonal coil arrangement

Applications:

Both the bridge mode and transmit-receive mode produce an absolute probe signal response. This arrangement is very expensive to manufacture so the number of applications is very limited.

Advantages:

Very low sensitivity to lift-off and surface roughness

Limitations:

This design is very rare due to the manufacturing cost. This probe style is also sensitive to flaw orientation.

5.5.2 ARRAY PROBES

Array probes are just groups of simple coils. These probe coils can be of any type and any operating mode. Arrays can quickly get complicated. There are many advantages to using array probes that outweigh the added complexity.

- Reduces inspection time
- A single pass covers a large area. With raster scans (multiple scans) and robotic scanning systems will cover larger areas
- Provides profilometry of the inspected region, facilitating data interpretation. C-scan capability
- Complex part geometry does not pose a problem, with custom probes available
- Improves reliability and probability of detection (POD)

Array probes can come in every coil type, coil arrangement, coil shielding type, coil core type and every operating mode. The geometrical positioning of the coils also becomes a factor involved in the performance and functionality of the probe. Custom arrays may be manufactured for specific applications.

Although setting up and using Eddy Current Array probes can be involved and complex, all array probes are just combinations of simple coil types and modes of operation.

Figure 5.15 shows scanning with a single absolute probe which can take a long time to cover an area. While igure 5.16 shows an array with the same coil which can quickly cover the same area.

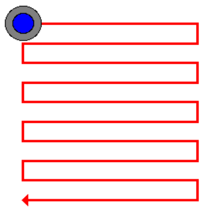

Figure 5.15 Single absolute probe scanning

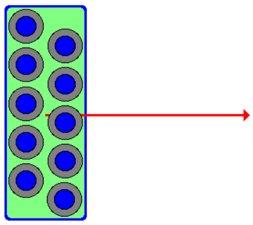

Figure 5.16 Array absolute probe scanning

Arrays usually reduce scan time but they can also be set up for increased detection of directional flaws.

Most array probes require encoders. With the addition of encoder data the Eddy Current signals will have a position and time associated with them. This addition of position enables the data to be viewed as a C-scan. C-scans are two and three dimensional colour plots. C-scans enable a very quick way to view multiple Strip charts and Lissajous at the same time. There are many styles of array probes. The most common are absolute or transmit-receive coil arrangements.

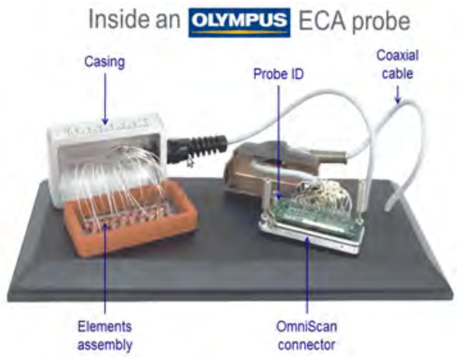

Figure 5.17 Array probe with an absolute coil arrangement consisting of 26 coils

5.5.2.1 ABSOLUTE COIL ARRAYS

Applications:

This array design has very diverse applications.

Advantages:

The coil arrangement is omnidirectional. Absolute arrays are simple to manufacture so they are very cost-effective.

Limitations:

Absolute coils are very sensitive to lift-off variations.

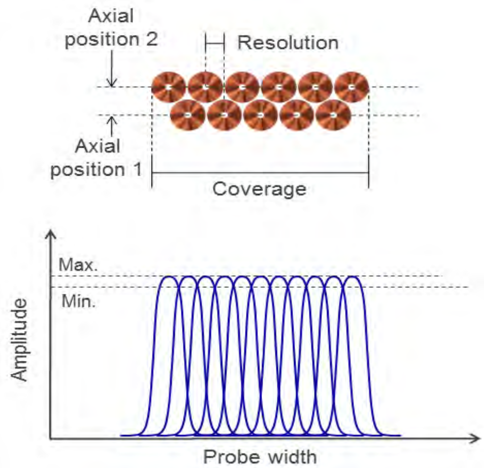

Figure 5.18 Absolute coil arrays

5.5.2.2 TRANSMIT-RECEIVE COIL ARRAYS

Applications:

This array design has very diverse applications.

