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Multivariate Regression Algorithm for ID Pit Sizing

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Abstract

This paper presents status of an EPRI program to enhance and improve the reliability of ID pit sizing for balance-of plant heat exchangers, such as condensers and component cooling water heat exchangers found in a nuclear power plant. More traditional approaches to ID pit sizing involve the use of frequency-specific amplitude or phase angle analysis techniques. The multivariate regression algorithm for ID pit depth sizing incorporates simultaneous input parameters of frequency, amplitude, and phase angle.

Summarized results of nondestructive evaluation (NDE) involving enhanced pit sizing from inside diameter (ID) of condenser tubing made of Type 304 stainless steel are presented. The latest analysis approach relied on both phase angle and amplitude information from multiple operating frequencies to better depth size ID-initiating pits. A total of 11 pits were selected for destructive analyses and a comparison made of the multivariate regression analysis results with the traditional univariate phase angle analysis results. The comparative results showed that the multivariate regression analysis produced better overall pit depth sizing results than the univariate phase angle-based sizing results. The selected pit samples for destructive sectioning showed a wide range of "ground truth" pit depth information, thus representing a good range of data set for validation. The statistically compared ground truth versus NDE estimates showed smaller overall mean regression error for depth sizing based on the multivariate regression analysis in comparison to the univariate phase angle analysis.

Background

The NDE method of multi-channel eddy current (EC) testing is an array of signals of up to 4 separate frequencies. An area of concern in Balance-of-Plant (BOP) heat exchanger tube NDE is ID pitting caused, for example, by microbiological organisms. The detection problem is to locate and discriminate the raw ID pit signal that is in the noisy EC tube signal trace. The sizing problem includes the measurement of the ID pit depth from the signal.

The eddy current signal used in NDE is a complex impedance signal based on the applied induction bobbin coils. The signal is multi-channel in that it can be acquired at up to four separate frequencies. Each frequency has a different 'skin' depth penetration, as predicted by Maxwell's Equations, and can provide different material property changes, including flaw conditions.

The complex signal for each frequency can be processed in Cartesian coordinate system of real (x) and imaginary (y) components, or complex Polar coordinate system. Typically, the signal of interest is displayed as a combination of the 2D Polar or ‘Lissajous’ pattern and the X and Y strip charts. The signal of interest from which flaw depth estimates are made is the sharp transition line which is defined by the signal phase angle. This transition line is highlighted as thick lines in Figure 1.

