Detection and Sizing of Baffle Plate Erosion and Fretting using Eddy Current Array Technology

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Abstract
The paper describes the evaluation of current state of the art Eddy Current Array (ECA) technology used for the detection and sizing of heat exchanger tube baffle plate erosion and fretting type defects. For validation purposes, all defects were also subject to Internal Rotary Inspection System (IRIS) ultrasonic evaluation. Results of the study indicate that a probability of detection (POD) figure of 84.6% is achievable for the ECA method with a probability of sizing (POS) mean measurement error of approximately +6.9% when compared to the IRIS sizing results.

Keywords: eddy current, IRIS, ECA, heat exchanger tubes, heat exchanger, baffle plate, fretting, erosion

1 Introduction

An Eddy current Array (ECA) and IRIS inspection was performed on a tube bundle where a previous visual inspection had revealed that the tubes had suffered severe damage due to baffle plate erosion and fretting. The purpose of the study was therefore to determine the applicability of the ECA method for the detection and sizing of tube wall damage due to this type of defect mechanism.

It is assumed that the use of ECA probes would allow higher sensitivity to baffle plate fretting and circumferential cracking than is achievable using conventional bobbin type eddy current probes. When analysing bobbin coil data, it is very difficult to isolate small volume indications, such as a crack type defect, from within a complex signal comprising of superposition of a crack, a geometry change and the addition of material [1].

The ECA inspection was carried out using the Eddyfi Ectane multifunction tube inspection system, DefHi ECA probes and Magnifi 3.3R3 analysis software.

All accessible tubes were inspected using ECA. The damaged tubes were identified to be in a localised area towards the top of the bundle around where a number of tubes had previously been removed. Baffle plate fretting was found in the first 4 baffles from the tubesheet and tended to be most severe at baffles 2 and 3. Defects at baffle 4 tended to be more localised around the circumference. A sample of the 52 tubes identified by ECA was then inspected using IRIS which is typically sensitive to baffle plate fretting of 5% loss and above and has an accuracy in the region of +/-5% for defects of this type.

1.1 ECA Coil Configuration

ECA technology uses several individual coils, grouped together into one probe. To minimise cross-talk due to mutual inductance, individual coils are multiplexed, allowing the coils to work together. Internal diameter ECA probes used for tube inspection can have their coils organised in such a way as to completely sweep the interior circumference of each tube. The probe used in this study is the DefHi probe [2] supplied by EddyFi with coils configured in transmit-receive arrangement as illustrated in figure 1.

With this coil configuration, eddy currents induced in the tube wall flow perpendicular to any circumferential defects encountered, and therefore making them easier to identify and undertake estimates of circumferential length and position. A typical display for a detected defect using this configuration is given in figure 2.

