TRANSMIT-RECEIVE EDDY CURRENT PROBES

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In the last two decades, due to increased inspection demands, eddy current instrumentation has advanced from single-frequency, single-output instruments to multifrequency, computer-aided systems. This has significantly increased the scope of eddy current testing, but, unfortunately, it has also increased the cost and complexity of inspections. In addition, this approach has not always improved defect detectability or signal-to-noise.

Most eddy current testing applications are still performed with impedance probes, which have well known limitations. However, recent research at AECL has led to improved eddy current inspections through the design and development of transmit-receive (T/R) probes.

T/R eddy current probes, with laterally displaced transmit and receive coils, present a number of advantages over impedance probes. They have improved signal-to-noise ratio in the presence of variable lift-off compared to impedance probes. They have strong directional properties, permitting probe optimization for circumferential or axial crack detection, and possess good phase discrimination to surface defects. They can significantly increase the scope of eddy current testing permitting reliable detection and sizing of cracks in heat exchanger tubing as well as in welded areas of both ferritic and non-ferromagnetic components.

This presentation will describe the operating principles of T/R probes with the help of computer-derived Normalized Voltage Diagrams. We will discuss their directional properties and analyze the advantages of using single and multiple T/R probes over impedance probes for specific inspection cases. Current applications to surface and tube testing and some typical inspection results will be described.

1. INTRODUCTION

In the last two decades, due to increased inspection demands, eddy current instrumentation has advanced from single-frequency, single-output instruments to multifrequency, computer-aided systems. This has significantly increased the scope of eddy current testing, but, unfortunately, it has also increased the cost and complexity of inspections. In addition, this approach has not necessarily improved defect detectability or signal-to-noise.

Most eddy current testing applications are performed with impedance eddy current probes. The capabilities and limitations of this technology are well documented [1,2]. Research at AECL has led to improved eddy current inspections through the design and development of transmit-receive (T/R) eddy current probes. These probes, with laterally displaced transmit and receive coils, are similar to "sliding probes" [3], largely used in the aircraft industry. They have an improved signal-to-noise ratio in the presence of variable lift-off compared to standard impedance probes; strong directional properties, permitting probe optimization according to defect orientation; and good phase discrimination to surface-breaking cracks.

This paper describes the operating principles of T/R probes with the help of computer-derived Normalized Voltage Diagrams. Applications such as pressure vessel and nuclear steam generator tube inspections are discussed.

2. PRINCIPLES OF OPERATION

The operating principles of eddy current probes are as follows: a transmit coil is excited by an alternating current generating a magnetic field in its vicinity. This magnetic field induces electrical currents (eddy currents) in electrical conductors, in accordance with Faraday's Law of electromagnetic induction. Detector coils are then used to detect the magnetic flux through their windings. Conventional eddy current probes use the same coil as transmitter and receiver, and are called "impedance probes", because monitoring the voltage induced in them, with constant current excitation, is identical to monitoring their coil impedance. T/R probes use separate transmit and receive coils.

2.1 Normalized Voltage Diagrams

Normalized Impedance Diagrams have been used to display impedance changes of conventional eddy current probes. Figure 1(a) shows a conventional probe response to lift-off and test frequency for a non-ferromagnetic sample. In T/R probes, changes in the test sample are detected as changes in receive coil voltage, as Figure 1(b) shows. Therefore, the equivalent display is referred to as a Normalized Voltage Diagram.

The diagrams in Figure 1 were generated using computer modelling based on analytical solutions to Maxwell's equations derived by Dodd and Deeds [4]. These computer modelling programs were developed at AECL to assist in the development and understanding of T/R eddy current probes. Upon studying probe response to various probe and test parameters, the following (dimensionless) characteristic parameter was derived:

$$P_c = \frac{\omega \mu_0 \sigma s^2}{\mu_r} \qquad (1)$$

where ω is the angular frequency (2π x frequency), μ_r is the relative magnetic permeability, μ_0 is the magnetic permeability of free space, σ is the electrical conductivity and s is the coil spacing.

This parameter is similar to the one derived by Dodd [5] for impedance coils, except that the coil diameter is replaced with T/R coil spacing.