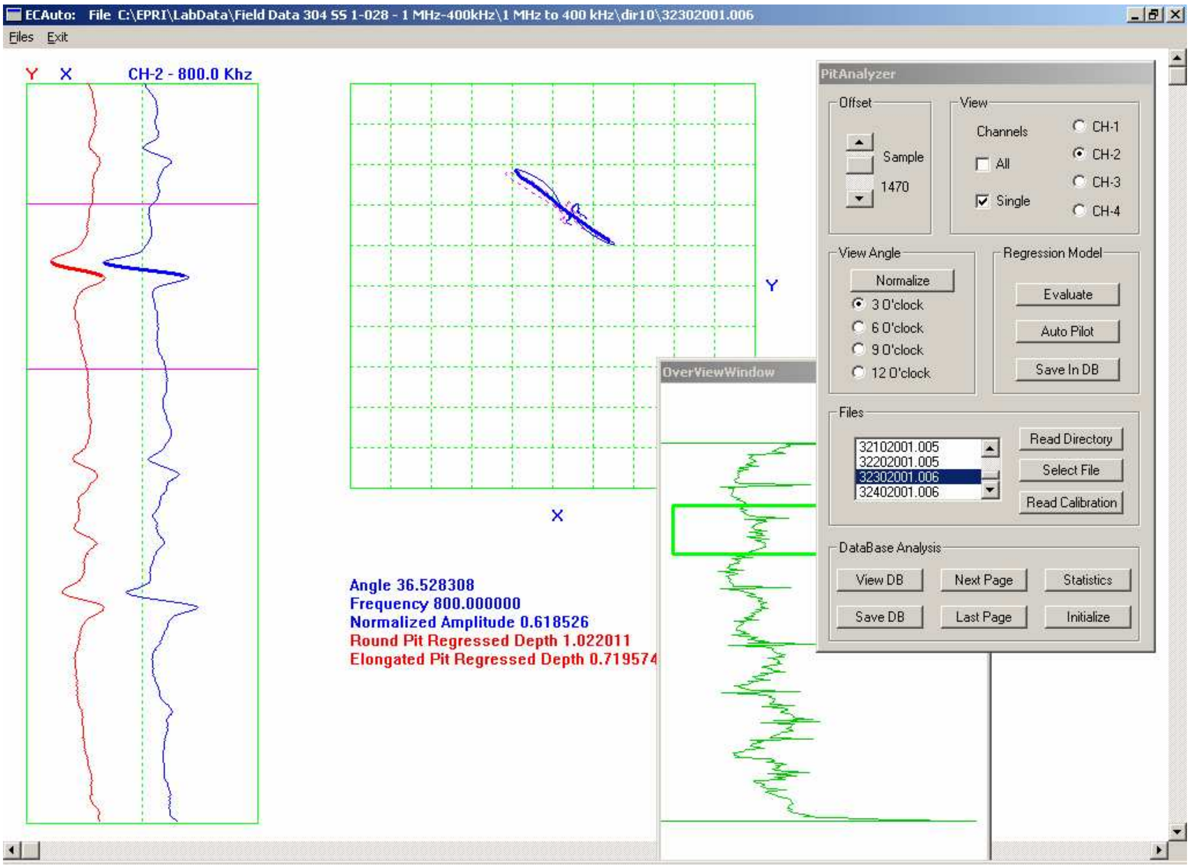

Figure 1
An ID Pit Signal Displayed as Complex Lissajous Pattern and by X and Y Strip Chart Components

The feature extraction process will involve signal measurements from polar or Cartesian coordinates of the normalized signals. In signal normalization, a calibration target is scaled and rotated to an angle of 40 degrees from the 9:00 O’clock position in the polar plane. This normalization is applied to all calibration signals.

The traditional method of estimating ID Pit depth uses phase angle or amplitude, which represents a univariate depth estimation algorithm. The current EPRI project (1) involves a multivariate method and uses amplitude, phase, and XY Ratio (ratio of peak-to-peak resistance / inductance normalized to value > 1.0), all measured as a function of eddy current frequency. In Figure 1, a real field pit is shown in terms of phase angle and amplitude at 800 kHz.

Multivariate Flaw Depth Regression Approach

The multivariate flaw depth regression approach is to build a mapping function, F(**x**), that maps normalized features into ID pit depth, where **x** represents vector features and F() represents a linear or nonlinear function. For linear functions, F() is a 2nd or 4th order polynomial function in features. For the nonlinear functions, F() is a layered set of sigmoid functions trained with a multilayer perceptron. Only the linear F() mapping will be discussed in this paper.

The approach for this ID pit depth sizing project was two-fold. The first was to construct multivariate depth regression functions for simulated but known size rounded and elongated ID pits in 0.75” and 1.0” diameter tubes, and compare the depth estimates with the univariate estimation method. This also allowed the fine-tuning of the regression functions by assessing the effect of pit morphology. The second approach was to use, directly or through an additional transformation, the rounded or elongated regression models to estimate the pit depth in the real field samples.

Calibration Data Sets

Tubing data for each calibration pit type were acquired four times by rotating the calibration tube at four different view angles of 3, 6, 9 and 12 O’clock positions for both rounded and elongated pits with pit depths of 25, 50, 75 and 100 percent thru-wall depth. Data were acquired at eight different frequencies from low of 100 kHz to high of 1MHz from both 0.75” OD and 1.0” OD tubing - only the 1.0” OD data will be used and discussed in this paper. Acquired data were displayed as an interactive 3D plot for this ID pit depth evaluation. The general display of the four elongated pit depths is shown in Figure 2.

