

AN EDDY CURRENT ANALYSIS SYSTEM FOR NUCLEAR FAN COOLER INSPECTION

DATA ANALYSIS AND INTERPRETATION

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INTRODUCTION

Accurate defect detection and sizing of flaws is of importance to the nuclear utility industry and the U. S. Nuclear Regulatory Commission, with decisions of economic and environmental consequence dependent on these results. Success to date has been achieved in the inspection of steam generators where eddy current techniques have been developing for several years. No NRC regulations currently require fan cooler unit (FCU) inspections; therefore, the corresponding in-service inspection (ISI) procedures are not nearly as mature.

Fan cooler units are large heat exchangers which cool the containment area. They are composed of thousands of 90/10 copper-nickel tubes (0.625-inch outer diameter and 0.049-inch wall thickness) with each tube encircled by hundreds of copper fins. Water circulating through the tubes removes heat from the air and also causes inner wall pitting through an erosion and corrosion process. There is concern that leakage from the FCUs could induce cracking in the pressure vessel should it reach that far. In response to this problem, some utilities have begun inspecting their FCUs on a regular basis.

In-service inspection procedures for FCUs are similar to those used in steam generators. An eddy current instrument, such as the Zetec MIZ-12, is used to collect and record data on analog magnetic tape. Human inspectors, typically provided by outside vendor companies, then use stripcharts made from these tapes to detect and size defects. Note that these defects occur on the inner wall for FCUs, versus the outer wall for steam generators. Some of the disadvantages associated with manual inspections are:

- time consuming,
- labor intensive, and therefore costly,
- subjective, and
- tedious.

In this paper, a computer-based system for automating the data analysis and interpretation is described. This system, the Eddy Current Analysis System (ECAS), was developed using classical

statistical and digital signal processing concepts to automatically detect defects. These detections are then processed to provide defect depth-related information. Some advantages to this approach are:

- faster generation of results,
- lower inspection cost,
- objective and consistent detection and sizing estimates
- in-house inspection capability, and
- powerful computer-based data management and archival capabilities.

A more detailed discussion of ECAS is given by Germana and Skiffington.¹

AUTOMATIC DEFECT DETECTION

Before discussing the actual defect detection process itself, several characteristics of the tube scan, a typical example of which is shown in Figure 1, are first described. There are four features of particular interest: the signal start, the signal stop, and two support plate locations. After the probe is pushed to the tube u-bend, the probe remains stationary in the tube, resulting in an almost constant signal level until it is pulled for data collection. The signal start is defined to be when the signal begins to deviate from this constant level. The signal end occurs when the probe reaches the tubesheet, and is characterized by a saturating unipolar pulse. The support plate signals also tend to saturate, first going negative, then positive.

The defect detection algorithm is based on a classical signal processing concept known as the matched filter (MF).² To use matched filtering, an approximation to the signal of interest, in this case pitting, is needed. Fortunately, pits have an easily discernable effect on the eddy current signal. A series of three large defects are shown in Figure 2, each of which is seen to have a negative lobe followed immediately by a positive lobe. This type of response is said to be a roughly antisymmetrical signal. An approximation to this defect response is given by an appropriately scaled version of the derivative of a gaussian pulse,

$$F(n) = -K\left(\frac{n}{\sigma}\right) \exp\left\{-\frac{1}{2} \left(\frac{n}{\sigma}\right)^2\right\}$$

as shown in Figure 3. An overlay of a typical defect and this waveform shown in Figure 4 depicts the degree of similarity between the two waveforms.

Since the probe is manually pulled, there are variations in probe speed between tubes that must be accounted for. The parameter σ is used to adapt the MF to these variations. If the probe speed is low, the eddy current signal will appear stretched and the MF waveform should be expanded. If the speed is high, the signal will appear contracted, and the MF should be compressed. These variations are effectively handled by using a larger or smaller value of σ , respectively.