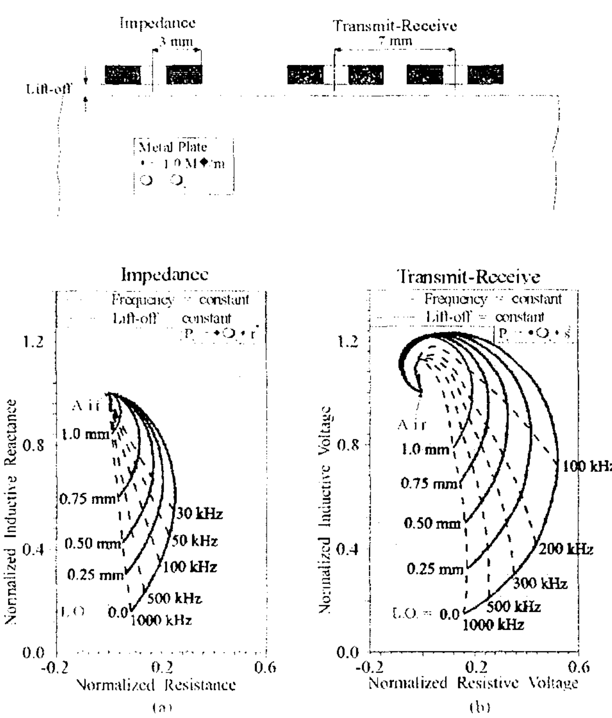

Figure 1. Normalized impedance display and normalized voltage plane display showing lift-off curves at various frequencies and frequency curves at various lift-offs.

2.2 Lift-off Response

One of the most important advantages of T/R probes over impedance probes is their ten-fold improvement in signal-to-noise ratio in the presence of lift-off.

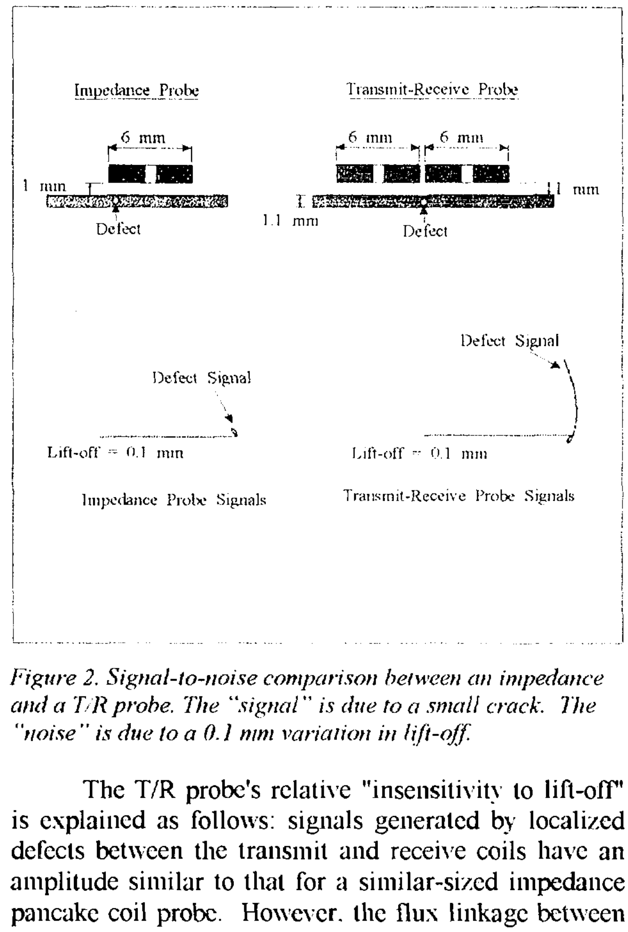

Figure 2. Signal-to-noise comparison between an impedance and a T/R probe. The "signal" is due to a small crack. The "noise" is due to a 0.1 mm variation in lift-off.

The T/R probe's relative "insensitivity to lift-off" is explained as follows: signals generated by localized defects between the transmit and receive coils have an amplitude similar to that for a similar-sized impedance pancake coil probe. However, the flux linkage between the transmit and receive coils is less than 10%. Therefore, probe response to global effects, such as a change in coil lift-off, tube deformations, U-bend transition or sleeve-to-parent tube gap, are only 10% of those for a similar-sized impedance coil. As a result, the signal-to-noise ratio of a T/R probe is five to ten times that of an impedance coil, as Figure 2 illustrates using computer simulations of small defect signals in the presence of lift-off.

2.3 Directional Properties

A T/R probe's maximum response corresponds to variations in the induced magnetic field in the region between the transmit and receive coils. These coil arrangements have directional properties, being sensitive primarily to defects in line with the T/R coils.

Figure 3 illustrates the response of a probe that has been optimized for detecting circumferential cracks in thin wall tubing. It plots experimental results of signal amplitude versus defect orientation from electric discharge machined (EDM) notches 100% deep by 10 mm long in an Inconel 600 calibration tube at 250 kHz test frequency. Signal amplitude from a defect at a 45° angle to the tube axis is one third the amplitude from a circumferential defect. Therefore, probe design can be optimized according to crack orientation.