Advantages:

T/R coils are very directionally sensitive which helps when inspecting for geometrical flaws. The T/R coil design can be made to maximize characteristics or minimize signal characteristics.

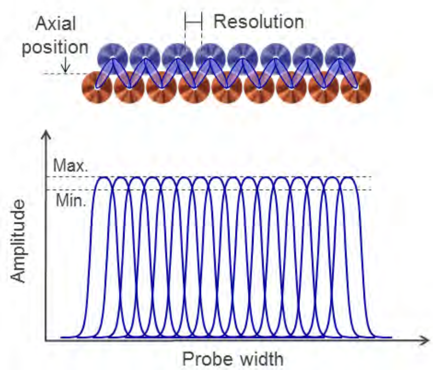

Figure 5.19 Transmit receive coil arrays

Limitations:

The directional sensitivity can also be a limitation for this style. The more units added to the array, the more complex the analysis and acquisition become. Equipment can quickly become complex and require specific circuitry (ASIC).

5.5.3 ENCIRCLING PROBES

Encircling coils operate and are designed exactly the same as ID tube probes. The only difference being that the probe goes on the Outer Diameter (OD) of the test material. Since the probe is not limited to the circular tube ID, some encircling probes can be rectangular or made to fit the material that they are testing. Encircling coils can be used to test round or rectangular tubing and solid stock such as round or bar stock. Most encircling coils are basic style differential and absolute mode setups. Although it is not common, array probes can be made into encircling probes.

Figure 5.20 Encircling coils [3]

The width of the coil is a function of the application and defects to be located. Wide coils are designed to cover large areas. Wide coils will be used to locate volumetric defects, e.g. conductivity, whereas narrow coils provide a smaller sensing area and are more responsive to small impedance changes such as those produced by discontinuities.

5.5.4 ANNULAR/RING PROBES[4]

Figure 5.21 Annular Eddy Current probe

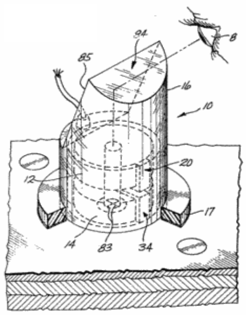

Figure 5.22 Probe sitting on test material

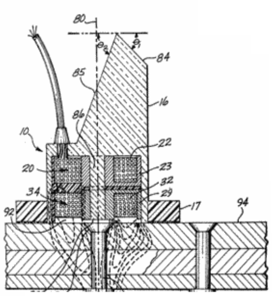

Figure 5.23 Side view of above annular Eddy Current probe

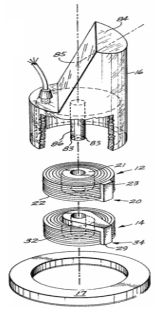

Figure 5.24 Inside view of annular Eddy Current Probe

Annular Eddy Current probes, as shown in Figure 5.21, are for detecting cracks in metal skins and adjacent fastener/rivet holes. Figure 5.22 shows the probe sitting on the test material. The design shown in Figure 5.24 is a transmit-receive coil setup. The transmit and receive coils are wound around two vertically stacked ferromagnetic core members. The ferromagnetic cores are held in place by an associated optically clear shoe member centred by a centring ring. The probe can be visually centred, as shown in Figure 5.22, to enable an accurate inspection of the entire circumference of a fastener hole. These types of probes provide a low frequency (90 - 700 Hz) Eddy Current inspection that is capable of inspecting multiple layers fastened together as shown in Figure 5.23

