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APPLYING COMPUTER MODELING TO EDDY CURRENT SIGNAL ANALYSIS FOR STEAM GENERATOR AND HEAT EXCHANGER TUBE INSPECTIONS

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INTRODUCTION

Licensing requirements for eddy current inspections for nuclear steam generators and heat exchangers are becoming increasingly stringent. The traditional industry-standard method of comparing inspection signals with flaw signals from simple in-line calibration standards is proving to be inadequate. A more complete understanding of eddy current and magnetic field interactions with flaws and other anomalies is required for the industry to perform consistently reliable inspections. Computer modeling is a valuable tool that is continually improving the reliability of eddy current signal analysis. Results from computer modeling are helping inspectors to properly discriminate between real flaw signals and false calls, and improving reliability in flaw sizing.

The traditional method of performing eddy current testing (ET) of steam generator and heat exchanger tubes is to compare eddy current signals from inspected tubes with those from calibration tubes. These calibration tubes have manufactured or simulated flaws in them. Many times these flaws are designed based on certain codes or standards such as those from the American Society of Mechanical Engineers (ASME) or the Canadian Standards Association (CSA). Flaw characterization and sizing is based on direct comparison of the signals from inspected tubes with these calibration flaws.

In recent years efforts have been made to validate inspections by comparing eddy current predictions with laboratory measurements of tubes removed from in-service steam generators, and highly accurate ultrasonic measurements of volumetric flaws. In some cases the comparisons between ET results and those from other more accurate flaw characterization methods have been generally poor. In these cases computer modeling has been used to establish reasons for the inaccuracies in flaw characterizations by ET. One cause of inaccuracies was that the calibration tube flaws did not realistically represent the actual in-service tube flaws being characterized.

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This paper discusses examples demonstrating how some significant eddy current signal analysis problems have been resolved using appropriate electromagnetic computer modeling tools.

DEPTH SIZING OF FRETTING WEAR FLAWS

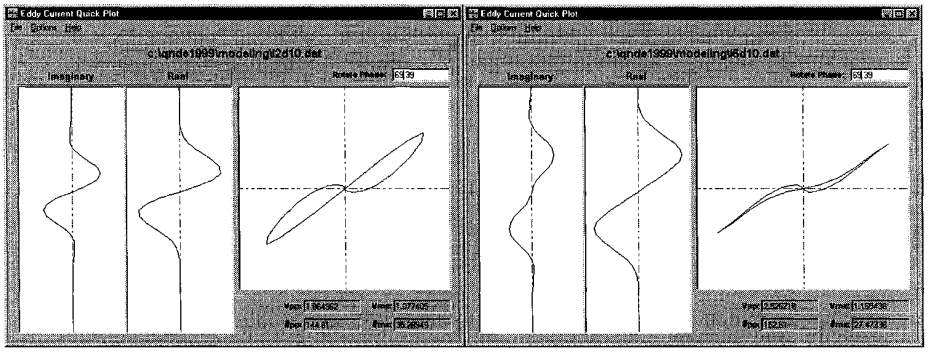
In the nuclear industry, eddy current inspection has been used to monitor growth of fretting wear flaws in steam generator tubes. These flaws are generated when the tubes rub against the support plates that hold the tubes in position.

ET is used to depth size these flaws. The traditional method of sizing these flaws with ET is to compare eddy current signal phase angles from inspected tubes with those from calibration tubes. However, these calibration flaws tend to be shorter in axial extent of the tube than real fretting wear flaws.

Figure 1 shows eddy current signals from a bobbin eddy current probe scanning a steam generator tube with 10% deep OD flaws that are 2 mm long and 6 mm long. These signals were calculated by using the Layer Approximation [1]. The comparison between these signals shows an 8° difference in measured phase angles of the two signals even though the flaws are of equivalent depth.

Fretting wear flaws were detected and sized in CANDU® nuclear reactor steam generators and preheaters with eddy current probes. Flaws with larger signals were sized using an industry standard method of comparing signals phase angles with those from flaws in a CSA standard calibration tube. A more accurate (but much slower) ultrasonic testing (UT) method was deployed to depth size some of these flaws to evaluate the accuracy of the eddy current method. Results from this comparison showed that the industry standard eddy current method was significantly undersizing many of these flaws.