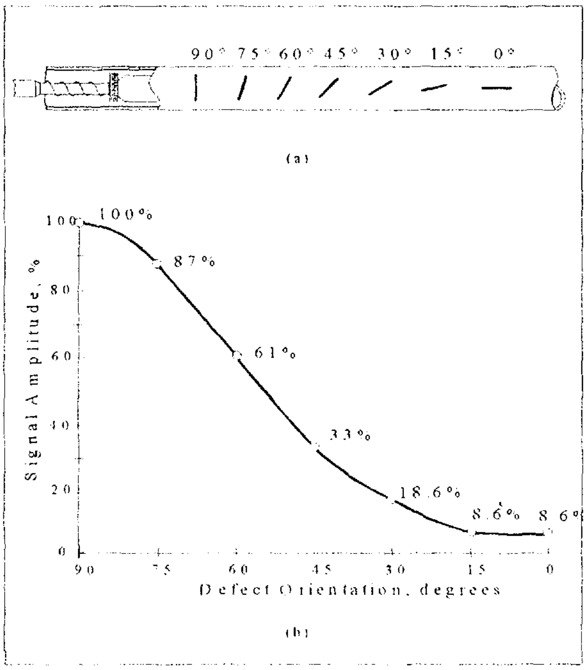

Figure 3. Plot of signal amplitude versus defect orientation for a differential C3 probe at 250 kHz from EDM notches 100% deep by 10 mm long in an Inconel 600 calibration tube.

2.4 Detectability of Surface and Sub-surface Defects

Figure 4 shows a plot of T/R and impedance probe responses to surface and sub-surface defects and lift-off. In conventional probes, using surface impedance coils, shallow surface defect signals follow trajectories nearly parallel to lift-off. In contrast, with T/R probes, there is a significant difference in the direction of the probe's voltage plane responses to defects and small lift-off variations. This characteristic is due to phase-lag effects in the magnetic field pattern in the periphery of the transmit coil, detected by the receive coil. Therefore, sensitivity to surface defects is significantly improved.

Figure 4 illustrates the increased detectability of sub-surface defects for the T/R probe compared with an impedance probe. A defect located 4 mm from the surface is still detectable with the T/R probe, while the response to the same defect is negligible with the impedance probe.

2.5 Inspection of Ferromagnetic Materials

Conventional eddy current methods can be used to detect cracks in ferromagnetic components, such as pipe welds, welds in support structures and turbine rotor bore surfaces, but crack sizing is limited to shallow cracks (<2 mm) [6]. T/R probes are extremely sensitive to crack-like defects that guide the magnetic field from the transmit coils to the receive coils [7]. That is, the eddy currents are forced to circulate around the crack, increasing the magnetic coupling between the transmit and receive coils, thereby increasing the voltage induced in the receive coils.

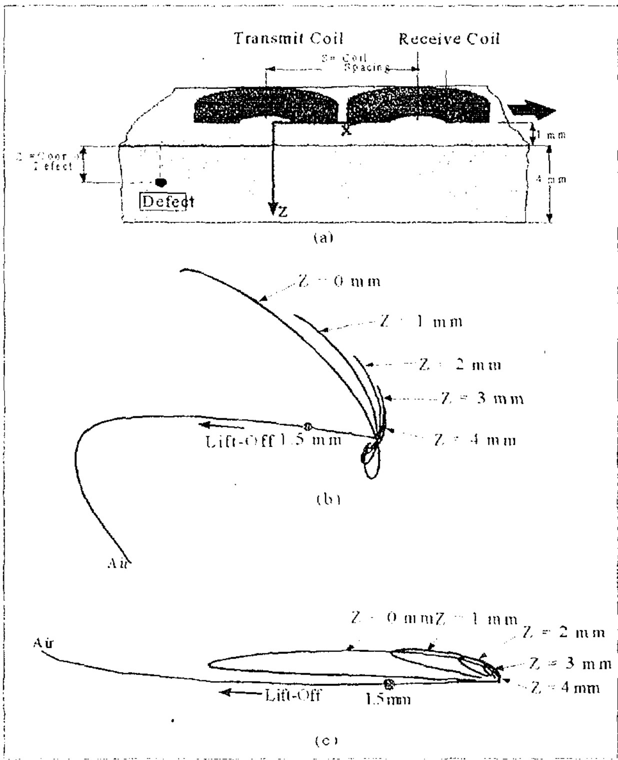

Figure 4. Signals from sub-surface defects in an aluminum plate with T/R (b) and impedance (c) at 500 Hz.