Figure 1 DefHi Eddy Current Probe Configuration

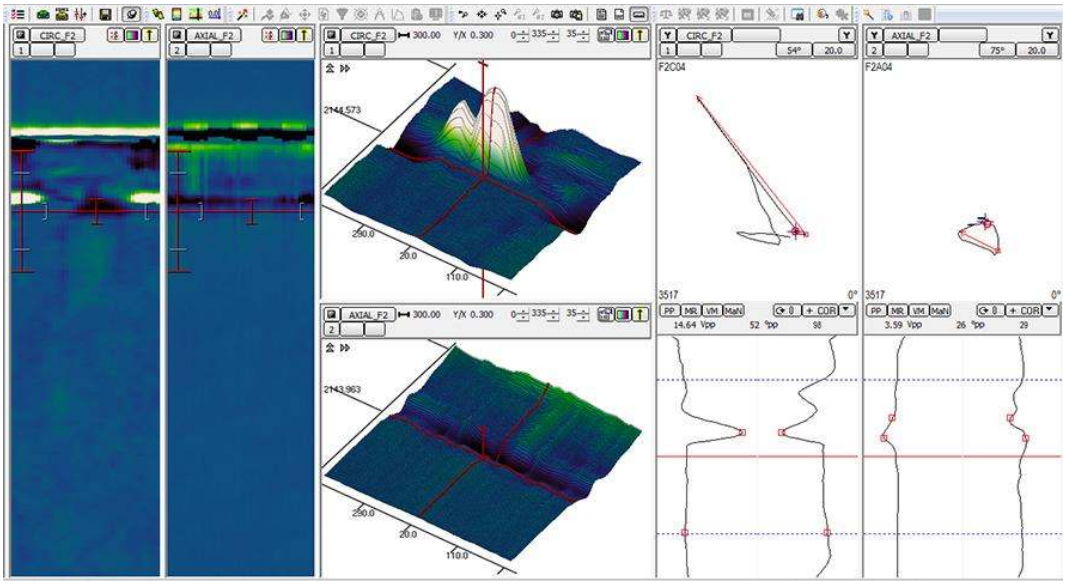

Figure 2 ECA Signal data for a deep circumferential crack

1.2 IRIS UT

The IRIS system utilises an ultrasonic transducer along with a water pressure powered turbine driven rotating mirror, to allow for through wall wave propagation, as illustrated in figure 3.

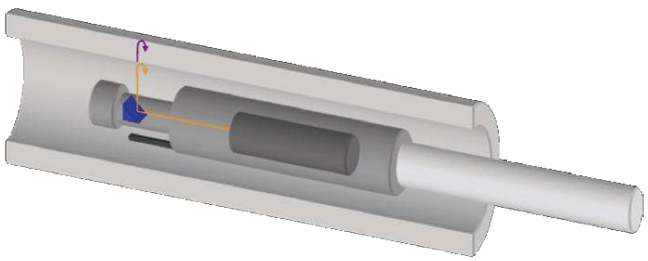

Figure 3 IRIS transducer principles [3]

A typical IRIS data display is given in figure 4, where it can be seen that inner and outer wall reflections are used to provide a cross sectional circumferential display of tube wall thickness.

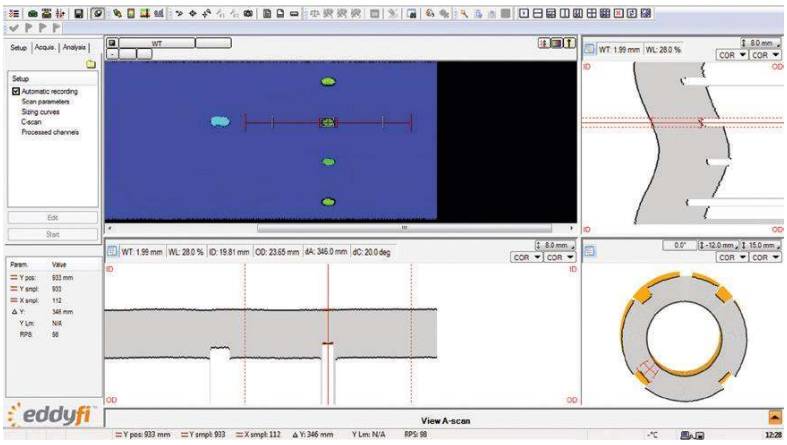

Figure 4 IRIS Data Display

1.3 Probability of Detection

Probability of Detection (POD) is a frequently used quantitative measure of the capability of an NDT method and/or procedure. The development and evolution of the various POD methods has resulted in a much better understanding of NDT procedures and the sensitivity of individual procedures to changes in materials, applications and processing parameters. Knowledge of the POD for a particular method provides a useful metric for quantifying and assessing NDT capabilities [4].

POD analysis is carried out on Hit/Miss data and can be visualised in the form of a POD curve. A POD curve estimates the capacity of an inspection technique to detect defects with respect to discontinuity feature. This could include parameters such as depth, length, orientation etc. For an ideal technique, the POD for flaws smaller than an established critical size would be zero. Whereas, discontinuities greater than this critical size would have a POD equal to 1, or 100% of probability of detection. In practise such ideal techniques do not exist, resulting in POD curves not having this ideal behaviour. Figure 5 illustrates a real and ideal POD curve [5].

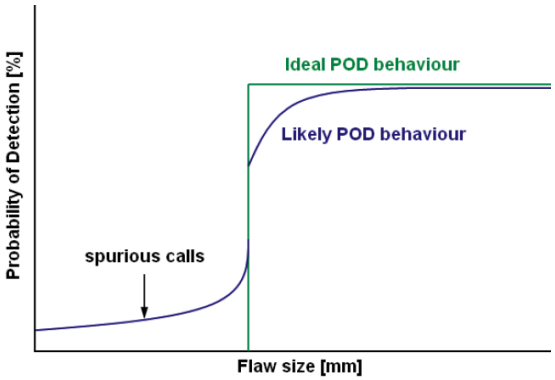

Figure 5 Ideal and likely POD Curve

1.4 ROC Analysis

With regards the assessment of the reliability of an inspection process, it is possible to extend the POD method to incorporate the four possible outcomes for a testing result, as indicated in figure 6.

