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Sizing of Inside Diameter Pits in Tubing Utilizing Two-variable Regression Curves

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ABSTRACT

The traditional approach to inside diameter (ID) pit sizing using the eddy current testing technique in heat exchanger tubing involves relating one variable (either signal amplitude or signal phase angle) to pit depth. The phase and the amplitude of an eddy current signal are dependent upon both the depth and the volume of the ID pit. The volume is a function of pit depth and pit morphology (effective diameter). Measurements of signal phase and amplitude can be used to construct a two-variable regression curve relating these parameters to depth. A two-variable curve should attenuate the effect of pit morphology on depth estimates. The principal question is whether a single measurement curve can accurately depth size ID pits of various morphologies. Calibration data sets consisting of machined pits of various diameters and depths were acquired. Two-variable regression curves were used to estimate the depth of machined and in-service pits of various diameters and depths. Traditional one-variable curves were also used to estimate the depth of these indications. The results of these analyses were evaluated to determine sizing accuracy.

KEYWORDS: heat exchanger tubing, inside diameter pitting, depth sizing, degradation.

Introduction

The goal of this study was to determine if inside diameter (ID) pit depth sizing using the eddy current testing technique in heat exchanger tubing could be improved by utilizing two-variable calibration curves. The central thesis of this study was to ascertain if a single measurement curve, constructed using two variables, would provide improved sizing performance on a variety of ID pit morphologies. The study was limited to copper-based alloys, 90/10 copper nickel (CuNi) and admiralty brass (ASME SB-111).

The traditional approach to ID pit sizing involves the use of one variable, amplitude or phase angle to depth measurement curves (ASME, 2001). One-variable measurement curves have provided less than optimum results when sizing ID pit depths.

The phase and amplitude of an eddy current signal are dependent upon the depth, as well as the total volume and shape, of a discontinuity (Cecco et al., 1983). This statement is validated by both eddy current theory and observation. A two-variable function relating signal amplitude and phase to depth should help to attenuate the effects of pit volume.

Commercially available calibration curve functions in eddy current software packages do not support the use of two variables. Regression analysis software was procured in order to construct the two-variable calibration curves. Examples of one-variable and two-variable curves were generated and are shown in Figure 1.

Two types of regression analysis techniques were utilized in this study. Linear regression analysis was utilized to evaluate sizing performance of the aforementioned eddy current testing techniques (EPRI, 1992). Multivariate regression analysis was utilized for the development of the two-variable (amplitude and phase) curves.

Methodology and Test Performance

The principal question addressed by this study was whether a single measurement curve could be used to accurately depth size ID pits of various morphologies. This study addressed the question by measuring artificial ID pits ranging in size and shape from 1.588 mm diameter round pits to 6.35 × 3.175 mm elongated pits; a smaller sample of real-world ID pits was also