Since the magnetic field in the peripheral region of the transmit coil is quite uniform, even small distortions originating from the bottom of deep defects are detected. This permits sizing of surface defects that extend much deeper than one standard depth of penetration.

Unlike conventional eddy current probes, these probes are relatively insensitive to magnetic permeability variations.

3. APPLICATIONS

T/R eddy current probes increase the scope of eddy current inspection by maximizing defect signal, minimizing noise amplitude and discriminating between defect signals and noise. T/R eddy current probes have been used with advanced multichannel computer-aided instrumentation, such as the Zetec MIZ-18, MIZ-30 and R/D Tech TC-6700, to inspect components that could not be reliably inspected with other eddy current or NDT techniques.

3.1 Surface Inspection

3.1.1 PWR Pressure Vessel Inspection

Pressurized water reactor (PWR) pressure vessels are periodically inspected to ensure that they will not fail due to cracking. The inner surface of these vessels is covered with approximately 7 mm thick stainless-steel cladding, weld deposited on a carbon-steel base material. Thermal fatigue cracking at the welded interface between the cladding and the base material is a concern.

PWR vessels are normally inspected with ultrasonic testing (UT) equipment optimized for detecting sub-surface cracks. Eddy current testing (ET) probes, in tandem with UT, enable inspectors to detect surface-breaking flaws in the stainless-steel cladding of the reactor lining at the same time. ET scans are useful for detecting shallow surface cracks that might be missed with UT, and for checking whether UT indications correspond to surface-breaking cracks.

Conventional ET, which is based on balanced impedance coils, is unreliable for detecting surface cracks in materials with magnetic permeability variations, typically found in heat-affected zones of welded stainless steel. These significant variations in permeability may also be found in nominally non-magnetic cast stainless-steel components.

An eddy current probe with multiple T/R pairs, called multi-G3, has been developed at AECL to detect surface breaking cracks in the stainless-steel cladding of a reactor vessel. Because of the significant decrease in signal amplitude as a function of defect orientation angle, the probe designed for PWR reactor vessel inspection comprises several T/R coil pairs oriented at 45° with respect to one another to provide 360° coverage. With this design, the defect can pass the probe with an orientation angle of no more than 22.5° with respect to at least one of the coil pairs. At 22.5°, the defect signal amplitude is approximately 70% of the signal from an identical defect scanned at the optimal angle. If the defect passes a coil pair at close to this 22.5° "worst" angle, it will pass another coil pair at a similar angle. Therefore, by comparing the signals generated in adjacent coil pairs, a signal analyst can integrate this directional effect into the defect depth prediction.