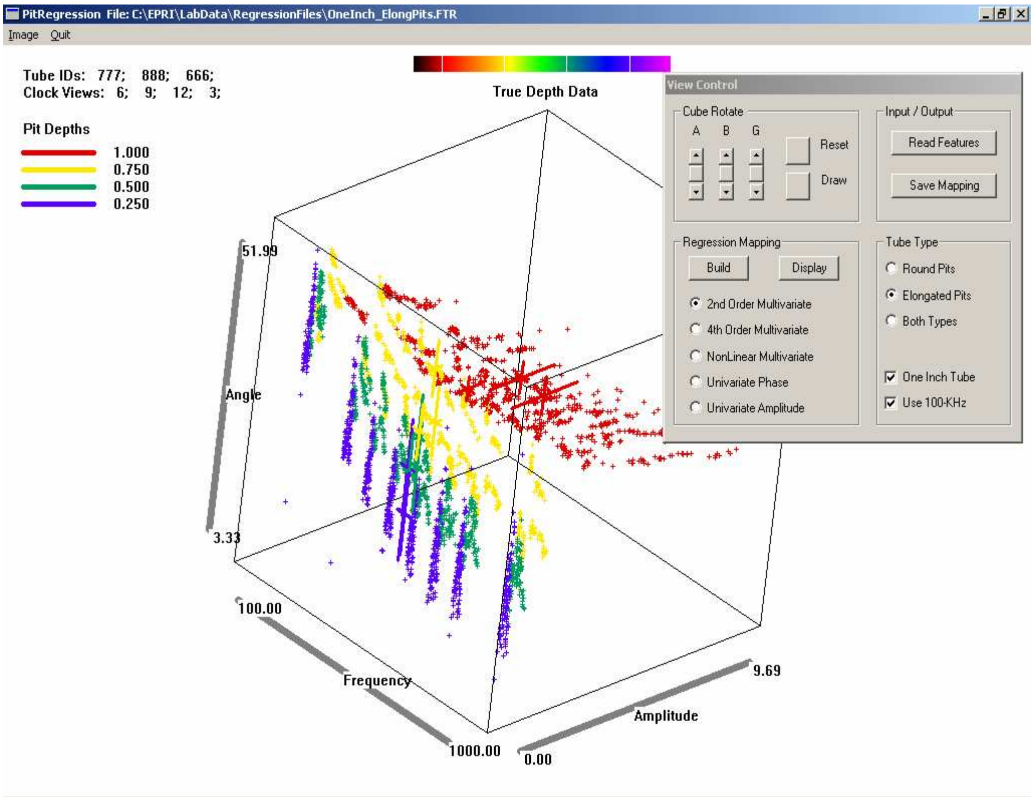

Figure 2
3D Plots of Four Elongated Pit Depths

Figure 2 showed the population of four different elongated pit depths in different colors. For each colored depth population, they represent raw data of three different size elongated pits at four different rotational positions at eight different operating frequencies. Basically, the compiled four elongated pit depth data are displayed in terms of operating frequencies, signal amplitudes, and phase angles. Raw individual data are shown as small crosses and the feature means and standard deviations are drawn as large crosses.

Figure 3 displays the numerical results of a 4^{th} order polynomial multivariate regression algorithm that maps the feature vectors to elongated pit depth. Displayed in the regression analysis window are the mapping function and the bias and variance of the regressed depths compared to true calibration pit depths. As shown, the mean error for elongated pit depth estimation was around 6 percent.