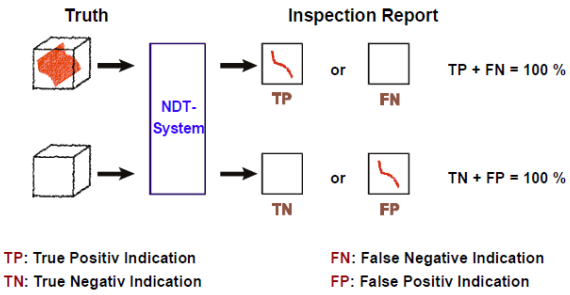

Figure 6 The four possible outputs for an NDT result

These four possible outputs can then be combined to produce POD and Probability of False Alarm (POFA) figures for the inspection method and used to create performance points on a receiver operating characteristic (ROC) reliability surface [5]:

$$PoD = \frac{TP}{TP + FN} \; or \; \frac{Total\ number\ of\ positive\ calls}{Total\ opportunities\ for\ rejection}$$

$$PoFA = \frac{FP}{TN + FP} \; or \; \frac{Total\ number\ of\ false\ positives}{Total\ opportunities\ for\ acceptance}$$

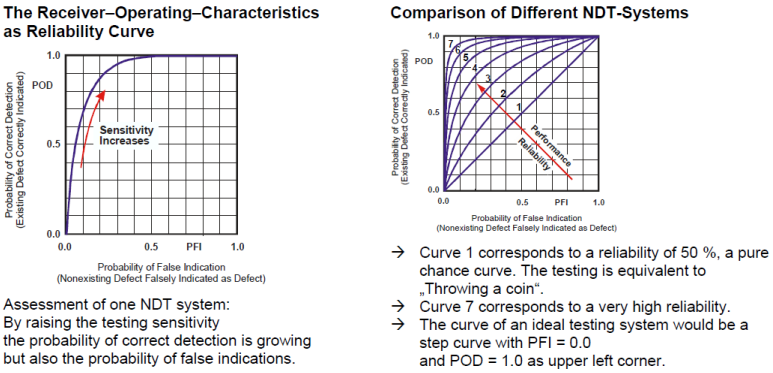

Figure 7 ROC reliability curves description

1.5 Probability of Sizing

Probability of Sizing (POS) is a measure of an inspection method's ability to accurately size a defect. An example of a POS distribution for a typical flaw size is given in figure 8 [6]. In this illustration it can be seen that in this instance, the method or procedure used will generally under predict the actual defect size.

Extending this for a whole range of flaw size estimation and comparing them to their true size allows for the production of a POS curve comprising a full range of defect sizes used in the POD study, an example of which is given in figure 9 [7].

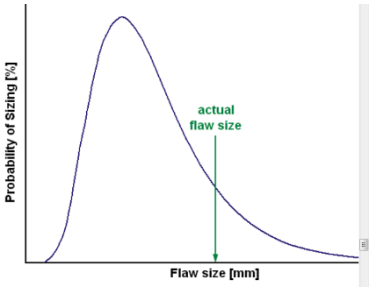

Figure 8 Typical sizing distribution

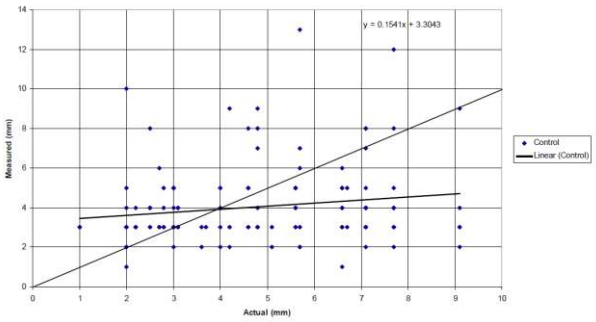

Figure 9 POS curve of estimated flaw size as a function of true flaw size

2 Inspection Details

The bundle consisted of 1014 off A213 Tp304L stainless steel U tubes, 5.8m in length with an outside diameter of 19.05mm and wall thickness of 1.65mm. For the eddy current inspection the DefHi-ERBC-148MF-N15B probe was used. This comprises of both bobbin and circumferential coils. An ASME type reference tube containing external flat bottomed holes of various depths and diameters and a 1.3mm diameter through hole was used for calibration purposes with an eddy current test frequency of 158 kHz utilised for the ECA evaluations.