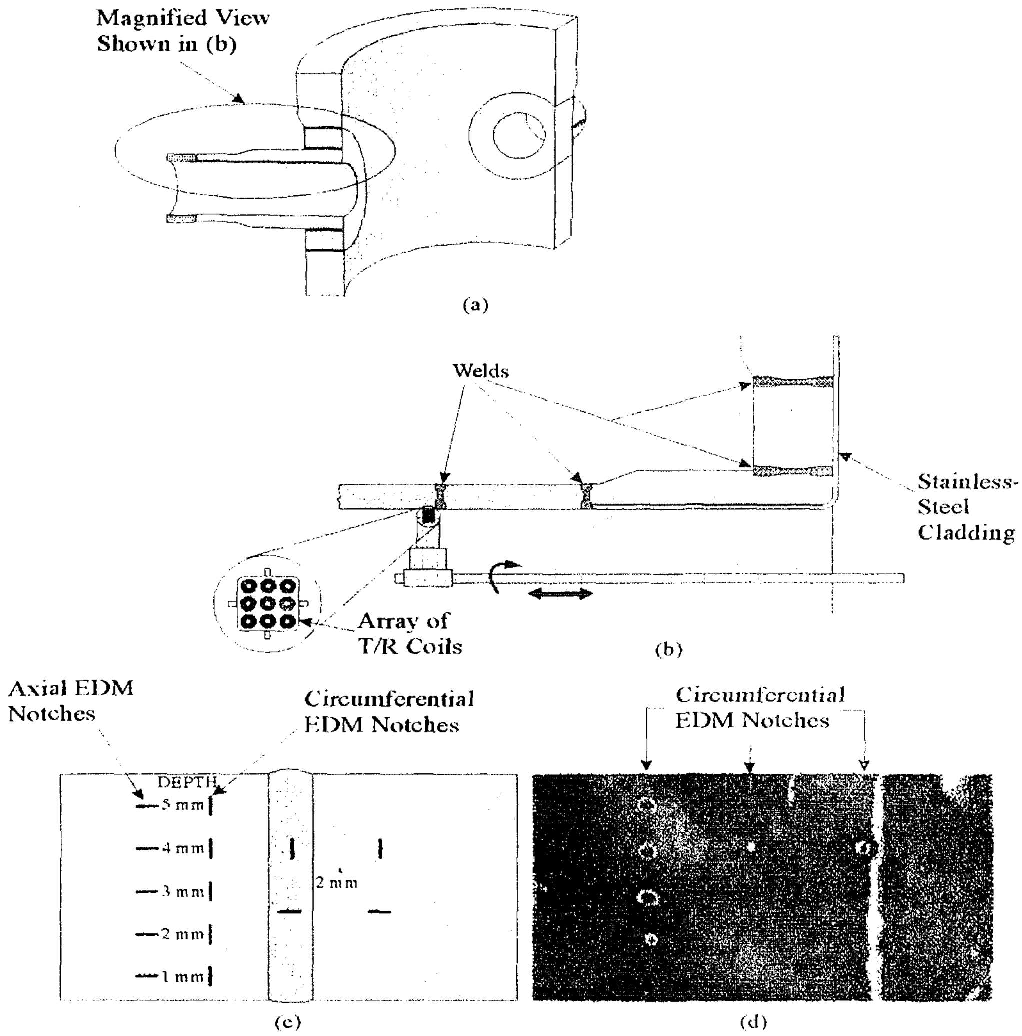

Figure 5. Eddy current detection of surface cracks in stainless-steel clad PWR pressure vessel.

Figures 5(a) and (b) illustrate the welded inspection areas, and a schematic of the array of T/R coils that comprise the probe. Figure 5(c) shows a calibration sample with circumferential and axial EDM notches. Figure 5(d) shows a C-scan display of the channel optimized for circumferential crack detection. Similar displays were produced by the other channels.

3.1.2 Inspection of Ferromagnetic Components

T/R probes denoted as G3 have been used to inspect steam drum nozzles, welds in nuclear reactor support structures, and turbine rotor bores [6] for surface-breaking cracks. They have also been used to inspect nuclear reactor vessel nozzle welds. Because of their insensitivity to lift-off and permeability variations, T/R probes can readily detect defects at welds. Figures 6(e) and (f) show undistorted signals from side-wall lack-of-fusion and fatigue cracks at welds. Defects deeper than 2 mm can be readily detected, and because signal amplitude is not significantly affected by the weld crown, depth can be estimated.

Another inspection application where the versatility of T/R probes was demonstrated was sizing of a manufacturing defect (cold shut?) on a 304 stainless steel valve casting. Ultrasonic testing was unreliable, because of the coarse grain structure in the casting. Large ferromagnetic variations in the material made conventional ET impossible. The defect signal was so large that lift-off and permeability noise were insignificant. Clear signals with a T/R ET probe indicated a 75 mm long and 6 to 7 mm deep (50% through-wall) defect.

3.2 Tube Inspection

3.2.1 Detection of Circumferential Cracks

Detection of circumferential cracks in steam generator (SG) and heat exchanger tubes continues to present a major challenge for NDT. Although UT can be used to detect such cracks, its inspection speed is very slow. ET requires specialized probes, and detection is often hampered by the presence of tube deformation, and conducting or ferromagnetic deposits.

Cracks in SG tubes can occur due to a variety of mechanisms, such as stress-corrosion cracking (SCC), fatigue cracks and intergranular attack (IGA). They can initiate from the tube ID or OD, and can be circumferential, axial or branching. They occur most frequently at tubesheet (TS) transition, support structures and U-bend regions.

A T/R eddy current probe, denoted as C3 [8,9], was developed to inspect 12.9 mm diameter, Inconel 600 SG tubes, that failed because of SCC at the U-bend transition. At this location the tubes presented internal and external deposits and were plastically deformed. The T/R probes were able to detect cracks where conventional eddy current probes had failed to detect any except those that had propagated completely through the tube wall.

