THEORETICAL AND EXPERIMENTAL STUDIES OF THE REMOTE FIELD EDDY CURRENT EFFECT

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INTRODUCTION

Conventional eddy current (EC) nondestructive testing methods, based on the principle of electromagnetic induction have been used over the years for defect detection. A low frequency alternating current is fed to the excitation coil which induces eddy currents in the material. These eddy currents generate a magnetic field, inducing a secondary voltage in the sensor coil. The change in the impedance of the sensor coil is used to indicate the presence of material inhomogeneities (Figure 1). Figure 2 shows a conventional eddy current probe and a remote field eddy current (RFEC) probe. The difference between the two is that in the conventional EC probe the exciter and the sensor are the same coil, normally operating between 1KHz and 10 MHz, while in the RFEC probe the exciter and the sensor coils are several pipe diameters apart with a frequency of operation from 40 to 160 Hz. The RFEC probe does not measure the change in the impedance of the sensor coil, rather the steady state A.C phase angle difference between the exciter and the sensor is monitored (Figure 3). Skin effect characteristics limit the eddy currents to the surface of the material, restricting the conventional EC testing methods to the detection of near surface inhomogeneities. The RFEC probe in contrast overcomes the above limitation due to its apparent sensitivity to both inner and outer diameter (ID and OD) defects [1]. Recently numerical models have been developed to develop a better understanding of the physics of the phenomenon [2-8].

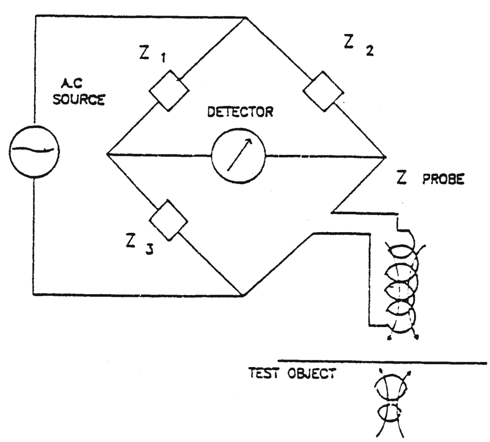

Fig 1. Conventional eddy current NDT test setup measuring the probe impedance.