3 Results Analysis

3.1 ECA and IRIS Signature Images

Figures 10 and 11 provide examples of both ECA and IRIS signatures for the same defect. In these examples it can be seen that, although the defects are detected in both instances, the ECA analysis is oversizing when compared to the IRIS analysis. Figure 12 is a photograph of typical fretting found during the evaluation.

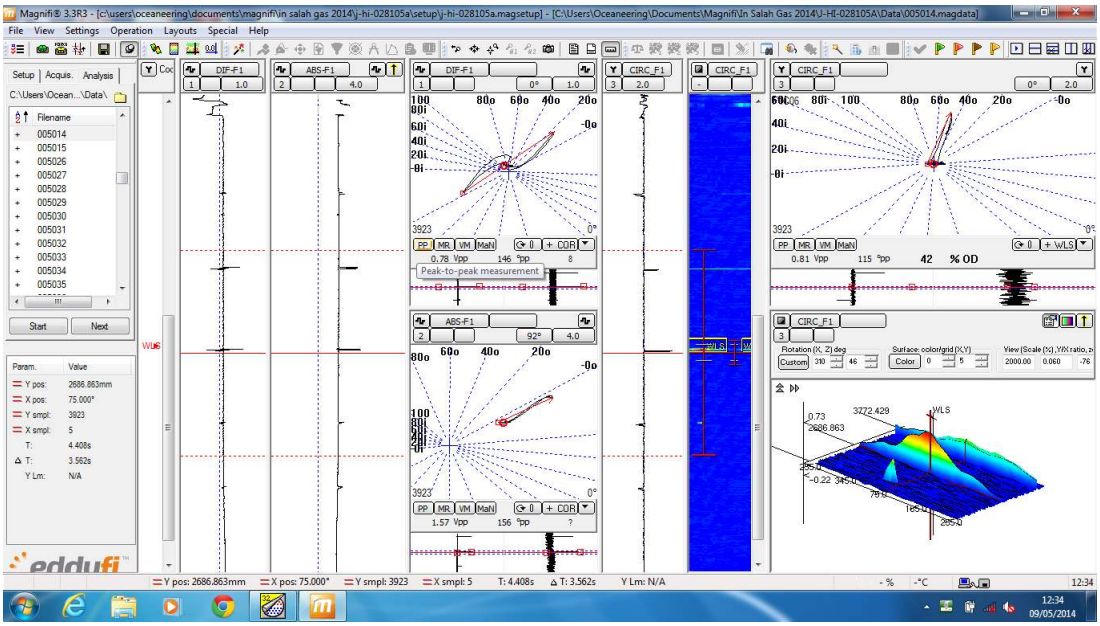

Figure 10 Baffle Plate Fretting - Row 5 Tube 14 - ECA 42% Estimated Loss at BP 3

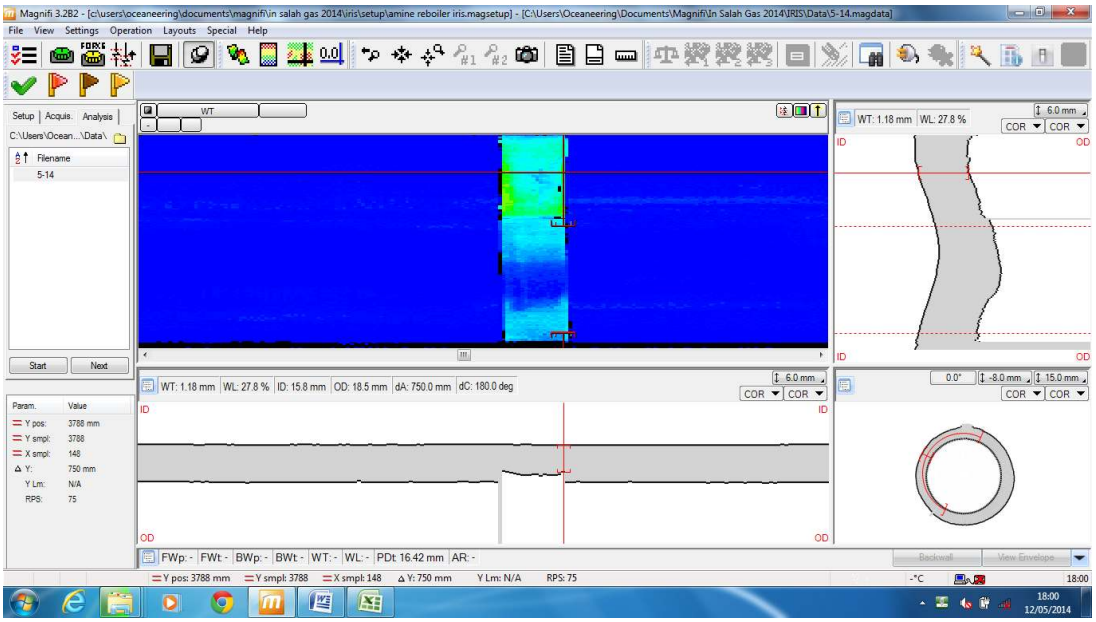

Figure 11 Baffle Plate Fretting - Row 5 Tube 14 - IRIS 28% Loss at BP3

Figure 12 Typical Fretting

3.2 POD Analysis

An attempt has been made to determine a POD figure for the ECA inspection method. Using the simple ROC approach, with values given in Table 1 below, this results in a POD figure of approx. 84.6%. An attempt at determining a PoFA figure is not possible in this case due to the non-existence of false positives.

Table 1

True Positives	148
False Positives	0
False Negatives	27
True Negatives	131

PoD	0.845714
PoFA	0