5.5.5 GAP PROBES(5)

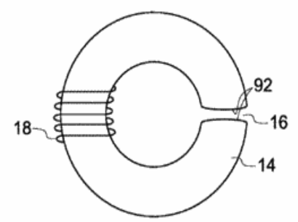

Figure 5.25 Simple gap probe coil design

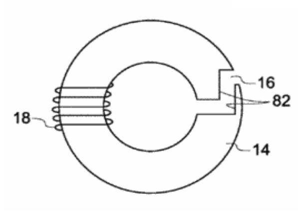

Figure 5.26 Simple gap probe with a shaped gap

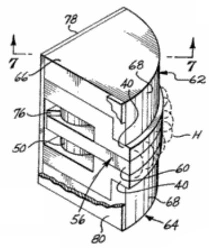

Figure 5.27 Quarter circle region design

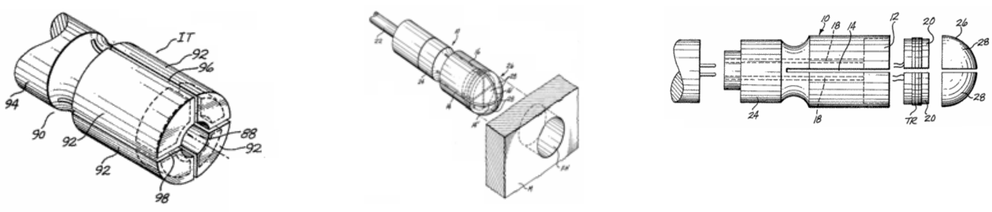

Figure 5.28 Tube inspection gap probe (3 views)

Figure 5.25 shows a very simple gap probe coil design. Figure 5.26 shows a simple gap probe with a shaped gap. The shape between the gaps in the core material will control the direction of the magnetic field lines. Gap coils can be made to fit very specific geometries required for an inspection. Figure 5.28 shows a model of a tube inspection gap probe. This design has 4 core sections that are magnetized by the 4 coils. This specific design has a gap along the length and the cap of the probe. The area between the cores or the gap region has a very specifically shaped magnetic field. When an indication or discontinuity enters this region it will alter the magnetic field and change the impedance in the gap coils. Figure 5.27 shows a design that is a quarter circle region. The upper half and the lower half of this design have a gap between them. This gap creates a magnetic field that enters the test material. The magnetic field is labelled H on the diagram. The core material creates the magnetic field that enters the test material. This means that the core material is the generator of the Eddy Currents. Core materials can be made from several materials. When a probe has many cores or generators different materials will be used in the same probe to help reduce the mutual coupling between different generators. The goal of the gap is for better control of the spatial extent and shape of the generated eddy-currents.