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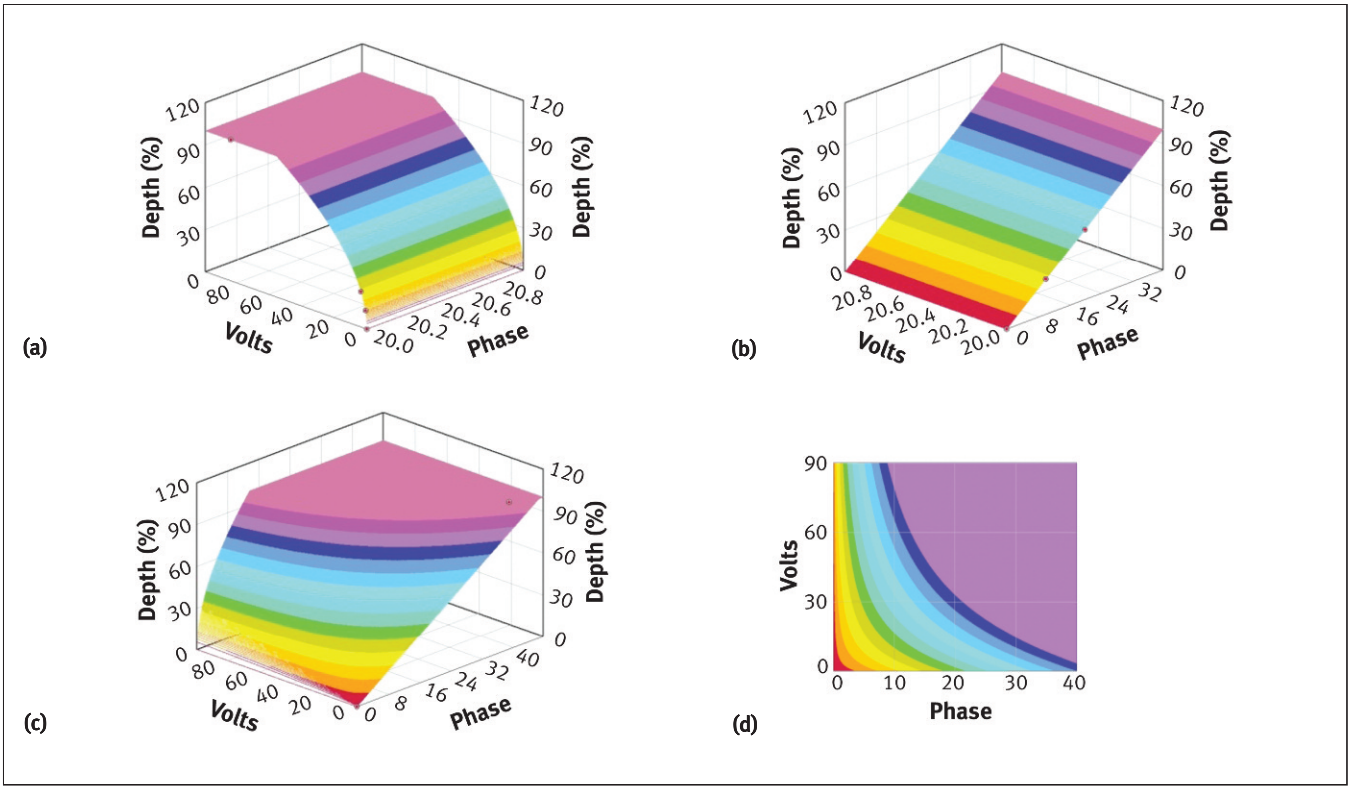

Figure 1. Curves generated from the regression analysis software representing one- and two-variable techniques: (a) one-variable amplitude curve; (b) one-variable phase curve; (c) 3D two-variable curve; (d) 2D two-variable curve.

measured. All of these discontinuities were measured using three separate techniques: peak-to-peak phase angle analysis (Vpp), maximum vertical amplitude analysis (VertMax or Vvm) and two-variable analysis (VertMax amplitude and Vpp phase angle). The results of these analyses were then evaluated for sizing accuracy.

Study Overview

To gather accurate results, this study:

- Constructed two-variable curves and developed a working model for ID pit sizing.
- Performed depth sizing of available data using both two-variable and traditional one-variable techniques.
- Applied adequate rigor to test samples to ensure that representative pit sizes and morphologies were evaluated. The data employed should contain ID pits of different morphologies (for example, round and elongated pits).
- Evaluated depth-sizing accuracy of two-variable and one-variable curves on a variety of pit morphologies.

Software

Regression analysis software requires the development of an equation in order to generate the measurement curves. The equation used in this study contained three distinct elements: independent variables (phase and amplitude of indications); dependent variables (depth of indications); and estimation parameters (parameters used during regression analysis to generate the best fit curve).

The equation was constructed so that the generated curve matched the data values of the control set as closely as possible. The equation was developed using two steps.