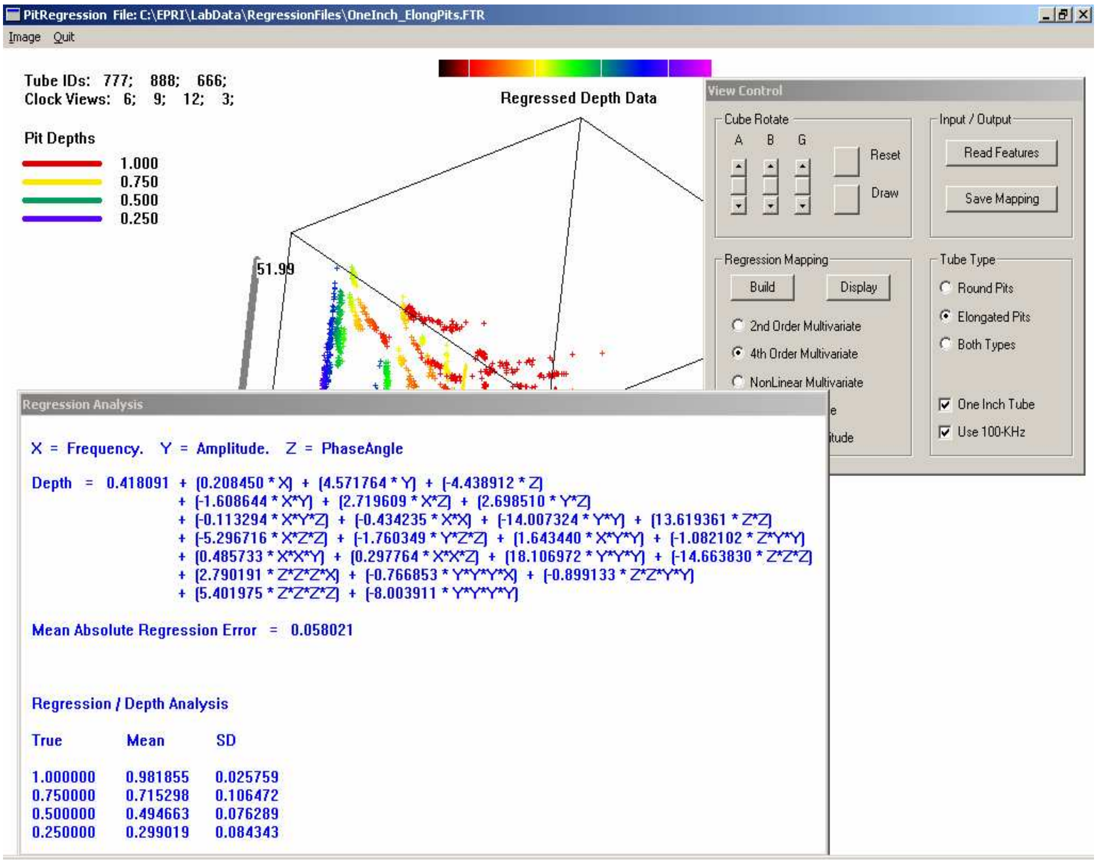

Figure 3
Multivariate Regression Analysis based on the 4th Order Polynomial Function

Figure 4 shows the regression results from a 2nd order univariate model using only phase angles from the elongated pits. For this univariate phase angle analysis, the frequencies were combined, whereas in the real field application, the phase angle-based pit depth estimation is conducted, for example, at a selected operating frequency of 600 kHz.