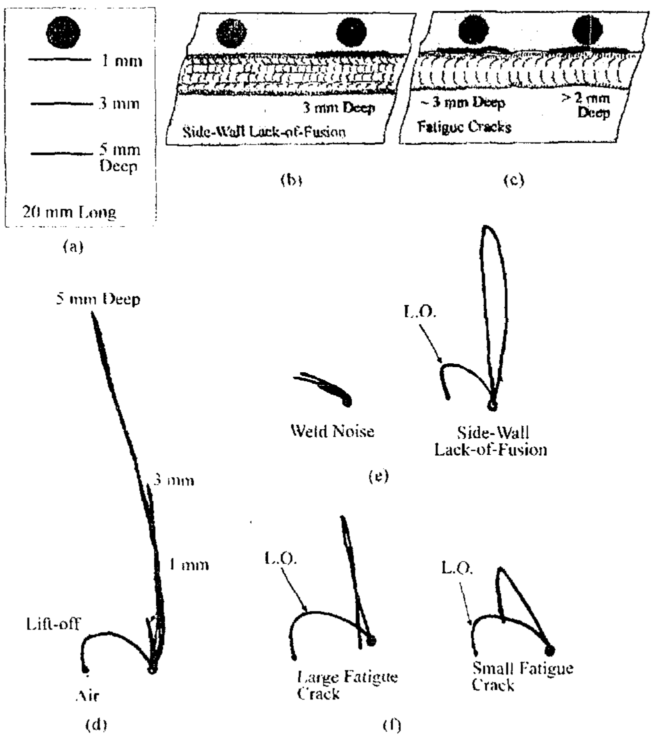

Figure 6. (a, b, c) Carbon-steel calibration and test samples.
(d) Calibration signals.
(e) Signals from side-wall lack -of-fusion and weld only.
(f) Signals from fatigue near welds.

The C3 probe is a differential multi-coil T/R probe. Figure 7 shows a C3 probe with eight sets of T/R coil units. It operates at several frequencies simultaneously. Unlike rotating pancake probes, the C3 has no moving parts, permitting single-pass inspections as fast as standard bobbin-type probes. The eight T/R units are contained in two separate bodies. Each probe body is encased in a metallic sleeve, with centering guides. The probe bodies are physically separated by a section of flexible cable, because a single solid body would be too long to go around tight U-bends. This is a robust design, but it is still flexible enough to easily negotiate U-bends as small as a 150 mm radius.

The field data shown in Figure 8 illustrates C3 probe signals from a tube with circumferential SCC at a test frequency of 250 kHz. The vertical component corresponds to probe response to the crack, while the horizontal component represents the distortion due to tube eccentric deformation.

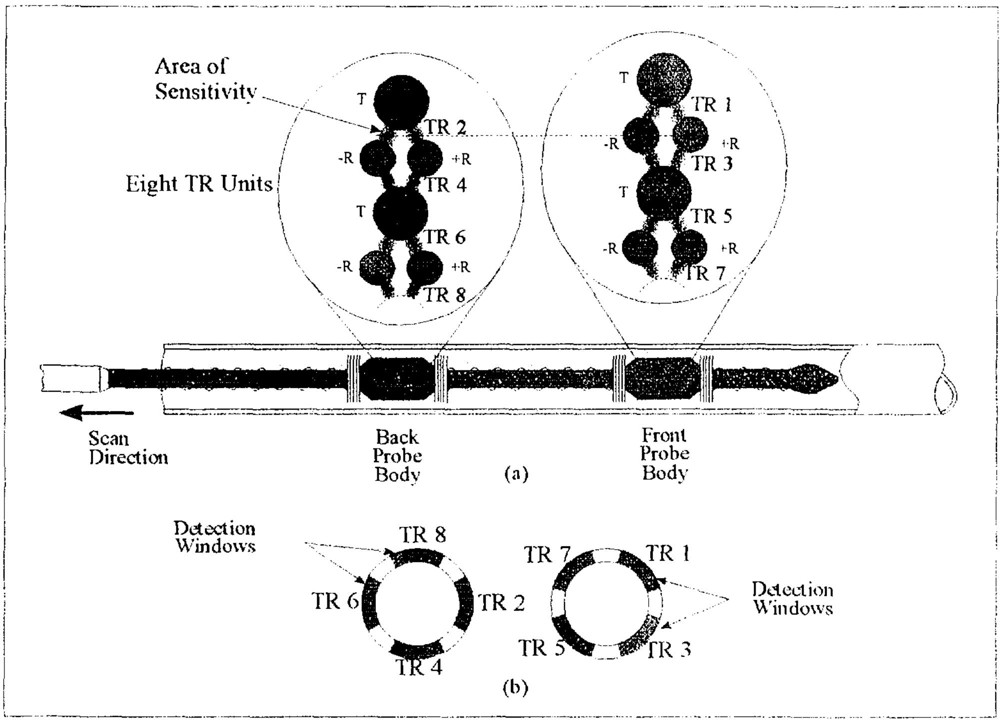

Figure 7. C3 probe showing T/R coil configuration and detection windows.

