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Advanced Eddy Current NDE for Steam Generator Tubing

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Abstract

As part of a multifaceted project on steam generator integrity funded by the U.S. Nuclear Regulatory Commission, Argonne National Laboratory is carrying out research on the reliability of nondestructive evaluation (NDE). A particular area of interest is the impact of advanced eddy current (EC) NDE technology. This paper presents an overview of work that supports this effort in the areas of numerical electromagnetic (EM) modeling, data analysis, signal processing, and visualization of EC inspection results. Finite-element modeling has been utilized to study conventional and emerging EC probe designs. This research is aimed at determining probe responses to flaw morphologies of current interest. Application of signal processing and automated data analysis algorithms has also been addressed. Efforts have focused on assessment of frequency and spatial domain filters and implementation of more effective data analysis and display methods. Data analysis studies have dealt with implementation of linear and nonlinear multivariate models to relate EC inspection parameters to steam generator tubing defect size and structural integrity. Various signal enhancement and visualization schemes are also being evaluated and will serve as integral parts of computer-aided data analysis algorithms. Results from this research will ultimately be substantiated through testing on laboratory-grown and in–service-degraded tubes.

I. Background

Eddy current (EC) testing is the conventional method for inservice inspection (ISI) of steam generator (SG) tubing that is exposed to corrosive, high-pressure, and temperature environments. This nondestructive evaluation (NDE) method has advanced significantly over the years in all areas associated with probe design, instrumentation, and computer-aided data analysis. Multifrequency instruments are routinely used for ISI of SG tubing, and the reported information on potential flaw indications is often based on the calibrated signal amplitude and/or phase from a single original. or processed channel. The information embedded in multifrequency inspection results, however, is not being fully utilized. This is attributed in part to the inherent complexity associated with the interpretation of distorted EC signals from complicated flaw geometries accompanied by extraneous artifacts, as well as to the time constraints that necessitate efficient and careful examination of NDE results on a large number of tubes. Conventional data analysis procedures for characterizing EC flaw indications, particularly cracks, in the presence of external/internal discontinuities and signal background fluctuations are often subjective and rely heavily on operator/analyst judgment and experience. Improved NDE techniques are therefore necessary to enhance detection and characterization of difficult flaws.

Bobbin coil probes have long served as the primary NDE tool for initial inspection of SG tubes. Circumferential windings of this probe are concentric with the tube inner surface and render this probe suitable for high-speed inspection applications. Due to their coil configuration, bobbin probes are inherently insensitive to narrow circumferential flaws that do not possess axial components. High-resolution inspection techniques that utilize multicoil rotating or array configurations are needed to compensate for bobbin coil limitations. Such probes incorporate small coils either as surface-riding rotating elements commonly referred to as motorized rotating pancake coil (MRPC), or multiple-element arrays. As a direct consequence of finer spatial resolution, application of such probes requires the use of more efficient signal processing and data screening procedures. Computer-aided data analysis could render more efficient manipulation of extensive NDE results, thus reducing ISI downtime by automating various stages of the process. Utilization of software-implemented calibration, detection, characterization, sizing, and visualization algorithms would further reduce analyst involvement and consequently allow for more effective and uniform data analysis results.

Corroboration of improved NDE techniques requires examination of a large number of simulated (i.e., electro-discharge machined [EDM] or laser-cut), lab-grown, and field-induced defects. Manufacturing and accurate characterization of a large collection of specimens is a laborious and costly process. Furthermore, complex degradation morphologies are difficult, if not impossible, to reproduce, and complications routinely arise when comparing NDE with destructive examination (i.e., metallographic) results. Accurate computational EM models are valuable tools for researchers and practitioners in EC-related NDE applications. Realistic 3-D computer-aided-design (CAD)–based models could provide a better understanding of the relationship between signal characteristics from different coil configurations and the presence of defects.