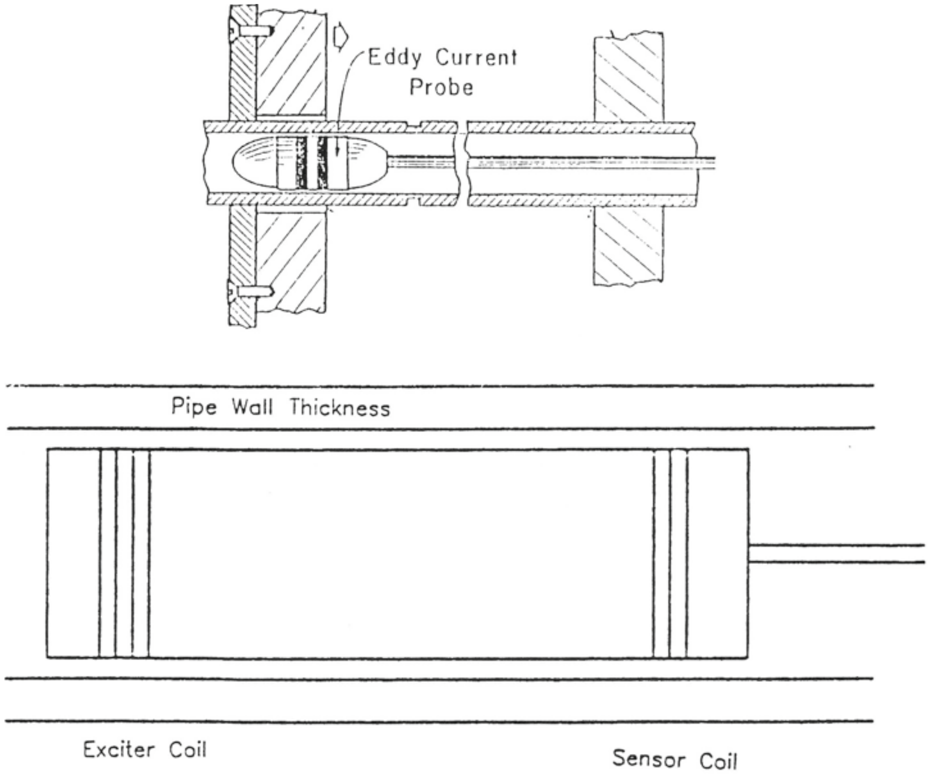

Fig 2. **Conventional EC and RFEC probe.**

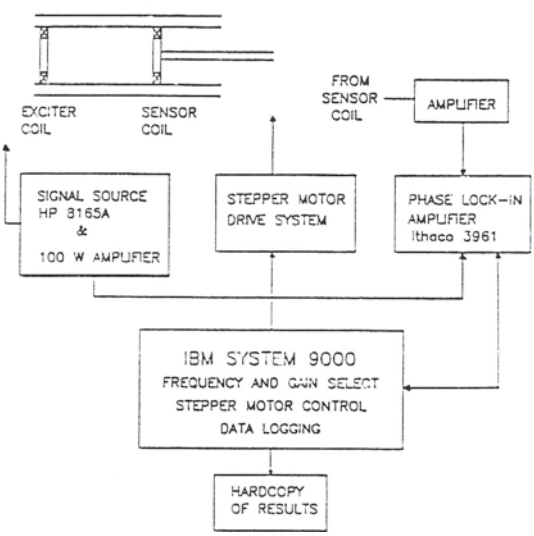

Fig 3. Experimental test rig block diagram to monitor the steady state AC phase angle difference between the exciter and sensor coils of a RFEC probe.

FINITE ELEMENT MODEL

The quasi-static form of Maxwell's equations describe the electromagnetic induction phenomenon characteristics of both the conventional EC and the RFEC effect. Because of the negligible displacement current term, the quasi-static equations reduce to

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \bar{A} \right) = J_s - j\omega\sigma\bar{A} \qquad (1)$$

where $\bar{A}$ is the magnetic vector potential, J_s is the source current density, ω is the angular frequency, σ is the electrical conductivity, μ is the magnetic permeability.

Finite element (FE) techniques have been successfully applied to model E.C phenomena for different geometries [9-11]. An axisymmetric finite element model has been developed to study the basic RFEC phenomenon [3]. This model has been further extended to study the effect of parameter variations on the RFEC phenomenon. Information on the details of the model and the basic physics of the phenomenon is available in references [2-4]. Space limitations preclude additional information in this paper.

FINITE ELEMENT PREDICTIONS

Figure 4a) compares the experimental finite element prediction for the RFEC probe magnitude and phase without a defect and Figure 4b) shows the phase characteristics for an axisymmetric defect at 40 Hz. The results confirm the validity of the FE approach.

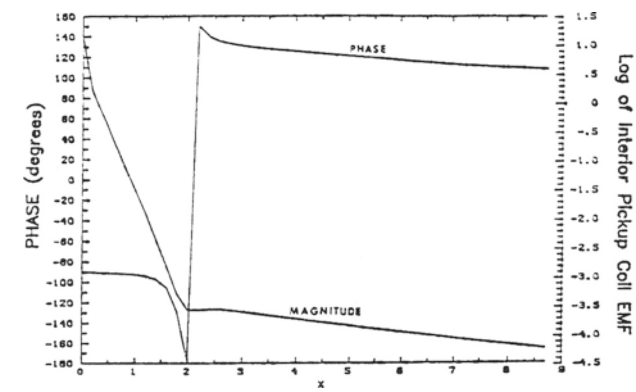

Fig 4a. Experimental and FE predictions for the RFEC probe magnitude and phase without a defect at 40 Hz.

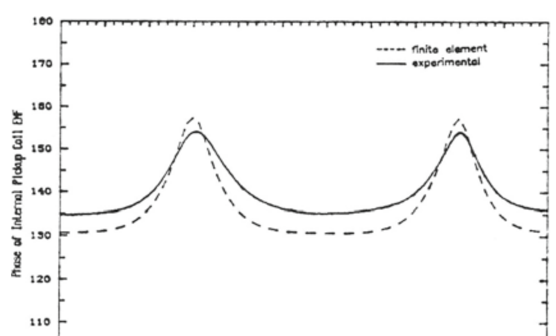

Fig 4b. Experimental and FE prediction for the RFEC probe phase characteristics with defect at 40 Hz.