The reason for the discrepancy in the sizing methods was that the real flaws tended to be longer with a more tapered shape than the calibration flaws which were used to depth



(a) (b)

Figure 1. Computer modeled eddy current signals from a bobbin coil probe scanning a steam generator tube with short and long flaws in it. The tube is 13 mm OD Inconel 600 (σ = 1 MSieman/m) with wall thickness of 1.1 mm. Operating frequency = 480 kHz. (a) Probe response to a 10% deep 2 mm long OD flaw. (b) Probe response to a 10% deep 6 mm long OD flaw.

size the real fretting wear flaws. More realistic calibration signals were needed for the eddy current probes to accurately size these in-service flaws.

The circumstances on this particular occasion did not allow for enough time to design, manufacture and scan a new calibration tube. Therefore a new calibration curve was quickly established with computer modeling using the Layer Approximation [1] to calculate probe responses to flaws with more realistic shapes. Eddy current flaw signals were re-sized using the new calibration curve and compared with UT flaw sizes in order to validate the new curve. Figure 2 is a plot of eddy current signal phase as a function of flaw depth. The points on the plot are the data from real flaws comparing the eddy current signal phase with depth measured by UT. Superimposed on this plot are the industry standard calibration curve, and the new calibration curve that was established by computer modeling.

Figure 3 is a sizing accuracy plot of eddy current measured flaw depth versus UT measured depth. Eddy current depth measurements made by using the industry standard phase calibration curve, and with the new curve that was established with computer modeling. This plot shows that the industry standard method generally undersizes these flaw whereas the flaw depths obtained by using the calibration curve derived by computer modeling tends to size these flaws more accurately.

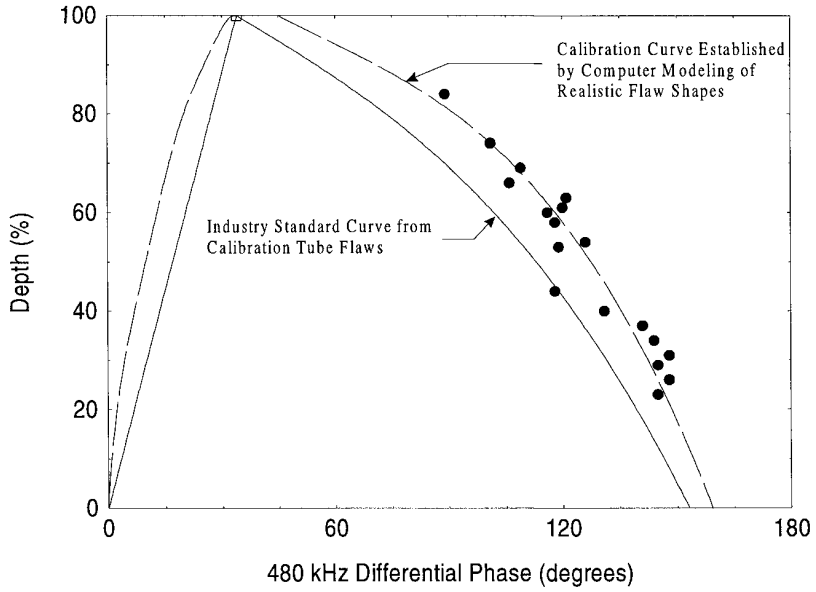


Figure 2. Industry standard and computer modeled calibration curves plotted along with ultrasonic estimated depths of scallop bar frets (●) and calibration tube defect depths as a function of 480 kHz differential phase.