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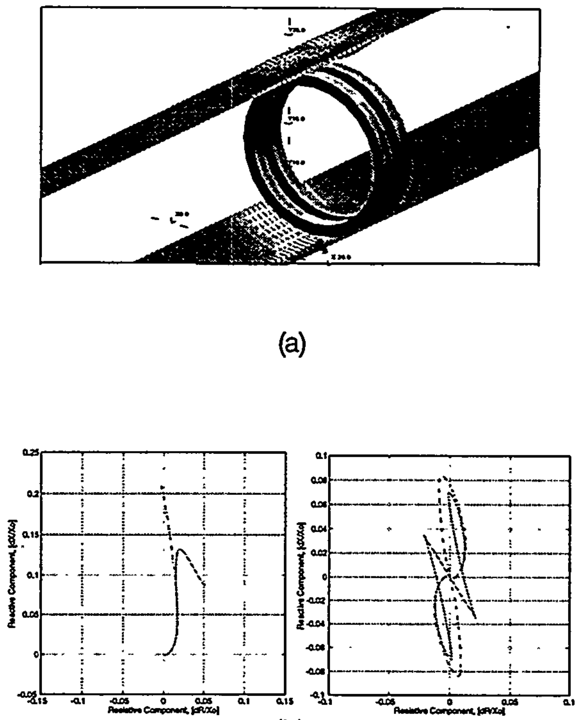
A review of research at argonne national laboratory (ANL) on various aspects of modern eddy current NDE for ISI of SG tubing is presented below.

II. Numerical EM Modeling

Interaction of induced EM fields with heterogeneous conducting media is an inherently complex phenomenon. Computationally efficient analytical solutions are available for only a limited number of ideal axisymmetric probes and test-piece geometries. Numerical solutions are therefore necessary to model more realistic NDE problems. To date at ANL, various analytical and computational modeling approaches to the application of EC probe response for the NDE of SG tubing have been evaluated. The finite-element modeling (FEM) approach was adopted and is being used to study various EC inspection issues of interest. A general-purpose 3-D EM modeling code is currently being utilized to study various conventional and emerging EC probe designs. The software in use is a versatile research tool capable of precise modeling of the complex geometries often encountered during ISI of SG tubing. So far, sample calculations with conventional absolute/differential bobbin and surface-riding impedance probes have been carried out to model axial, circumferential, and volumetric defects [1]-[6].

Representative test cases show visualization of FEM post-processor output for two different EC probes. Figure 1(a) displays the distribution of current density induced by a differential bobbin coil on an Alloy 600 tube with an axial flaw. The ideal flaw geometry modeled in this case is a 75% throughwall (TW), 25.4-mm (1.0-in.)-long axial notch with a narrow radial ligament in the center. The result shown here for a single coil position was part of an extensive study to determine the effect of narrow ligaments in axial cracks on the bobbin probe response [2],[4],[5]. Representative numerical solutions in the form of impedance plane trajectories for absolute and differential coil configurations for a 100% TW notch, with and without ligament, are shown in Fig. 1(b). This study revealed that the presence of ligaments in axial cracks that are known to affect tube structural integrity could also significantly affect EC response. Numerical results of this analysis were later verified through comparison with measurements on tube samples with EDM and laser-cut slots.

Figure 2 shows post-processor visualization of the numerical solutions on modeling of a surface-riding directional coil used as a supplementary probe for ISI of selective locations in SG tubing. Due to the unavailability of simple analytical solutions for such probe configurations, development and assessment of such technology is often made through experimental investigations. Accurate EM models could help in the determination of probe response to various NDE parameters of interest and to further optimize coil designs through efficient simulations. This theoretical investigation was initiated to help answer some fundamental questions regarding probe response as a function of flaw geometry and orientation.



(a)

(b)

Fig. 1. (a) Distribution of current density at 100 kHz on 22.2-mm (0.875-in.)-diameter Alloy 600 tube induced by differential bobbin coil under a 25.4-mm (1.0-in.)-long, 75% OD throughwall notch with a 0.127-mm (0.005-in) radial ligament; (b) comparison of impedance plane signal trajectories for absolute (left) and differential coils with and without ligament being present.

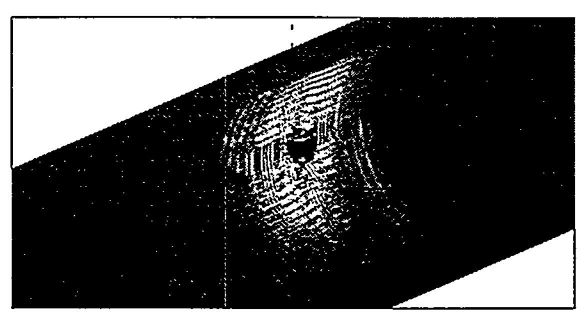
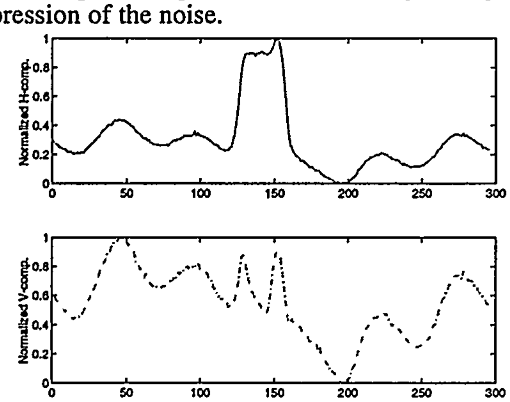