The parameter variation studies include frequency characteristics, pipe wall thickness, pipe inner diameter, and coil width and depth variations. There is also a comparison of the flux plots from an ID and OD defect.

Figures 5 to 10 illustrates the phase and magnitude prediction for the RFEC probe. It is obvious that the probe is sensitive to higher frequencies, magnitude attenuation is higher with increasing pipe wall thickness and pipe inner diameter. The exciter coil dimension variations indicate a negligible change in the RFEC characteristics. Figures 11 and 12 show the instantaneous flux contours and phase characteristics for an ID and an OD defect. The plots confirm that the probe is sensitive to both ID and OD defects.

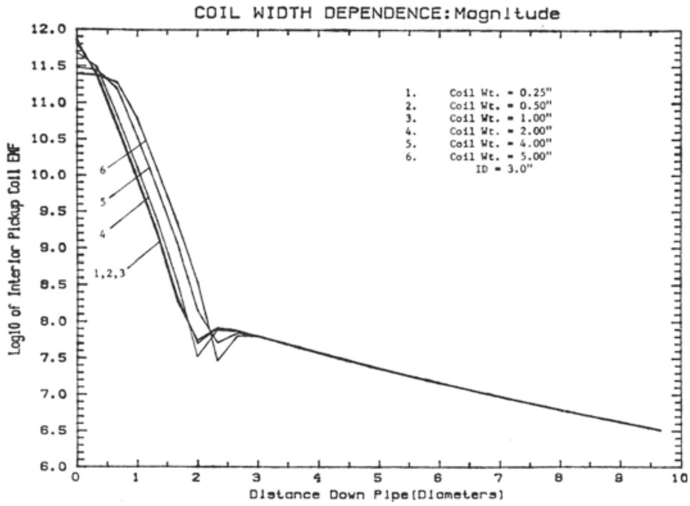

Fig 5 FE prediction of probe magnitude characteristics for exciter coil width variations.

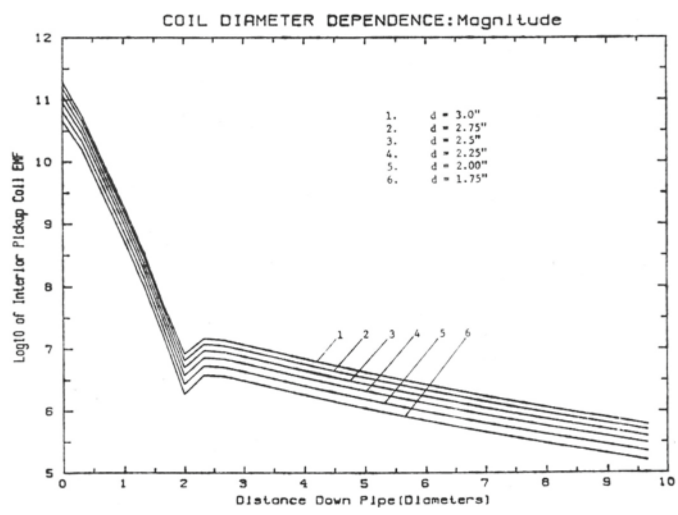

Fig 6 FE prediction of probe magnitude characteristics for exciter coil diameter variations.

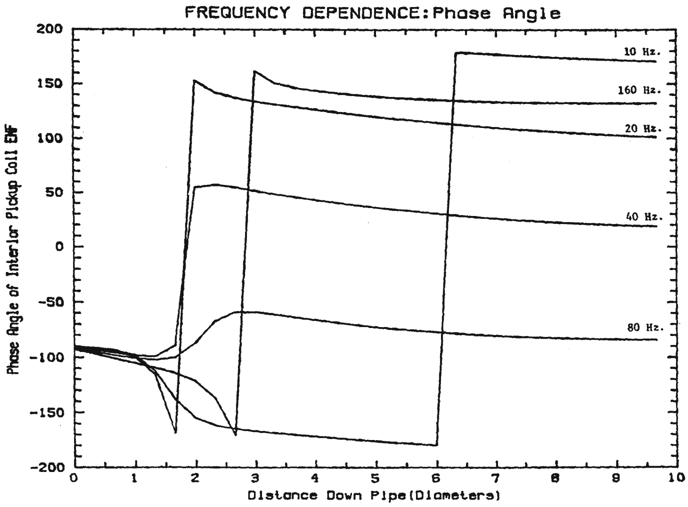

Fig 7 FE prediction of probe phase characteristics for various excitation frequencies.