1. Recorded phase, amplitude and depth measurements from a control set of calibration standard pits and field samples. This control set contained data from as many ID pits as possible.
2. Experimented using various equations to determine the equation that best fit the control data set as a whole. Examination of the regression output data generated during this process helped to validate the equation.

A primary consideration was to validate that the equation and software generated the measurement curve in the same general form, whether all available discontinuity data were included or only selected data points were used.

Table 1 details regression analysis outputs from the regression analysis software. Results from a regression equation used early in the study were compared to the final regression equation used. An explanation of selected terms used in the analysis is also included.

TABLE 1
Regression analysis output

Value	Pit sizing algorithm, early function	Pit sizing algorithm, final function
Standard error of estimate	23.55	2.50
Average deviation	18.79	1.54
Maximum deviation for any observation	37.30	6.23
Proportion of variance explained (R^2)	61.27%	99.56%
Adjusted coefficient of multiple determination (Ra^2)	58.04%	99.53%

TABLE 2
Pulled tube pit data

Tube	Pit	Description	Depth (mils)	Depth (%)
10–31	1	Tight pit cluster, 3.175 mm diameter	16	32
10–31	2	Pit cluster, 6.35 mm diameter	17	35
10–31	3A	4.763 mm diameter pit	25	51
10–31	4A	Two joined pits, 6.35 mm axial extent	27	55
19–35	1A	1.588 mm diameter pit	22	45
19–35	1B	Two 1.588 mm diameter pits	–	–
19–35	2B	One 1.588 mm diameter pit, several smaller pits	–	–
19–35	3	2.381 mm diameter pit	16	33

Terms and Definitions

The average deviation is the average overall observation of the absolute value of the difference between the actual value of the dependent variable and its predicted value. The maximum deviation for any observation is the maximum difference (ignoring sign) between the actual and predicted value of the dependent variable for any observation.

The proportion of variance explained (R^2) indicates how much better the function predicts the dependent variable than by just using the mean value of the dependent variable.

The adjusted coefficient of multiple determination (Ra^2) is an R^2 statistic adjusted for the number of parameters in the equation and the number of data observations. It is a more conservative estimate of the proportion of variance explained, especially when the sample size is small compared to the number of parameters.

Measurement Methodology

Depth measurement of artificial pits with known depths and morphology was performed in order to assess sizing accuracy. Data on phase and amplitude from the standard entries used for set-up were recorded and input into the regression analysis software to construct the two-variable, amplitude and phase versus depth curves. Next, traditional one-variable curves were constructed in the eddy current analysis software using prime frequency phase angle and low frequency amplitude techniques.

Prime Frequency

The first prime frequency calibration curve is a Vpp phase angle versus depth, using the 3.175 mm diameter pits as calibration curve set points. The second prime frequency calibration curve is a two-variable curve relating Vvm amplitude and Vpp phase to depth, using a [0, 0, 0] point, various 100% through-wall holes and the approximately 50% pit measurements to simulate a typical field calibration.

Low Frequency

The low frequency ($\sim F_0/8$) calibration curve is a Vvm amplitude versus depth, using 3.175 mm diameter pits as calibration curve set points.

These calibration curves were utilized to analyze the following eddy current technique data sets.

- Eddy current data from 15.88 × 1.24 mm admiralty brass tubing containing ID pits. This data set contained pits of various morphologies.
- Eddy current data from 15.88 × 1.24 mm 90/10 CuNi tubing containing calibration standard entries with various pit morphologies. Each sample was recorded four times and the standard was rotated 90° between pulls. This practice induced variations to the signal phase and amplitude dependent on how the coil was affected by the ID pit.
- Eddy current data from 15.88 × 1.24 mm 90/10 CuNi tubing containing ID pits that were measured mechanically after the tubes were removed from the heat exchanger. This data set contained pits of various morphologies, as shown in Table 2.