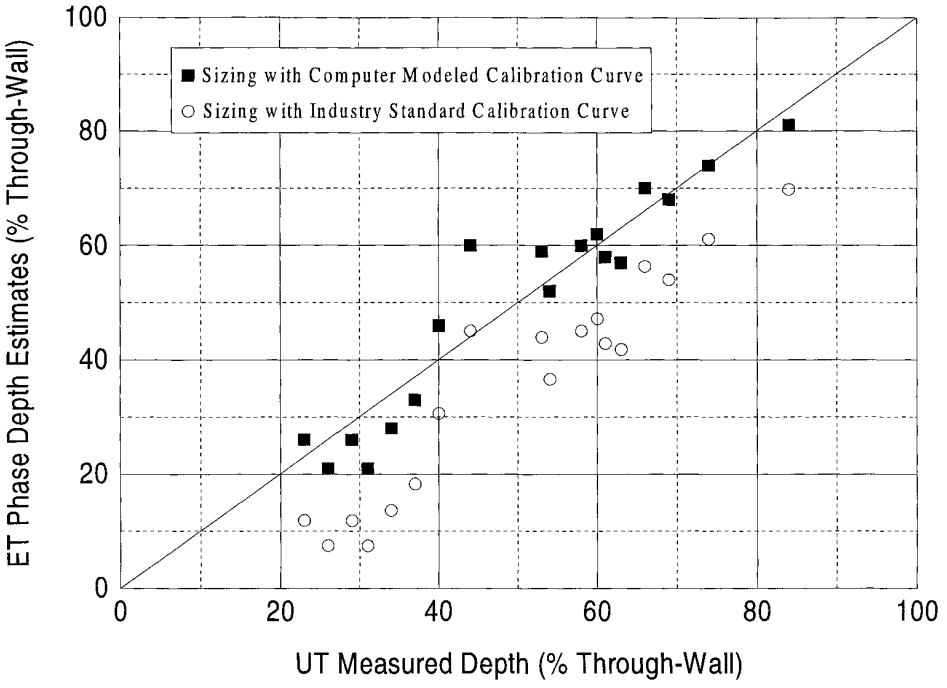


Figure 3. Plot of percentage depth of scallop bar frets determined from calibration curves established by computer modeling of realistically shaped flaws (■) and the industry standard calibration curve (O).

SIZING OF ID MANUFACTURING FLAWS IN FERROMAGNETIC TUBES

Several years ago, an eddy current inspection of a steam generator with mildly ferromagnetic Monel 400 tubes revealed the presence of inside diameter (ID) flaws that appeared to be very deep, many of which were sized as 100% through-wall depth. With so many flaws sized to be so deep, the steam generator should have been leaking water through these flaws, but no leaks were observed. To keep a steam generator in operating condition, tubes with deep flaws are required to be plugged. However, with so many flaws that were detected, the number of plugs required would have severely limited the life of the unit. Therefore an explanation was required that needed to identify where these eddy current signals came from.

Depth sizing of these flaws was based on the phase angle of the flaw signal. A typical calibration curve is shown in Figure 4.

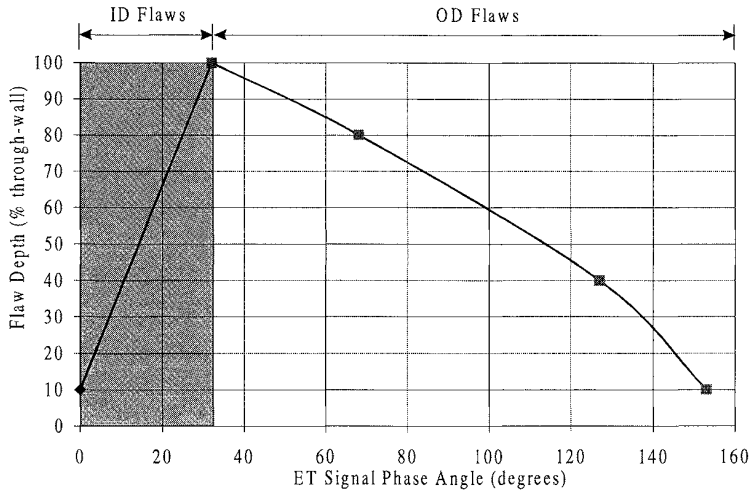


Figure 4. Typical flaw depth sizing calibration curve based on eddy current signal phase (Monel 400 steam generator tubes at 160 kHz frequency). Signals with phase angles between 0 and 32 degrees (shaded region) are from ID flaws. Signals with phase angles greater than 32 degrees are from OD flaws.

Because the tube material was ferromagnetic, magnetic saturation probes were required to perform reliable eddy current tests. The most basic magnetic saturation probe is composed of the eddy current coil windings wrapped around a cylindrical center magnet. The magnetic field from the center magnet saturates the ferromagnetic tube so that the tube material interacts with the electromagnetic fields from the eddy current coils as a nonferromagnetic material. In order to provide structural strength and mechanical wear resistance, the coils and the magnet were encased in a thin titanium sleeve. This sleeve was thin enough so that the electromagnetic fields from the coils could penetrate through the sleeve and into the tube that was being inspected.

Laboratory tests and computer modeling were performed that showed that when the probe's centering guides wore out, the probe offset significantly affected the phase angles of flaw signals. The Burrows model [2] of eddy current interaction with a flaw was used with the equations derived by Dodd, Cheng and Deeds [3, 4] as basis functions. In the model, the tube radius parameters were changed to vary the distance from the probe coils to the flawed section of the tube. This is how probe offset toward and away from the flaw was simulated.