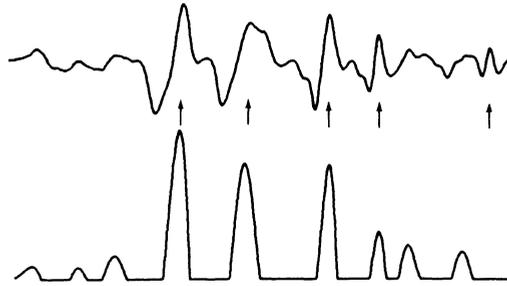


Figure 2. Typical defect response signal and corresponding matched filter output. Only positive values of the MF output are shown.

To adjust σ , an estimate of the probe speed must be obtainable. This is easily provided by looking at the apparent distance between support plates, or between one support plate and the tubesheet. This distance is linearly related to σ . The true distance is a known constant and any apparent deviations from this nominal value are directly attributable to variations in probe speed. Note that the probe speed is assumed to be constant within a given tube — there are only between-tube variations. If the probe speed is not constant within a tube, there is no known way to adjust for its effect, given the current data. In practice, however, constant probe speed within a tube is a quite reasonable assumption.

To detect defects, the MF waveform, with σ appropriately adjusted, is correlated with the eddy current signal. Signal regions containing defect-like signatures will cause high positive peaks at the same position in the MF output. Peaks above a threshold indicate possible defects. This threshold is currently set at 30% of the MF energy. At this level, the threshold provides good detection performance with a low false alarm rate. A typical tube and the corresponding MF output are shown in Figure 2.

Once a possible defect has been located, additional processing is performed to further reduce the false alarm rate. This processing examines the individual contributions of each lobe (negative and positive) to the total MF output. It is expected that these contributions should be roughly equal due to the antisymmetrical shape of the MF waveform and defect response. If they are not approximately equal, the possible indication is called a false alarm. Figure 5 graphically illustrates this procedure for a false alarm and a valid defect.

The detection algorithm, as previously mentioned, is dependent on the waveform shaping parameter σ . An oversensitivity to σ is undesirable, since this would result in highly different detection sets for slightly different σ 's. Fortunately, though, the detection process is very robust to the actual value of σ used. In fact, experience has shown that very large differences, on the order of 30% of the true value, result in very similar detection sets, with most differences being associated with the lower amplitude defects.