Signal-to-noise at this eccentrically deformed tube section is excellent. Figure 8b and c show plots of probe response (vertical component) from each T/R unit in sequence versus circumferential location. These plots were used to predict crack extent. The comparison of predicted crack profiles with destructive examination results shows a very good correlation.

Since the first field trial in 1992, which demonstrated that the probe is effective in detecting and sizing SCC as shallow as 40% deep, it has been used routinely for in-service inspection of nuclear steam generators.

More recently, inspection companies in the United States, Europe and Japan have expressed interest in T/R array probes. One example was the use of the C3 probe to inspect 22.2 mm diameter Inconel 600 tubes in PWR steam generators for internal SCC in the U-bend region. The probe, first evaluated in short U-bend samples with laboratory-induced SCC, was able to detect cracks as shallow as 25% deep; field evaluation showed that the single-pass C3 probe had a defect detectability that was as good as or better than rotating pancake coil (RPC) probes.

3.2.2 Probes with Equal Sensitivity to Axial and Circumferential Cracks

A growing area of interest has been the detection of both circumferential and axial cracks at the tubesheet transition region in nuclear steam generators.

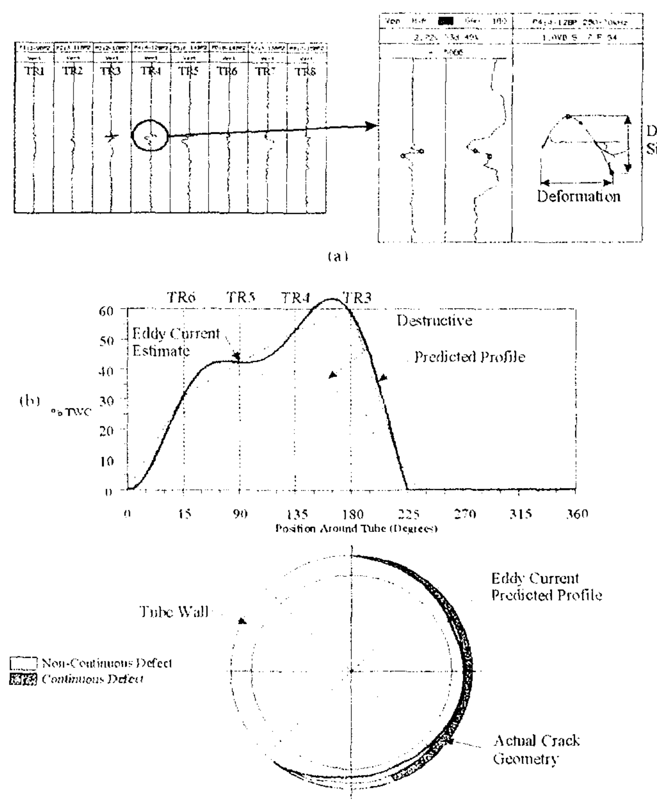

Figure 8. (a) C3 response to a circumferential OD stress corrosion crack at the U-bend.
(b, c)Comparison between the actual crack geometry

and the eddy current predicted profile.

Computer modelling studies were conducted to design a probe with equal sensitivity to both circumferential and axial cracks. This probe, denoted as C5, has sensitivity to all modes of failure and it can be used for rapid single pass inspection of tubing. The probe consists of three bodies: the front and middle bodies contain 12 to 24 T/R units, and the back body contains conventional bobbin coils. Figure 9(b) shows typical computer-predicted responses to volumetric defects, circumferential cracks and axial cracks. Figures 9(c) and (d) show C5 probe coverage to circumferential and axial cracks.