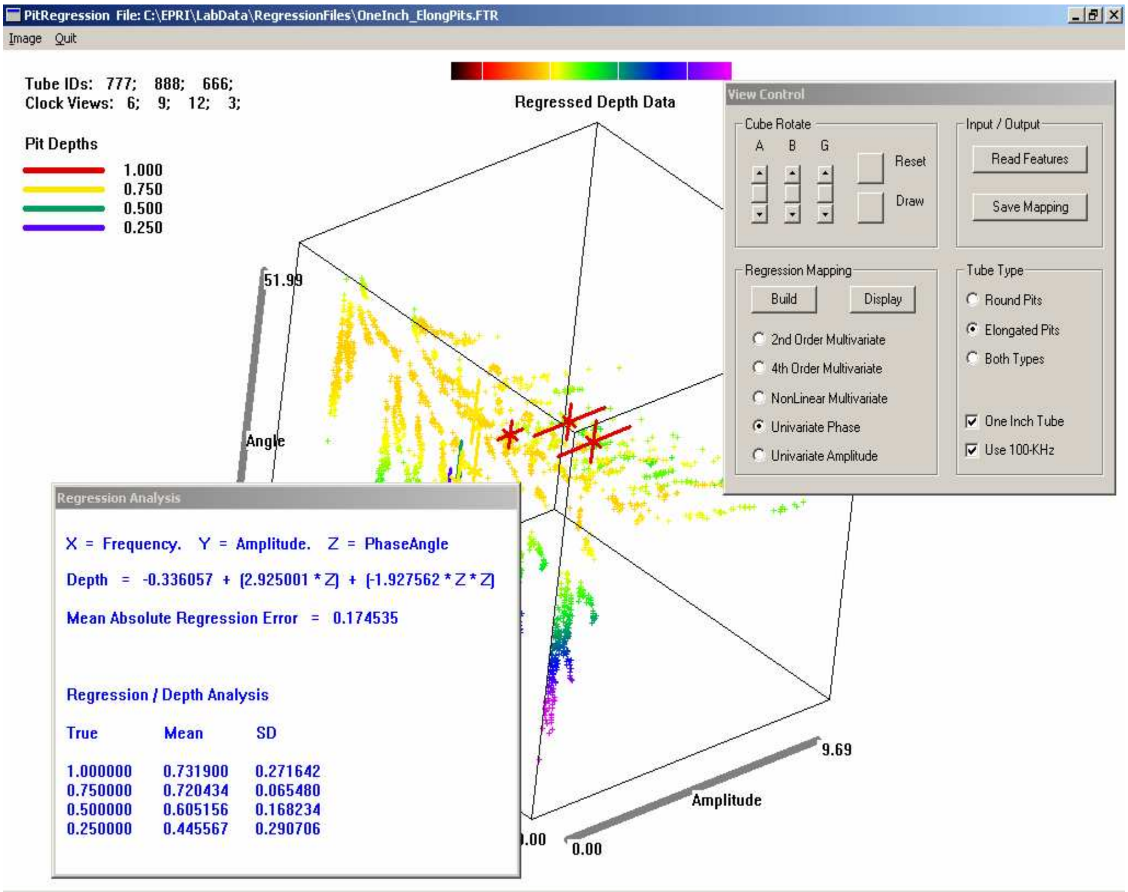

Figure 4
Univariate Regression Analysis based on the 2^{nd} Order Phase Angle Function

Based on the increased mean regression error of 17 percent, the multivariate method was shown to be superior to the univariate analysis method. The favorable results based on the elongated calibration pits were found to be equally applicable in evaluating the field pits.

Evaluation of Field Data Sets

Pit morphology (rounded vs. elongated) is a critical factor in the regression analysis. Building a higher order linear or a nonlinear multivariate regression function using combined rounded and elongated pits resulted in a larger mean error. This indicated that the sizing models for the two pit types are indeed different. The regression model selection based on either rounded or elongated pits is currently under development by considering the XY ratio function.

For evaluating the field pits, an assumption was made that they were more elongated than rounded pits. The elongated calibrated pits presented ideal shapes and the field pits were modeled as an extension of the ideal pit shapes. Thus, to evaluate the field data, an algorithm that transformed the ideal elongated pit model, named as the Transformed Elongated Regression (TER) model, was developed and applied to the actual field pits. The TER is a first-order transformation of the depth estimate from the ideal elongated model. To develop this transformation model, ten of the 12 field pit results were used. Figure 5 shows cross sections from several of the sectioned field pits showing the elongated nature of the field pits.