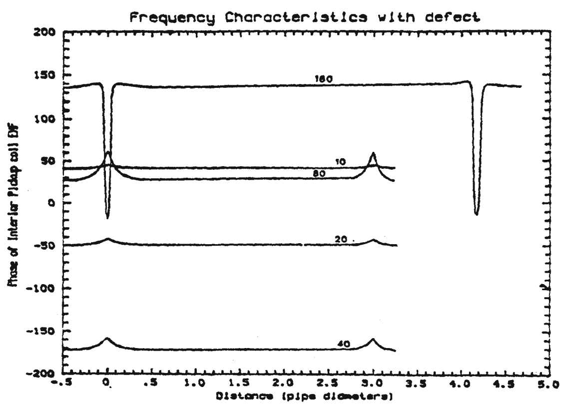

Fig 8. FE prediction of phase characteristics for various excitation frequencies with a defect at 40 Hz.

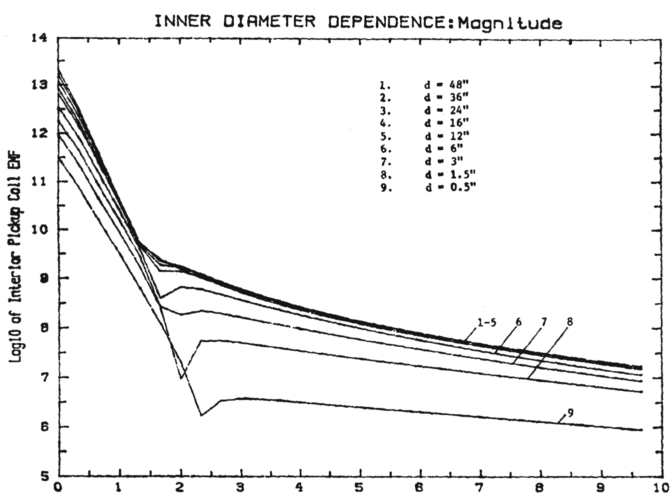

Fig 9 FE prediction of probe magnitude characteristics for pipe inner diameter variations.

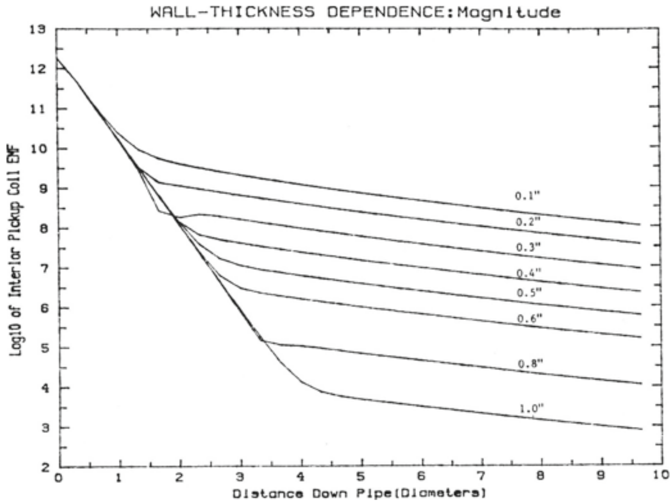

Fig 10 FE prediction of probe magnitude characteristics for various pipe wall thickness.

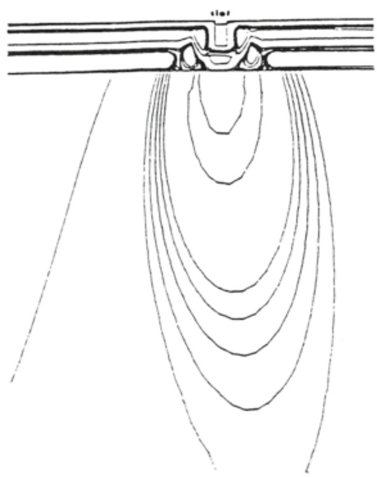

Fig 11a. FE prediction of instantaneous flux contours for a ID defect.