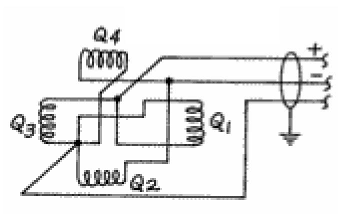

Figure 5.29 Differential mode

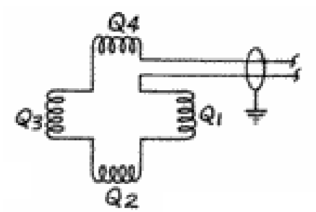

Figure 5.30 4 Coils in series absolute mode

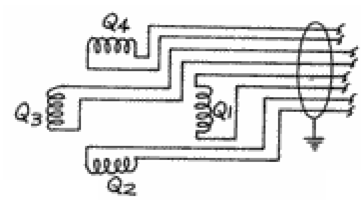

Figure 5.31 4 Coils in parallel absolute mode

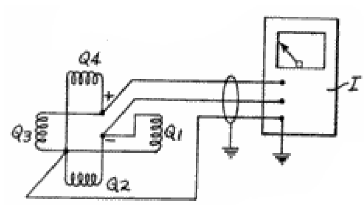

Figure 5.32 Differential mode connected to a meter

5.5.6 ID TUBE PROBES [1]

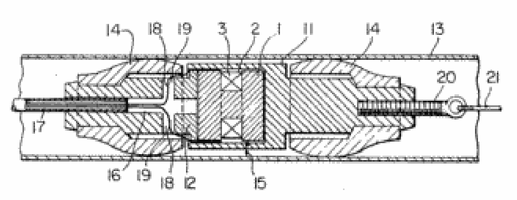

Figure 5.33 Bobbin tube probe

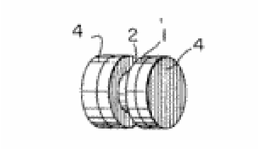

Figure 5.34 Bobbin with single groove and two permanent magnets

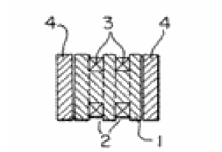

Figure 5.35 Bobbin with two grooves and magnets

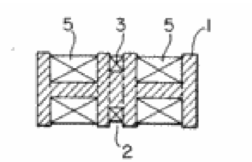

Figure 5.36 Bobbin with single groove and two outer grooves

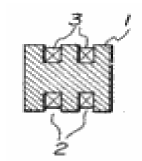

Figure 5.37 Bobbin with two grooves and no magnets

Figure 5.34 to Figure 5.37 show different types of common bobbin designs. Figure 5.34 shows a single groove for test coils and two permanent magnets to magnetically saturate the test material. Figure 5.35 shows a bobbin with two grooves for the test coils which enables this design to operate with differential mode or absolute mode, or both; it also has magnets at either end of the bobbin. Figure 5.36 shows a single groove for the test coil and two outer grooves for a DC supply to magnetically saturate the test material. Figure 5.37 is the same as Figure 5.35 without magnets; these two are the most common bobbin probe designs used.

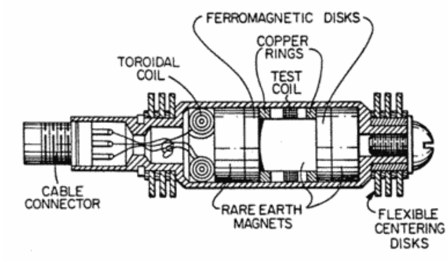

Figure 5.38 Bobbin probe diagram with centring discs

With current technological capability, most bobbin probes operate in both differential and absolute mode at the same time. It is also very common to have multiple channel machines that also work in multiple frequencies at the same time as well as multiple modes. Bobbin probes may have centring mechanisms. Centring disks are no longer very common. Most probes use plastic pedals for the centring mechanism.

When inspecting material that is slightly magnetic, or slightly ferromagnetic, it is common to magnetically saturate the material so it behaves as if it was non-magnetic. This in effect sets the material's relative permeability to 1. There are two methods used to magnetically saturate a test material. Magnetic saturation is accomplished with the use of magnets, or with a coil carrying DC current. Probes with magnets are called mag-bias probes. Probes with DC saturation coils are called DC saturating probes. DC saturating probes are more common in RFT (Remote Field Testing).

The bobbin material can also be made from high μ and electrically resistive metal. Other designs have the test coil capable of carrying the AC probe signal and the DC bias signal in the same coils. Permanent magnets can be made from materials such as Alnico 5, Alnico 8, Barium Ferrite, or a rare earth-cobalt alloy such as Pt-Co.

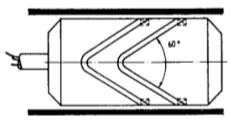

Figure 5.39 A Zig Zag style probe (1)

Not all coils are circular bobbins. Some coils are shaped in specific geometrical patterns to benefit in finding directional flaws. There are several shaped coils such as the above zig zag probe; this style probe is very good at detaching circumferential defects in finned tubing.

There are also rotating probes (rarely used today). Rotating probes are basic pancake coils or surface probes that rotate around the ID of a tube. Both differential and absolute RPC (rotating pancake coil probes) are available.

Surface probes can be added together to create multi-pancake probes. The transmit-receive mode also can be applied to multi-pancake coil probes.

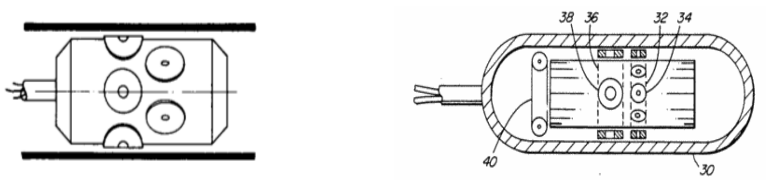

Figure 5.40 Two early designs for array probes (1)

There are many designs for tube array probes. Tubular array probes virtually operate the same way that surface array probes operate. Even the X-probe is just a grouping of simple pancake style transmit-receive coils wrapped around a cylinder.

5.5.7 OTHER PROBE MODELS

Different samples of Olympus, Zetec, TRECSCAN, and Eddyfi Probes are shown below.