Fig. 2. Distribution of current density at 100 kHz on 22.2-mm (0.875-in.)-diameter Alloy 600 tube induced by directional coil on good section of tube.

III. Data Processing and Display

Research on ISI technology is also connected with the assessment of modern signal processing and data analysis algorithms in application to NDE of SG tubing. The work has focused on implementation of frequency and spatial domain filters, automated data analysis schemes, and construction of more effective visualization methods. Computer-aided data analysis and display methods can improve detection and identification of SG tubing degradations. Spatial and frequency domain algorithms could be applied in real time to help enhance the resolution and dynamic range of inspection results acquired with conventional and modern probes. Various algorithms have been implemented to process and display the EC inspection results in an automated manner. These programs have been primarily implemented under the MATLAB environment and take advantage of the graphical user interface capabilities of this software.

Figure 3 shows the results from typical applications of digital filters for enhanced detection of EC signals in the presence of artifacts and background variations. Figure 3(a) is the absolute bobbin coil trace from a support plate, accompanied by large baseline fluctuations. Figure 3(b) shows the processed data segment subsequent to application of a high-order finite-duration impulse response filter, resulting in significant suppression of the noise.



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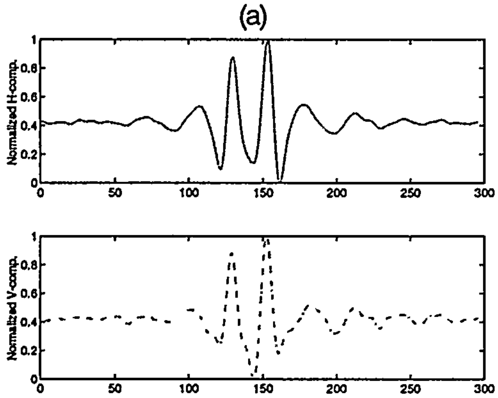
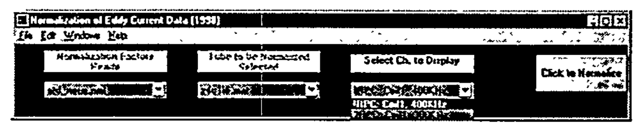


(b)

Fig. 3. (a) Original and (b) filtered data for 400 kHz absolute bobbin coil signal for tube support plate indication.

Figures 4 and 5 show typical user interface tools and processed EC readings in different formats. Figure 4 shows bobbin and rotating pancake coil (RPC) readings that were manipulated and displayed by an automated calibration routine. Visualization of RPC data in both mesh plot and image formats is shown in Fig. 5. The isometric plot simultaneously displays both horizontal and vertical signal components by using elevation and color mapping. For the image display, the depth of each indication is proportional to the intensity of each pixel. The EC readings were made on a calibration standard tube with machined holes and grooves of various sizes. Multiple-frequency display of the processed data as layered slices, also shown in Fig. 4, allows determination of flaw origin (i.e., OD vs. ID). Because the depth of penetration of eddy currents is proportional to the operating frequency, these image slices, in effect, represent different radial cross sections of the tube. In all cases, the shape and orientation of each indication closely matches the corresponding artifact on the tube.