With regards defect detection and minimum wall loss detectable, a binary regression analysis was undertaken, using the IRIS results as a means of determining the presence of a defect to carry out a Hit/Miss comparison. The results of this analysis are given in figure 13, where the Hit/Miss, POD and -95% curves are given. From this analysis it can be stated that the ECA method, as applied in this study results in a 90% probability of detecting wall loss (A_{90}) in excess of approximately 10%. Extending this to include a lower 95% confidence limit ($A_{90/95}$) increases this slightly too approximately 14.5%.

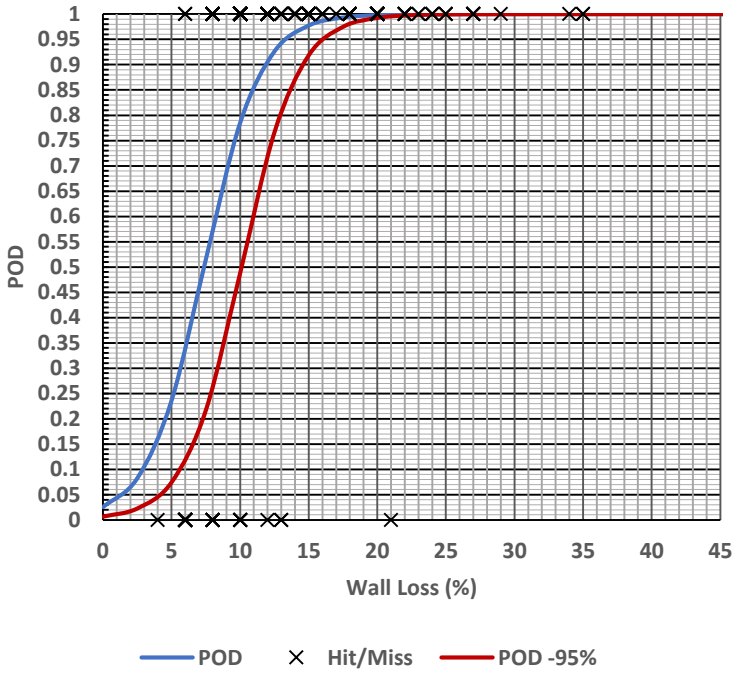

Figure 13 **ECA POD Analysis**

3.3 POS

To determine the relative sizing accuracy for the ECA method a POS has been performed. As the actual true flaw sizes aren't known directly the evaluation is performed comparing ECA size estimates to sizes resulting from IRIS analysis of detected defects. The resulting scatter plot given below in figure 14, provides a direct comparison of the two sizing estimates obtained from the two NDT methods.