Sizing Performance Results

ID pit depth sizing performance was evaluated using the linear regression analysis technique (EPRI, 1992). This evaluation technique compares the depth measurements from the various techniques to the physically measured depth of the discontinuity. Three values are generated during regression analysis that can be used to measure sizing accuracy: slope of the regression line, correlation coefficient and root mean square error (RMSE). A fourth value was also included in this study: maximum deviation. This value reflects the largest variance when depth sizing a specific pit indication in a data set.

Table 3 shows that depth sizing accuracy improves as the correlation coefficient increases, the slope of the linear regression line approaches one, and the RMSE and maximum deviation values decrease. These values, for various tube materials and pit morphologies, are detailed in the Figures 2a–c, 3a–c and 4a–c.

TABLE 3
Sizing performance goals

Value	Minimum criteria	Ideal
Slope of regression line	>0.7 and <1.3	1.0
Correlation coefficient	>70%	100%
Root mean square error	<20%	0%
Maximum deviation	None established	0%

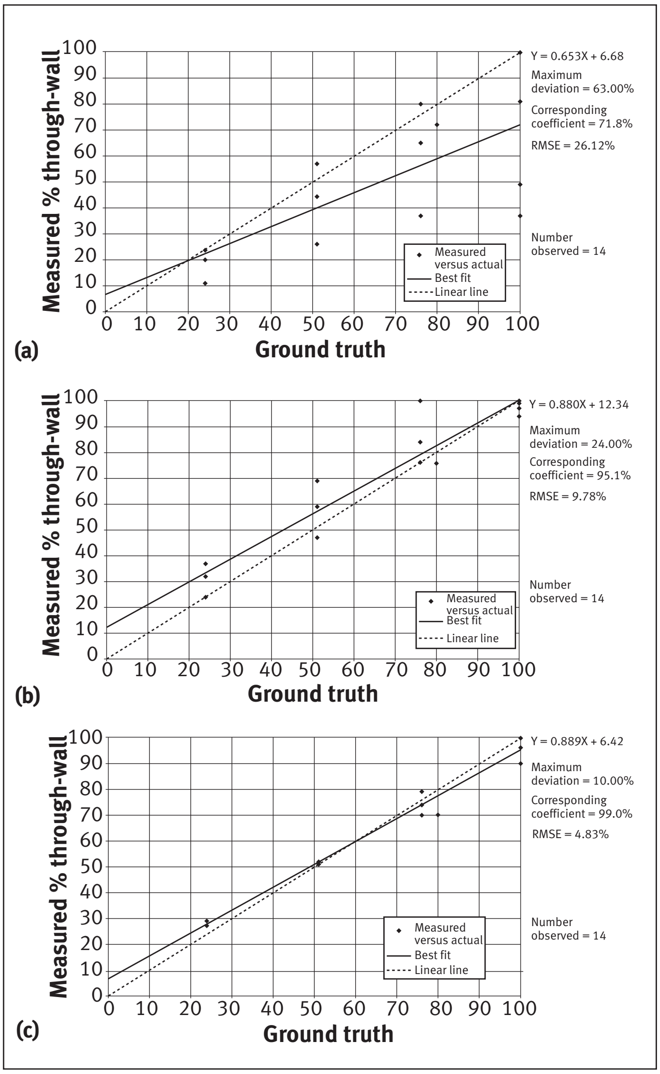

Figure 2. Plots reflecting sizing accuracy on the admiralty brass data set: (a) low frequency amplitude versus depth technique (note the maximum deviation and root mean square error [RMSE]); (b) prime frequency phase versus depth technique (note that maximum deviation, correlation coefficient and RMSE are improved); (c) prime frequency two-variable technique (note the low maximum deviation, high correlation and low RMSE).