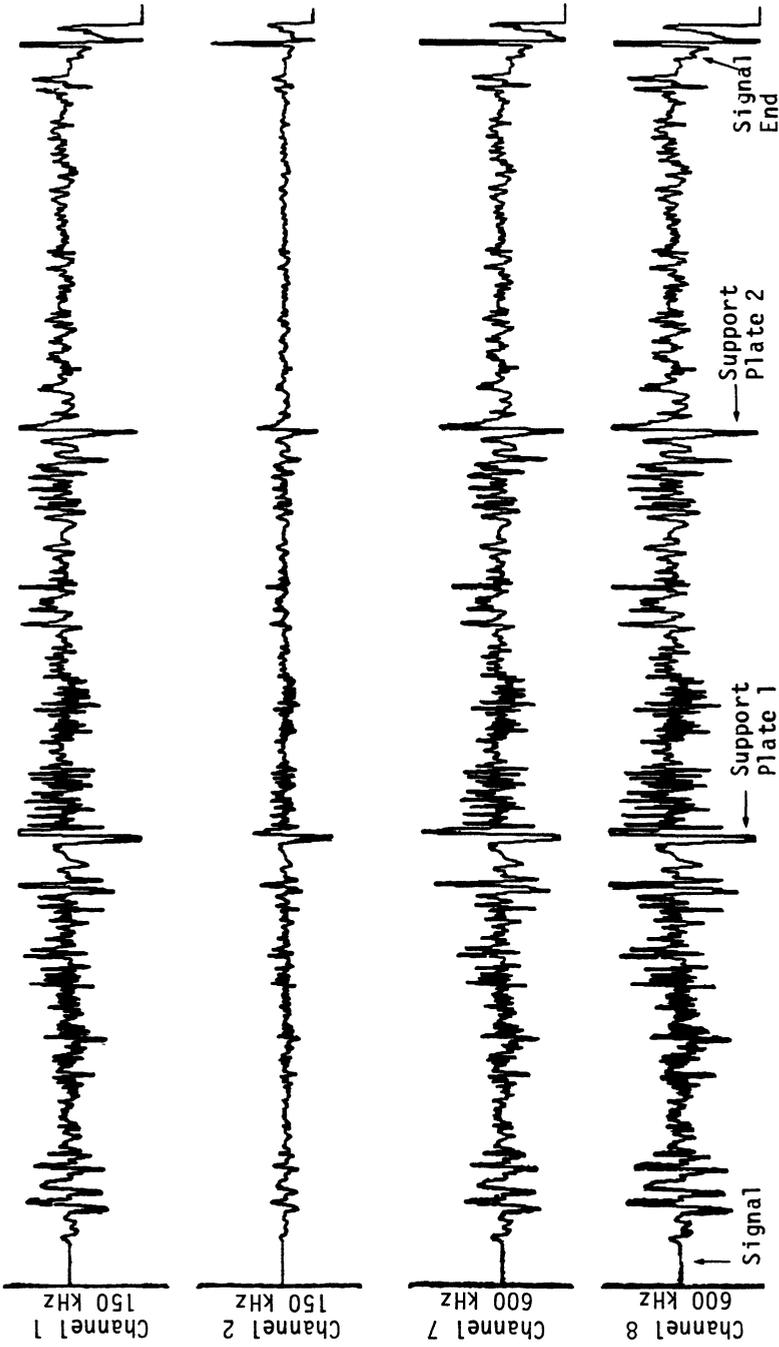


Fig. 1. Stripchart of typical tube. (Only four of the eight channels are shown here due to space limitations.)

$$F(n) = -k\left(\frac{n}{\sigma}\right) \text{Exp} \left\{ -\frac{1}{2}\left(\frac{n}{\sigma}\right)^2 \right\}$$

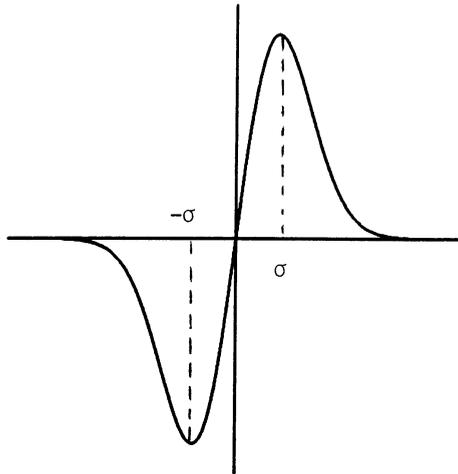


Fig. 3. Matched filter waveform.

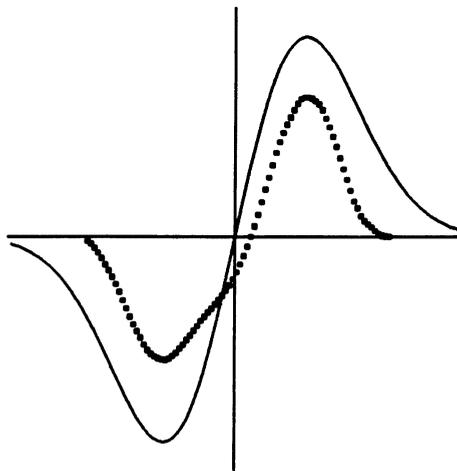


Fig. 4. Overlay of a defect and matched filter, $\sigma = 20.0$.