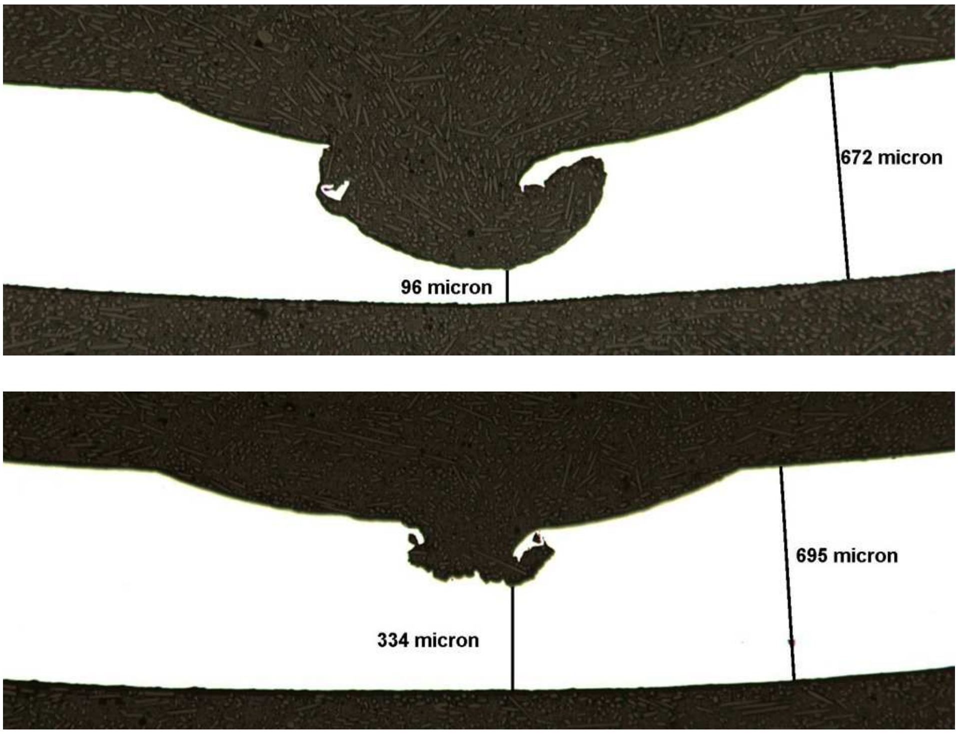

Figure 5
Cross Sectional Views Showing Elongated Nature of Field Pits

Evaluation Results

A total of 12 pits were selected for destructive analyses and a comparison made of the TER analysis results with the traditional phase angle-based analysis results from the 600 kHz data.

Figures 6 and 7 provided NDE estimates to destructive estimates based on the two analysis methods.

The comparative results clearly showed that the TER produced better overall pit depth sizing results than the univariate phase angle-based sizing results. The data samples showed a wide range of "true depth", thus presenting a good data set for validation. The field analysis results confirmed the earlier results shown with the elongated calibration pits where multivariate regression resulted in smaller overall mean regression error for depth sizing in comparison to the univariate phase angle analysis.