Figure 5.41 Rotating scanner probe

Figure 5.42 Manual bolt hole probe

Figure 5.43 Pencil probe

Figure 5.44 Surface or spot probe

Figure 5.45 Weld probes

Figure 5.46 Sliding probes are designed to inspect rows of fasteners

Weld probes are designed to inspect ferrous welds. They provide a cost effective alternative to magnetic particle inspection, which requires the part to be prepared (cleaned) prior to inspection.

Figure 5.47 Bobbin probes

Figure 5.48 Rotating pancake coil probes

Figure 5.49 Remote field probes

Figure 5.50 The x-probe tubular array probe

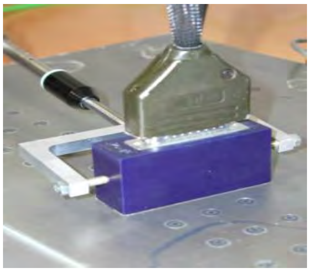

Figure 5.51 Hall element array probe

Figure 5.52 Flexible array probe

5.6 FACTORS AFFECTING CHOICE OF SENSING ELEMENT

5.6.1 TYPE OF PARTS TO BE INSPECTED

The type of part that is being inspected is a very important factor in choosing the right type of probe.

For surface testing, material conductivity can influence the operating frequencies and the depth of penetration. If the goal of the inspection is to inspect very deep (≥4mm), then the coil diameter has to reflect the depth of penetration. A large diameter coil will penetrate deeper than a small diameter coil. The diameter of the flaw also factors into the diameter of the coil. Also, metal that has a higher conductivity is more difficult to penetrate deeper than metal with a lower conductivity.

For tube or bar stock testing, either an encircling coil or an ID tube probe can be used. If the inspection goal is to find very specific directional flaws, array probes might be required.

The largest factor would be the permeability of the test material. If the material has $\mu_r>1$ the material would either need to be magnetically saturated or tested with RFT.

5.6.2 TYPE OF DISCONTINUITIES TO BE DETECTED

The depth of the indication influences the coil size. The diameter of the indication can influence the amplitude of the Eddy Current signal.

The location of discontinuity can also be a factor in choosing a sensing element. If the flaw is located near support structures or the edges of test material, special types of probes can be used.

For flaws that have directional orientation special probes have been made to find specific flaws. For example, circumferential oriented cracks in tubes can easily be missed with ID bobbin tube probes. Zig zag, RPC and many array probes have been designed to detect circumferential oriented cracks in tubes with a higher degree of success.

Knowing the manufacturing techniques used on the test material can help find flaws. Certain manufacturing processes can introduce flaws. If you know that a specific type of process was used, the flaws that are common for that process can be inspected for.

5.6.3 SPEED OF TESTING REQUIRED

With modern technology speed does not usually factor into the system requirements. Speed of an inspection also depends on the speed of analysis. Array technology can take longer to analyze than simpler bobbin or pancake probes. Arrays can cost much more than simpler surface probes but they can also save more time if the region that needs to be scanned is a large area. Array probes can have an upper limit to the speed if the required sample per centimetres is large. Equipment can vary in sample rate and probe response.

If the more complex probe is not required, then the simpler and cheaper probe should always be used.

5.6.4 AMOUNT OF TESTING (PERCENTAGE) REQUIRED

For all NDT inspection methods it is very common to only inspect a percentage of test material. This percentage is called a sample. Sampling statistics are used to estimate characteristics about the entire population or the entire test material. The entire test material is rarely inspected because the cost is too high and takes too long. As the scope of the inspection increases, the probability that something was missed decreases, but the complexity of data analysis increases proportionately.

When testing an item that has been used, or in-situ, the inspection is called a Fitness-For-Service inspection. All standards have specific documentation about failure mechanisms for all parts that are inspected. The API 579-1/ASME FFS-1 Fitness-For-Service is one of the more common standards that show how to calculate the probability of failure for a test piece. There are also standards for determining the choice of sample for inspection. To satisfy a Fitness-For-Service inspection, a 100% inspection is almost never required.

For Eddy Current testing, it is common to inspect an item with two probes. The purpose of using two probes is to look for different flaw types and for ease of analysis. In nuclear power plant steam generators, bobbin probes are used for a large sample of the tubing, while an array probe is used for a much smaller sample. This is mainly due to the complexity in analyzing the collected data.