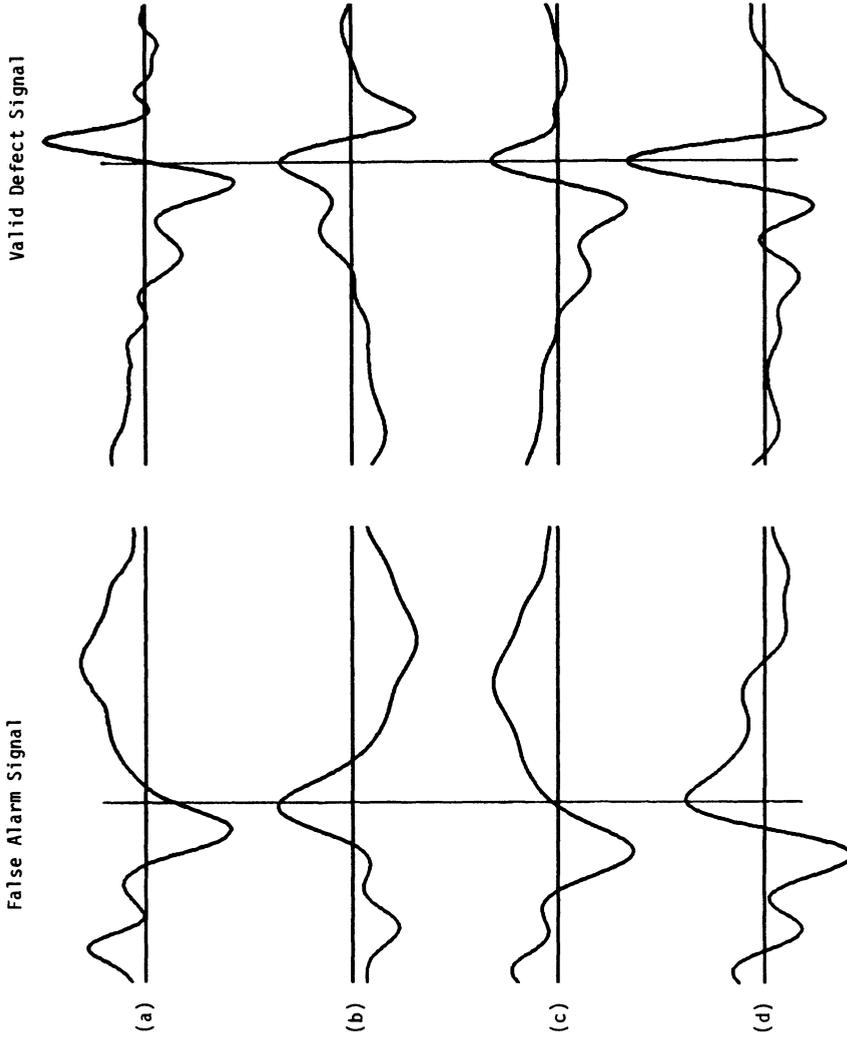


Fig. 5. False alarm example: (a) Eddy current signal, (b) Contribution due to negative lobe of MF, (c) Contribution due to positive lobe of MF, (d) Total MF output.

One way of verifying the detection performance is to compare the ECAS results with known defect locations within a tube. This was done using a section of tube provided by a utility. A map of the inner tube wall, the eddy current response signal, and the MF output are shown in Figure 6. Note the good agreement between the location of the larger defects, the eddy current response, and the detections. Shallow defects not detected with the current threshold level are less than 20% throughwall. Therefore, they are of less importance relative to the larger ones. These results are very encouraging, and help corroborate the ECAS detection algorithm.

The performance of ECAS was also compared to that of human inspectors during a 1982 utility outage. In this test, the system detected all large defects found by the inspectors. In addition, many smaller defects missed by the inspectors were detected by ECAS. Based on this comparison, one can conclude that ECAS performs at least at the level of human inspectors with regard to critical FCU defect detection.

DEFECT SIZING

As mentioned previously, utilities are interested in the bottom line -- accurate and reliable defect sizing. To achieve this goal, good ground truth data and a good calibration standard are necessary; unfortunately, though, neither was available during this study. However, some useful insights and qualitative results for sizing were obtained from the available data as described below.