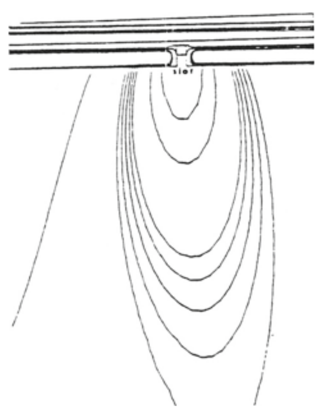

Fig 11b. FE prediction of instantaneous flux contours for a OD defect.

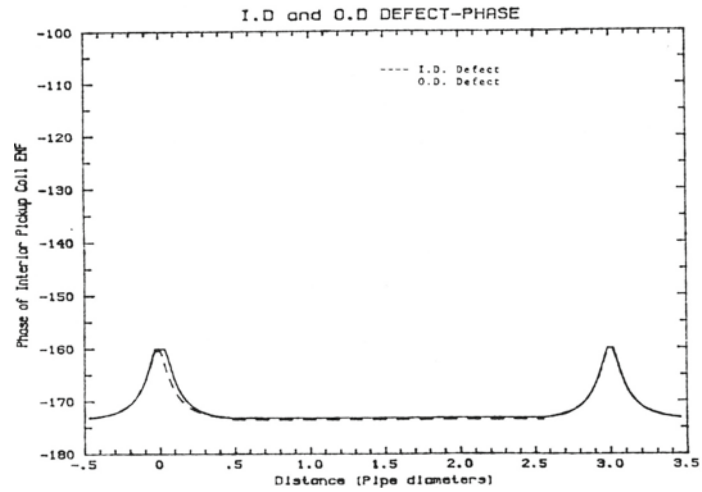

Fig 12. FE prediction of phase characteristics for a ID and OD defect at 40 Hz.

Differential eddy current probes have been used extensively to test steam generator tubing in a number of industries [11,12] and it has been shown that the corresponding impedance plane trajectories can characterize defects. A similar approach has been used to plot the RFEC probe characteristics [13]. A single sensor coil conventional RFEC probe was used to simulate a differential signal. The differential signal y(n) can be synthesized from the absolute RFEC signal x(n) using the relation y(n) = x(n)-x(n-N). The distance between the differential sensor coils d is given by d = Nd', where N is an integer number and d' is the incremental distance moved by the probe. If the real and imaginary component of the sensor coil induced voltage are plotted in the complex plane, a closed trajectory is obtained, analogous to the conventional EC complex impedance plane trajectory (Figure 13).

CONCLUSIONS

The RFEC probe characteristics is governed by the quasi-static form of the Maxwell's equations and so can be modeled by conventional eddy current finite element code thus confirming that the RFEC phenomenon is a diffusion process strictly governed by the parabolic diffusion equation. The parameter variations studied show the capability of the finite element code to help in understanding the physics of the phenomenon, and also serve as a useful tool for probe design. This study also confirms the RFEC probe sensitivity to both inner and outer diameter pipe wall defects. Defect characterization using the RFEC trajectories scheme is a novel and useful technique. Furthermore, the finite element code can be easily extended to larger pipe diameters.

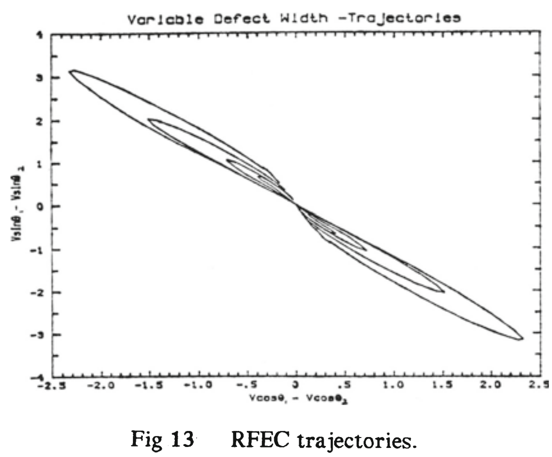

Fig 13 RFEC trajectories.

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