Figure 5 shows calculated signals for differential impedance bobbin coil probes. One probe in the figure has no center magnet or titanium shield because it was designed for inspecting nonferromagnetic tubing. The other probe has the center magnet and titanium sleeve. The signals from the first probe exhibit a small amount of variation in signal phase, 14°, due to the probe offset. This explains why eddy current inspections of nonferromagnetic tubes do not suffer badly due to signal phase variations due to probe offset. However, the probe with the center magnet and external titanium shield exhibits a large amount of variation in signal phase, 35°, due to probe offset. This amount of variation is larger than the full phase range for sizing ID flaws (0° to 32° as shown in Figure 4). The reason for the significant signal phase variation from the magnetic saturating probe is that the eddy currents in the center magnet (which is also an electrical

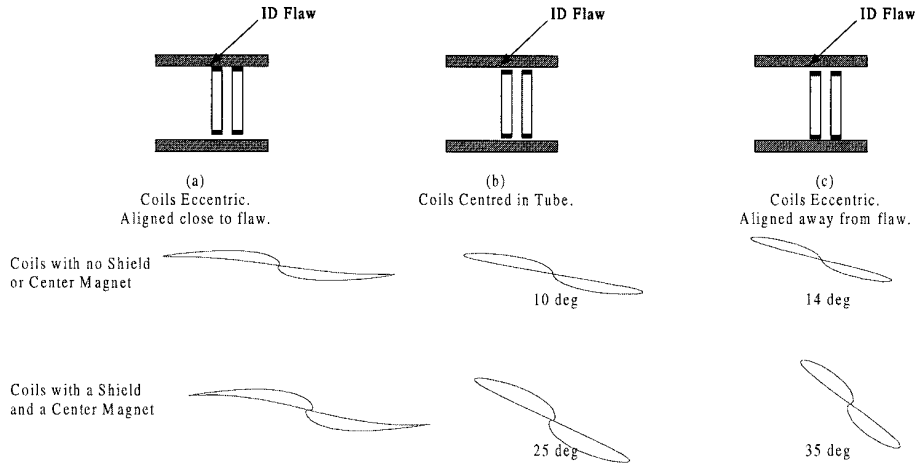


Figure 5. Calculated signals from differential bobbin coil eddy current probes detecting a small flaw on the ID surface of the tube with probe coils offset toward the flaw, in the center of the tube and offset away from the flaw. One set of signals was calculated from coils with no center magnet or external shield. Another set of signals was calculated for coils with a center magnet and an external titanium shield on the probe.

conductor) and the titanium shield alter that phase angle of the magnetic fields from the eddy current coils so that the flaw signal changes phase with varying distance between the probe and the tube section with the flaw.

This computer model was also used to simulate a differential transmit receive (with active primary and passive secondary coil windings) eddy current probe. Using the computer model to determine the optimum distance between the transmit and receive coils, a design was established that exhibited very little signal phase angle variation due to offset distance from the flaw in the tube. Results of these calculations are shown in Figure 6.