A similar procedure used in steam generator defect sizing can be used in fan cooler inspections. Steam generator defect sizing relates amplitude and phase measurements to defect depth via a calibration curve. This curve is synthesized using a calibration standard, which is a tube containing outer-wall drilled holes of known depth and diameter, simulating actual defects. As part of the steam generator inspection procedure, the eddy current probe is first pulled through the standard. Fabricated defect amplitude and phase measurements obtained from this standard pull are then used to build the calibration curve. Defect size estimates are made by comparing the defect phase and amplitude to the calibration curve.

For FCUs, defects occur on the inner wall. Therefore, the calibration standard must have drilled holes or EDM notches on the inside. A FCU calibration curve would be created from the FCU standard and used as described above.

Of course, the best approach is to use actual defect depth information to synthesize an estimator. Such information is difficult to obtain because it requires physically removing tubes and measuring the actual defects. If it does become obtainable in the future, a feature-based linear regression approach, such as the ALN methodology,³ can be used to generate an estimator.

The current sizing program computes three measurements -- pulse width, amplitude, and phase -- for each defect. Width is a single-channel measurement, while amplitude and phase utilize both the X and Y channels at a specified frequency (e.g., 600 kHz). Width is defined as the distance between the most negative and most positive part of

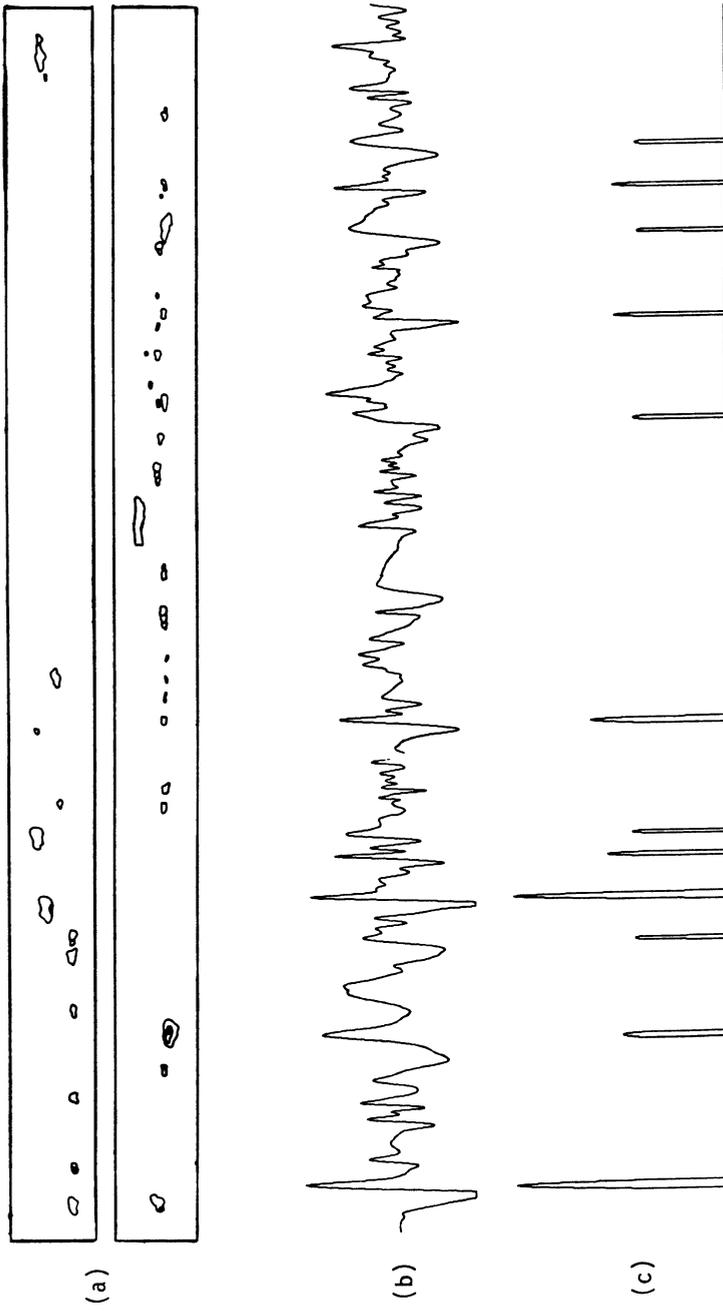


Fig. 6. Comparison of tube interior and ECAS detections:
 (a) Defect map of tube interior;
 (b) Eddy current response signal;
 (c) Matched filter output.