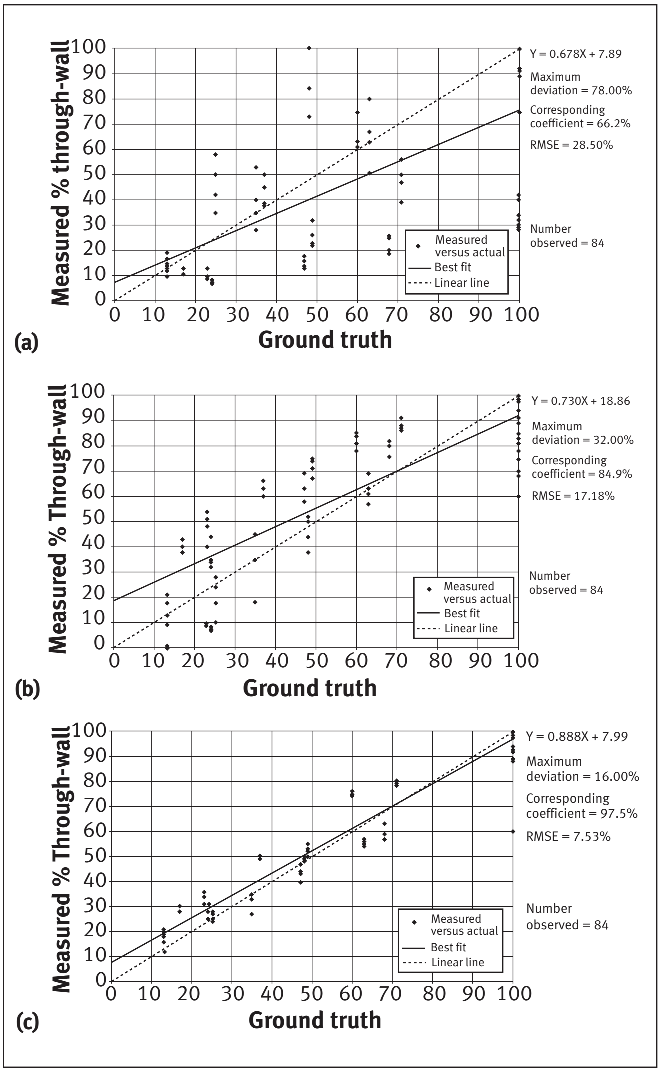

Figure 3. Plots reflecting sizing accuracy on the 90/10 CuNi data set containing machined pits: (a) low frequency amplitude versus depth technique (note the larger data set and that maximum deviation and root mean square error [RMSE] are high); (b) prime frequency phase versus depth technique (note that maximum deviation, correlation coefficient and RMSE are improved over Figure 3a); (c) prime frequency two-variable technique (note the low maximum deviation, high correlation and low RMSE).

TABLE 4
Technique sizing performance

Value	One-variable amplitude	One-variable phase angle	Two-variable amplitude and phase
Slope of regression line	0.802	0.812	0.852
Correlation coefficient	74.6	91.9	97.9
Root mean square error	22.54	11.8	6.49
Maximum deviation	54.66	23.0	12.66