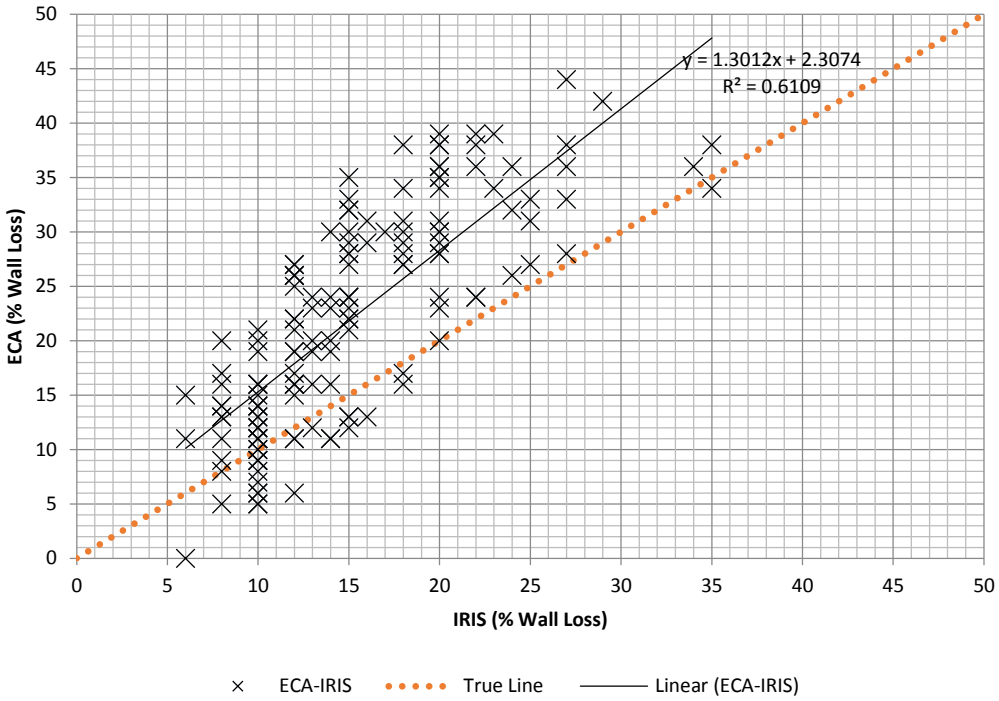

Figure 14 POS Plot - ECA flaw size as a function of IRIS flaw size

A linear trend line has also been added to the plot, along with the resulting equation. The trend illustrates both a positive system offset along with a gradient greater than 1, indicating that the ECA method generally oversizes detected defects when compared to size estimates resulting from application of the IRIS method. This trend of oversizing generally increases as a function of defect size. This can be further illustrated if the distribution of sizing errors for discrete flaw sizes is analysed. To this end, ECA sizing error distributions for defects indicating IRIS size estimates of 10%, 15%, and 20% have been developed. These are given in figure 15, below.

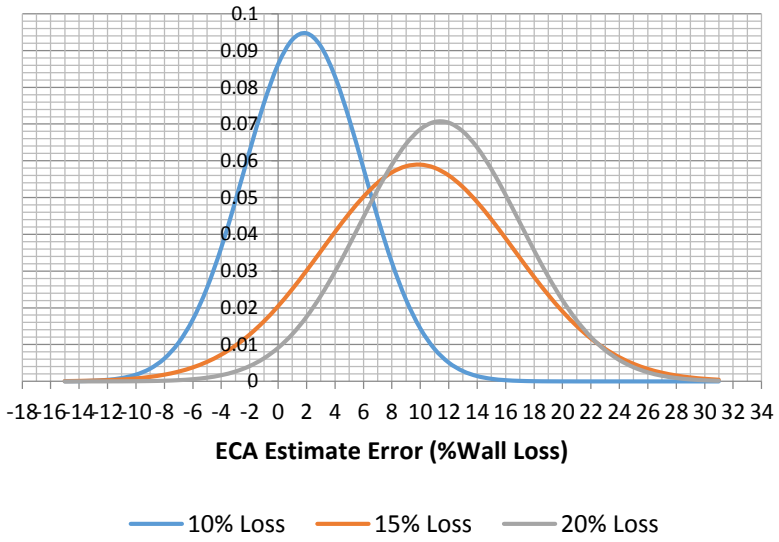

Figure 15 Sizing Error Distributions for 10%, 15% and 20% Wall Loss Defects

As indicated in the figure, we can see that the mean sizing error increases as a function of defect severity, from approx. 4.2% for 10% wall loss to approximately 11.4% for 20% wall loss defects.