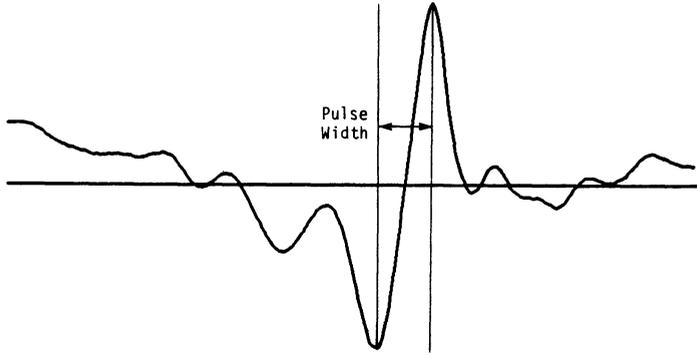


Fig. 7. Definition of defect pulse width.

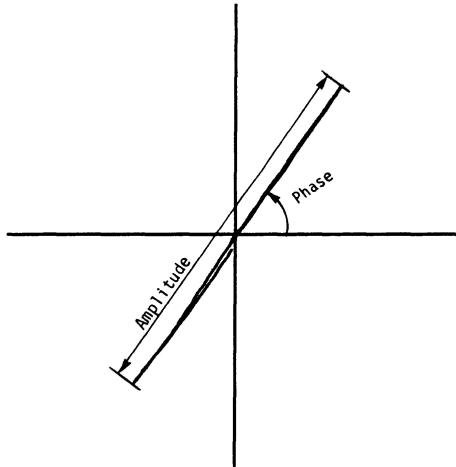


Fig. 8. Defect lissajous pattern with amplitude and phase measurements defined.

the defect response, as shown in Figure 7. Phase and amplitude are defined in Figure 8.

For steam generator defect sizing, phase is an important indicator of depth, in contrast to fan coolers, where phase remains fairly constant. This phase difference is probably attributable to variations in the eddy current penetration depth into the tube material -- inconel for steam generators and 90/10 copper nickel for fan coolers. This phenomena must be further researched to determine if phase is correlated with depth in fan cooler tubing.

Due to the lack of either an adequate calibration standard or ground truth defect data in this study, the relationship between defect measurements and defect depth has not been completely quantified. For now, though, decisions based on amplitude alone give a qualitative indication of defect depth. Large amplitude measurements are usually associated with deep defects, and vice versa. This type of information was reported by GRC personnel to a utility during a 1982 outage and was used as an aid in determining which tubes should be plugged. As a check, several tubes were pulled during that outage and qualitatively analyzed to determine the accuracy of the calls, with good agreement being found.

DISCUSSION

The major outcome of this research was the development of ECAS, an integrated system for eddy current signal analysis. This system provides a general framework for analyzing multifrequency eddy current data collected from FCUs. In addition, the data structures and data management facilities contained within the system are suitable for many other types of eddy current signals, including steam generator inspection data.

Defect detection is performed automatically by ECAS, as are preliminary sizing computations. This automation of the data analysis and interpretation process is the major contribution of this research to the field. No other automatic system for FCU data analysis currently exists, to the best of the authors' knowledge. The major weakness of this work lies in the system's present inability to generate quantitative defect depth estimates, although fairly good qualitative estimates are available.

Future research will be directed toward acquiring the appropriate data and building a good defect depth, diameter and/or volume estimator for FCUs. Other research will be aimed toward applying the concepts and techniques used in developing ECAS to other tubing materials and configurations, in particular, to nuclear steam generators.

REFERENCES

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