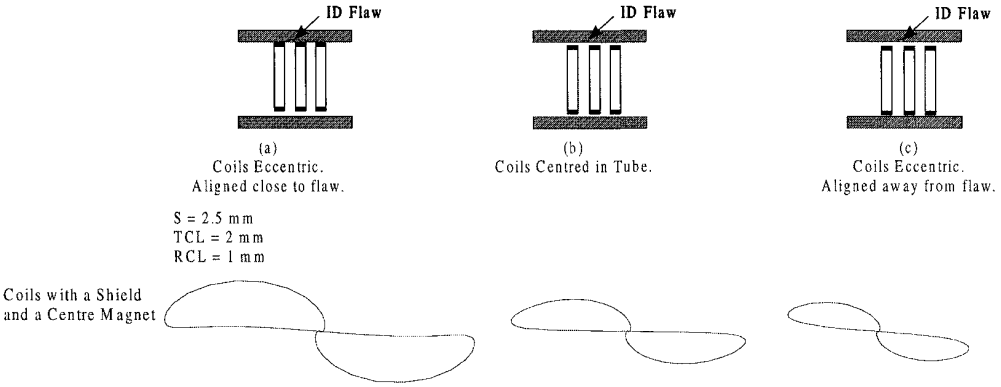
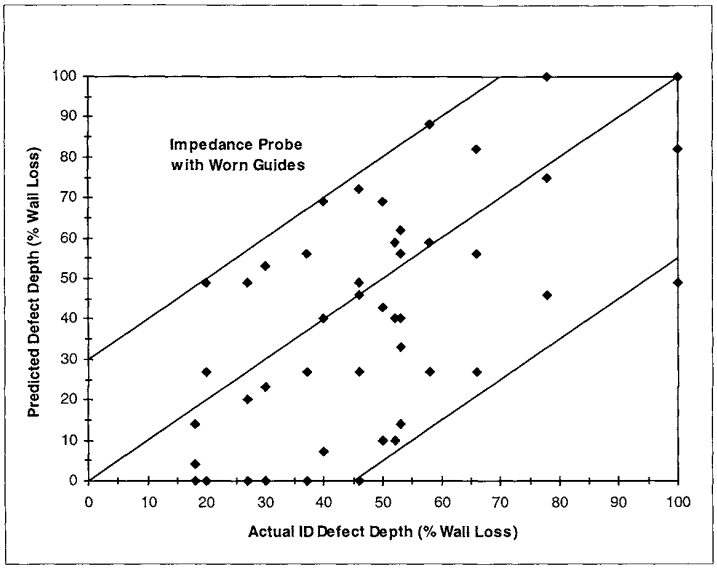
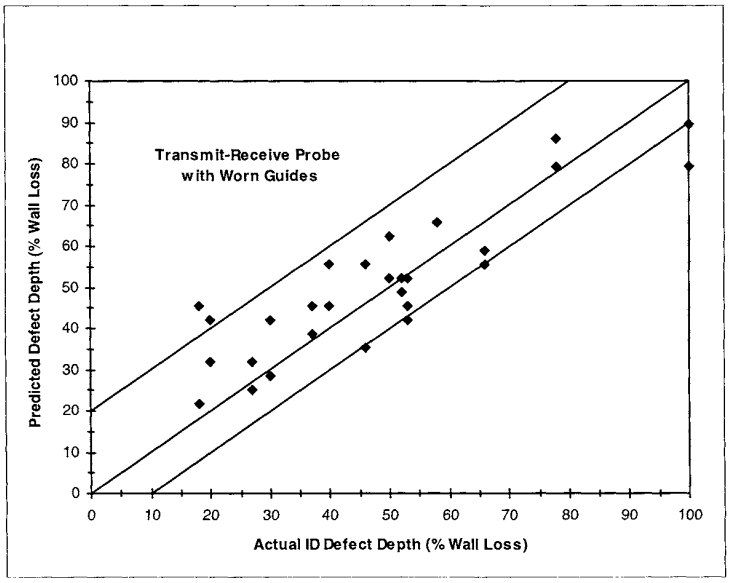


Figure 6. Computer modeled signal of a differential transmit-receive eddy current bobbin probe scanning a steam generator tube with a shallow ID surface flaw. The probe coils have a center magnet and an external titanium shield.



(a)



(b)

Figure 7. Plot of laboratory eddy current results using predicted ID defect depth versus actual ID defect depth at 160 kHz for: (a) the differential bobbin impedance probe with center magnet and titanium sleeve having worn out guides producing a combination of signals for centered, minimum, and maximum probe off-sets, and (b) the differential bobbin transmit-receive probe using the same centered, minimum, and maximum probe off-sets.

Having used the computer model to design such a probe, a prototype was manufactured and laboratory tested. A magnetic saturating differential impedance bobbin probe and the new transmit-receive probe had the centering guides removed which allowed them to be offset significantly from the center of the inspected tubes. Various tubes with ID pitted flaws of various depths were scanned with the probes. Sizing of the flaws was performed both from the eddy current signal phase, and by molding the internal flaws. Sizing accuracy results are illustrated in Figure 7 above.

These plots show that the transmit-receive probe exhibited far better accuracy in sizing these ID flaws than the impedance probe.

Many of the tubes with the ID signals that were originally sized as being deep were re-scanned. The ET signals that were considered to be from deep flaws were found to be non-repeatable. Since these effects were discovered improved probe centering guides and a probe acceptance criterion based on calibration tube scans have been implemented. With probe centering carefully monitored, no flaw signal has been detected that could be sized as being deep.

SUMMARY AND CONCLUSIONS

To properly depth size volumetric flaws, Eddy Current Probes signals should be compared with more realistic flaw geometries than those used in Industry-standard calibration standards. Computer modeling is a useful tool in providing realistic flaw signals with which eddy current probes can be calibrated.

Eccentricity of magnetic saturating eddy current probes due to probe guide wear can influence phase sizing.

When using Impedance Magnetic Saturating Probes, Probe centering should be carefully monitored when using signal phase to size flaw signals.

Laboratory tests have validated a computer modeling based design of a transmit-receive magnetic saturating probe that exhibits much less signal variations due to probe eccentricity in a heat exchanger or steam generator tube.

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