To provide an overall estimate of sizing accuracy and dispersion, summary statistics and the distribution of sizing measurement errors (ECA-IRIS defect size estimates) were produced. These results are given in table 2 and figure 16 below.

Mean	6.88590604
Standard Error	0.527283044
Median	7
Mode	9
Standard Deviation	6.436309797
Sample Variance	41.4260838
Kurtosis	-0.904483938
Skewness	0.010782266
Range	26
Minimum	-6
Maximum	20
Sum	1026
Count	149

Table 2 Summary Statistics for ECA-IRIS measurement differences

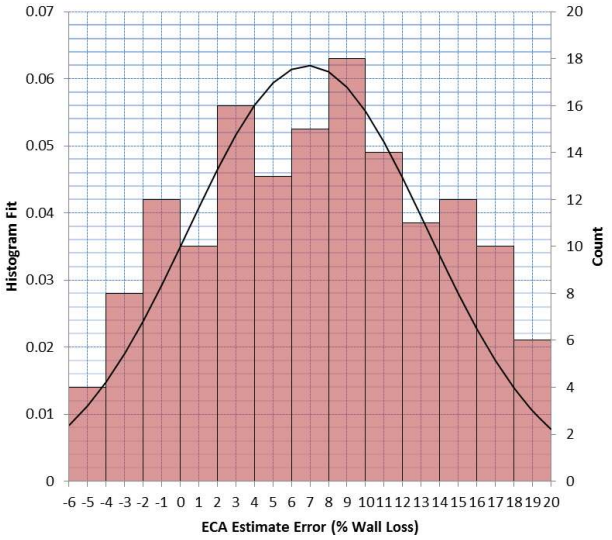

Figure 16 Distribution of ECA Measurement Errors

From these results it can be stated that the mean ECA measurement error when compared to the IRIS estimated defect size is approximately +6.9% with a standard error of approximately 0.53%.

4 Conclusions

The paper has reported the evaluation of an ECA procedure used for the detection and sizing of boiler tube baffle plate erosion and fretting type defects. The study has indicated that in general the ECA method tends to oversize detected defects of this type when compared to an IRIS inspection. Some of the inaccuracy of ECA is likely to be associated with the reference tube used to establish the sizing curve. A reference tube consisting of asymmetric wear scars of various depths, rather than flat bottomed holes, would be more representative of baffle plate fretting.

In summary, overall a probability of detection of figure of 84.6% for the ECA method when used to detect baffle plate erosion and fretting type defects. In addition, it was also found that defects of this type in excess of 10% wall loss could be detected with a 90% probability of detection.

References

1. EddyFi Application Note, Assessing Circumferential Cracking in Non-Ferromagnetic Heat Exchanger Tubes, 2015. Available from: http://www.eddyfi.com/wp-

content/uploads/2015/03/application-note-circumferential-cracking.pdf [Accessed: 19/01/16]

2. EddyFi, High-Definition Multiplexed Eddy Current Array Tubing Probes, 2015. Available from: http://www.eddyfi.com/wp-content/uploads/2015/10/spec-sheet-DefHi-multiplexed-eca-tubing-probe.pdf [Accessed: 19/01/16]

3. EddyFi, Tubing Inspection Probe Catalog, 2015. Available from:http://www.eddyfi.com/wp-content/uploads/2016/01/catalog-tubing-probes.pdf [Accessed: 20/01/2016]

4. George A. Matzkanin and H. Thomas Yolken, A Technology Assessment of Probability of Detection (POD) for Nondestructive Evaluation (NDE), NTIAC, August 2001

5. BAM, Assessment of Reliability of Non-destructive Testing, February 2014. http://www.bam.de/en/fachthemen/referenzverfahren/referenzverfahren_medien/701en.pdf [Accessed: 20/01/2016]

6. F. Van den Abeele and P. Goes, Non Destructive Testing Techniques for Risk Based Inspection, Sustainable Construction and Design, 2011.

7. HSE, Information for the procurement and conduct of NDT – Part 4: Ultrasonic Sizing Errors and their implication for Defect Assessment, 2008. http://www.hse.gov.uk/comah/sragtech/ndt4.pdf [Accessed: 20/01/2016]