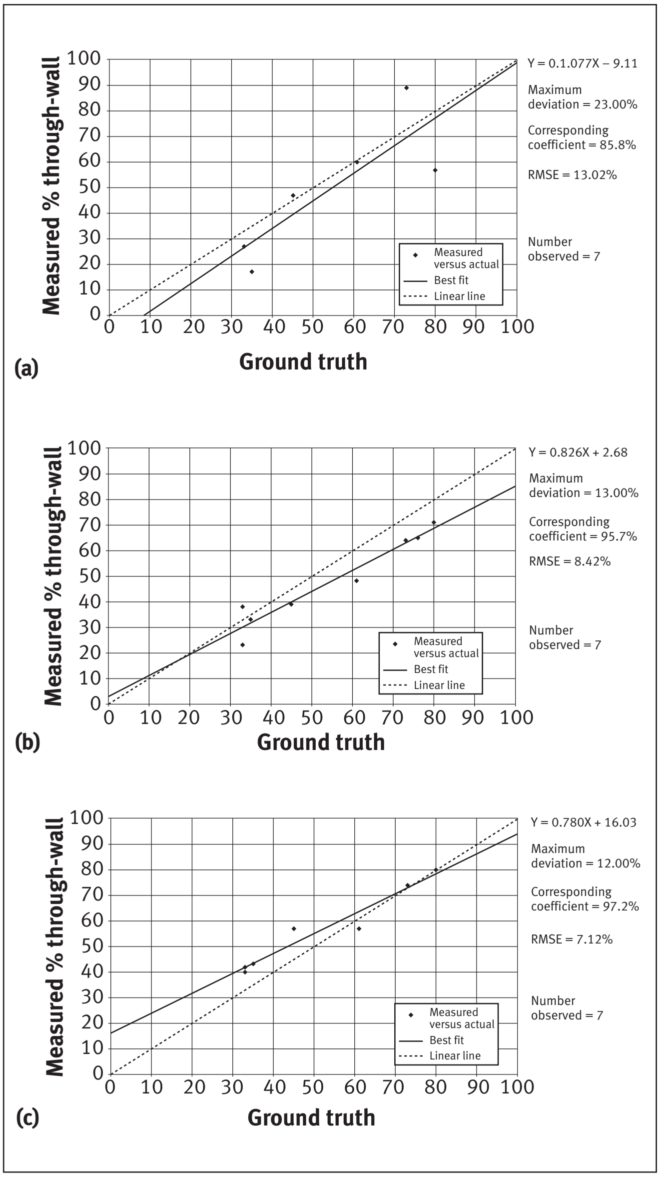

Figure 4. Plots reflecting sizing accuracy on the field data 90/10 CuNi data set. The actual pit depths from a set of inside diameter pits were later measured mechanically: (a) low frequency amplitude versus depth technique; (b) prime frequency phase versus depth technique; (c) prime frequency two-variable technique.

The three plots in Figures 2a–c reflect sizing accuracy on the admiralty brass data set. This data set contained 14 pit indications and was from in-service tubing containing pits that were subsequently mechanically measured.

The three plots in Figures 3a–c reflect sizing accuracy on the 90/10 CuNi data set. Numerous calibration standards of various morphologies were utilized in this data set. This data set contained the most pit indications (84 pits) and also the widest variation in pit diameter and shape.

The three plots in Figures 4a–c reflect sizing accuracy on a data set of actual pits in 90/10 CuNi tubes removed from service in the field. This data set contained the fewest number of samples.

Table 4 summarizes the average sizing accuracy of the different measurement techniques evaluated. A significant number of pit indications (105 pits) are included in this calculation. The two-variable technique provides notable improvements in RMSE and maximum deviation when measuring pits of varying morphologies; this is important because pits observed in operating heat exchanger tubing can vary greatly in morphology, even within the same section of tube.

Conclusion

The two-variable regression analysis technique, using phase angle and amplitude, provided the best correlation factor and lowest RMSE of the techniques examined. Amplitude analysis was found to provide the lowest correlation and highest RMSE of the evaluated techniques. Phase angle analysis was found to provide better correlation and lower error (greater accuracy) than amplitude analysis. Variances in pit shape, or morphology, had an adverse effect on sizing in all three of the techniques analyzed; two-variable analysis tended to attenuate this effect.

REFERENCES

ASME, *Boiler and Pressure Vessel Code, Section V Nondestructive Examination, Article 8: Eddy Current Examination of Tubular Products*, American Society of Mechanical Engineers, New York, New York, 2001.

Cecco, V. S., G. Van Drunen and F. L. Sharp, "Eddy Current Manual," Vol. 1, *AECL Report, AECL-7523*, Chalk River Laboratories, 1983.

EPRI, "Electromagnetic NDE Guide for Balance of Plant Heat Exchangers," Revision 2, *Report TR101772-R2, Project 3232-01*, Electric Power Research Institute, December 1992.