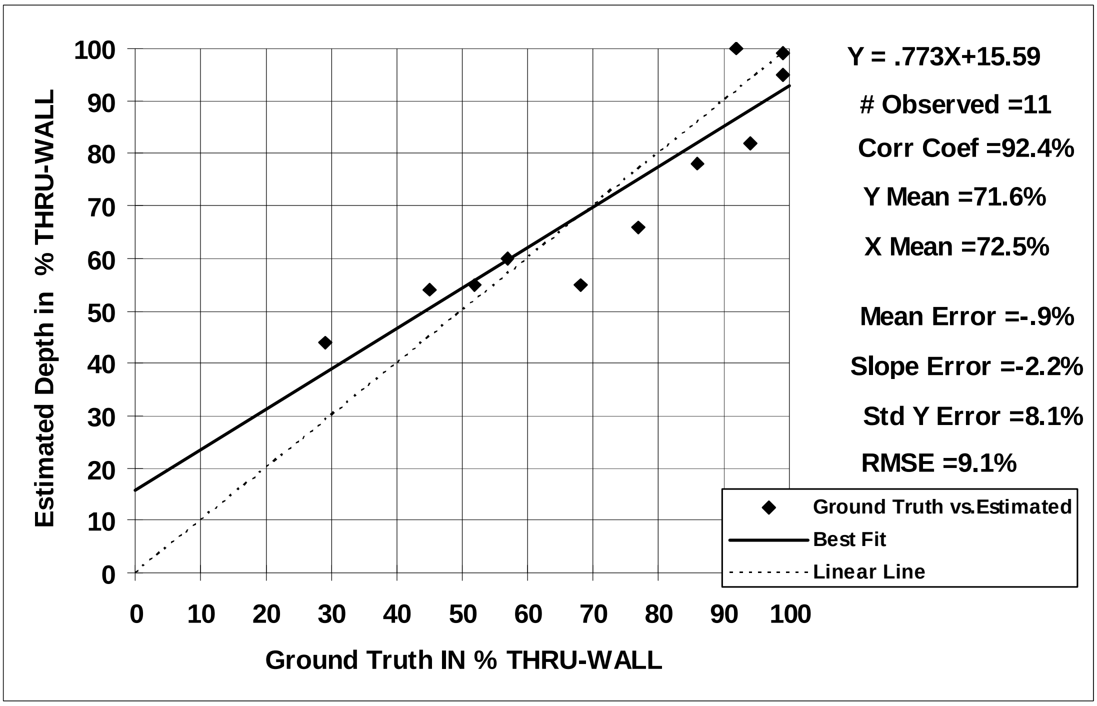

Figure 6
Transformed Elongated Regression Model Analysis Results

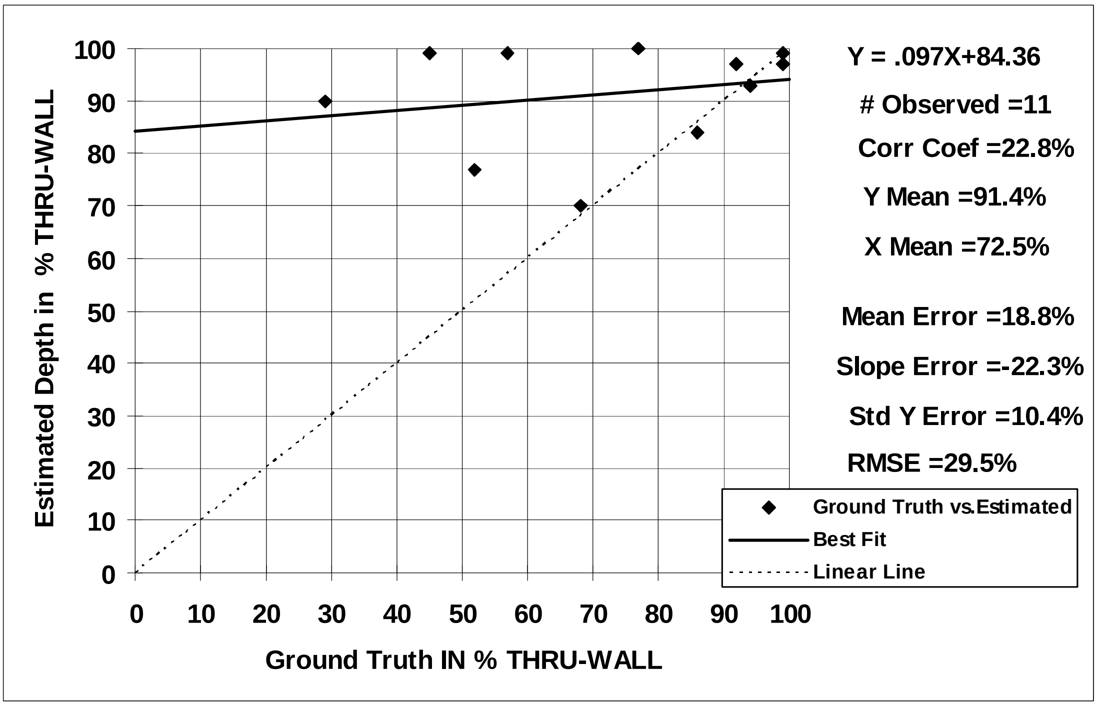

Figure 7
Univariate Phase Angle-Based Analysis Results

Summary

The following observations are made based on the work done to date.

- Multivariate regression analysis was superior to traditional phase angle-based analysis
- Destructive sectioning of field pits confirmed the presence of more elongated pits with tunneled and cavernous pit morphology
- The multivariate regression analysis based on elongated pits represented more accurate pit depth sizing of actual field pits

It should be noted that the developed analysis algorithm is damage- and eddy current data-specific and as such similar but new algorithm need to be developed if any of the following parameters change.

- Different damage mechanism
- Different bobbin coil types, for example, use of low- or high-frequency probe versus intermediate-frequency probe
- Different fill-factor probes, for example, use of 80% versus 85%

Finally, the developed regression-based algorithm needs to be further validated by comparing with actual field pits to ensure accuracy and applicability. Also, increasing the database and adding pit complexity will lead to model refinements and more robust pit depth estimation algorithms.

Reference

1 K. Krzywosz, Nondestructive Evaluation: Enhnaced ID Pit Sizing of Heat Exchangers, EPRI Report, 1013454, November 2006.