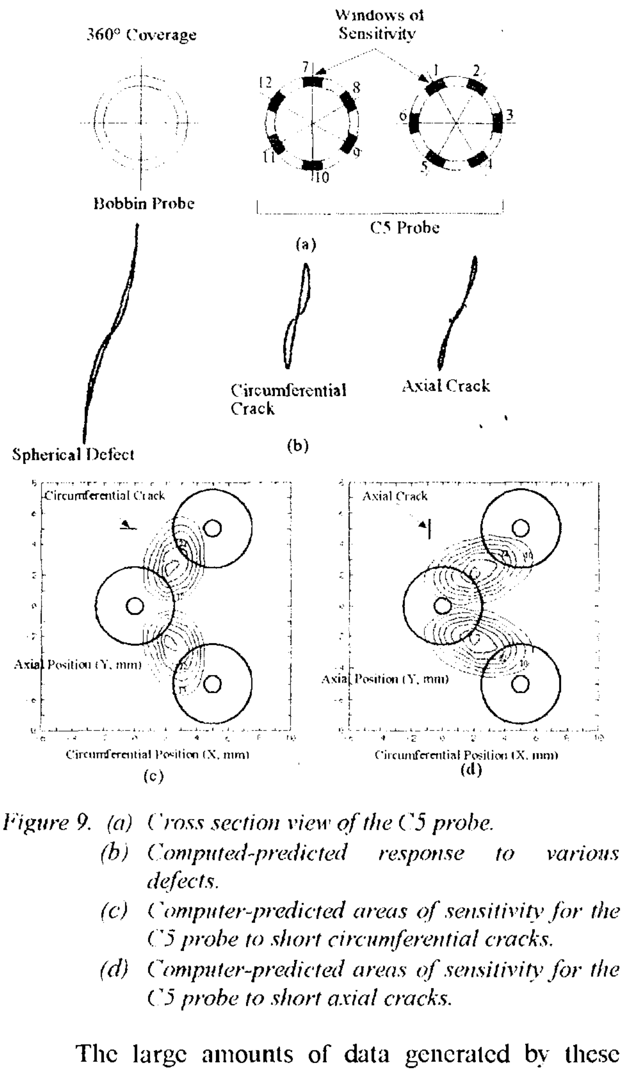

Figure 9. (a) Cross section view of the C5 probe.
(b) Computed-predicted response to various defects.
(c) Computer-predicted areas of sensitivity for the C5 probe to short circumferential cracks.
(d) Computer-predicted areas of sensitivity for the C5 probe to short axial cracks.

The large amounts of data generated by these probes can be dealt with efficiently by presenting the data in C-scan display format. Figure 10 shows a C-scan display of C5 probe data from a Copper-Nickel tube with internal pitting. It illustrates one of the advantages of using T/R array probes over standard bobbin probes. The C5 probe can detect and size each individual pit while a bobbin probe only generates one signal integrating the eddy current response from the entire circumference. Thus an array probe, with the aid of C-scan display of data, gives the analyst an intuitive tool to visualize tube artifacts.

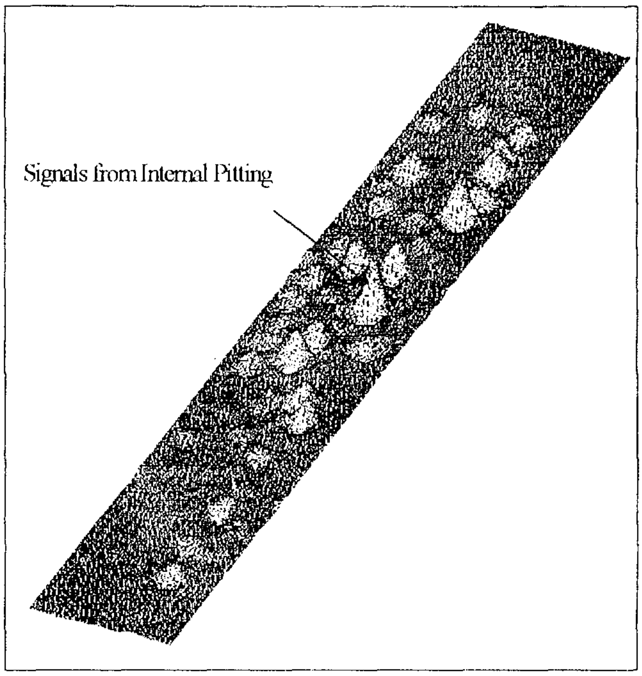

Figure 10. C-scan display of C5 data from a Copper-Nickel tube with internal pitting.

4. SUMMARY/CONCLUSIONS

T/R probes with laterally displaced coils can be used to detect cracks in ferromagnetic and non-ferromagnetic components. They increase the scope of eddy current testing by maximizing defect signals and minimizing "noise" effects from lift-off, electrical conductivity and magnetic permeability variations.

T/R probe directional properties enhance their detectability of defects with a preferential direction (cracks). By adjusting coil orientation and/or using multi-coil arrangements, they can be adapted to solve each kind of inspection problem.

The relative "insensitivity" of T/R probes to global effects, such as lift-off or permeability variations, improve the signal-to-noise ratio. They are more suitable than impedance probes for inspecting components with geometric distortions.

Computer modelling can be used to calculate T/R eddy currents and magnetic fields, as well as probe/sample response. The capability for performing such mathematical simulations significantly increases confidence in this new technology.

These probes are fully compatible with commercially available eddy current instruments.

5. ACKNOWLEDGMENTS

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