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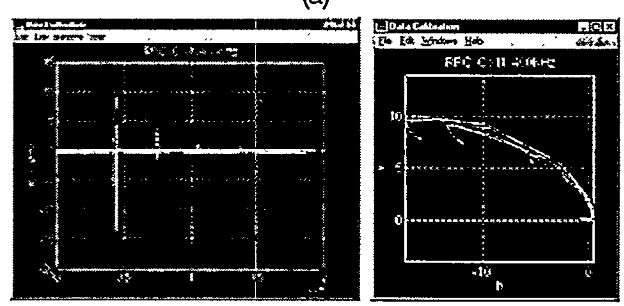

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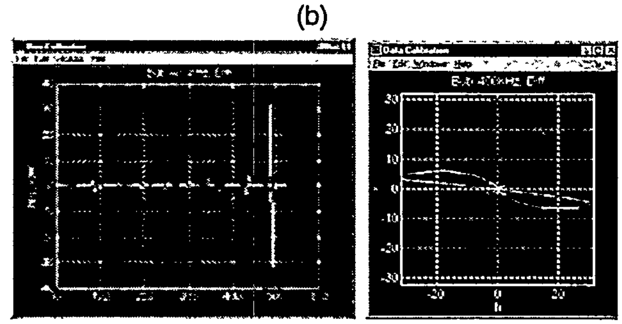

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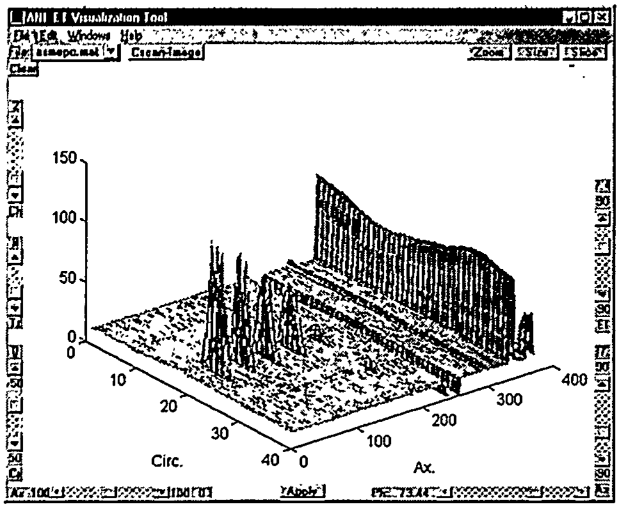
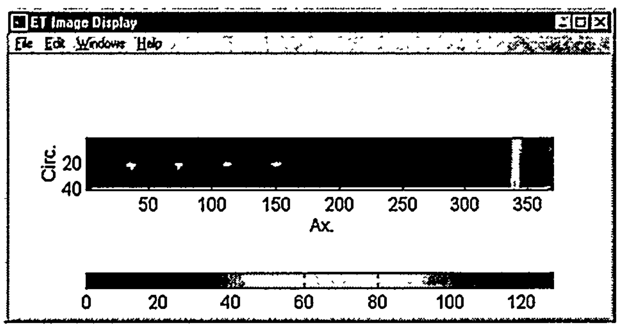
Fig. 4. Typical (a) user interface tool, (b,c) stripchart (left) and Lissajous pattern (right) display of calibrated EC inspection results by an automated calibration routine. Measurements were made on (b) groove standard with 2.92-mm (0.115-in.)-diameter primary pancake coil of three-coil rotating probe and (c) ASME standard with an 18.4-mm (0.725-in.)-diameter bobbin probe.



(a)



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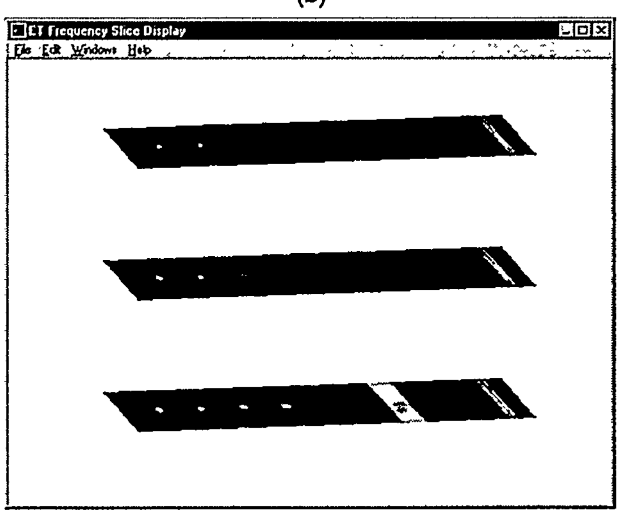

(c)

Fig. 5. Outputs of data visualization showing (a) mesh plot, (b) image display, and (c) frequency slice display of ASME standard tube. Indications from left to right consist of 100%, 80%, 60%, 40%, four 20% OD machined holes, simulated tube support plate, and 10% OD and 20% ID circumferential notches.

IV. Multivariate Data Analysis

Research efforts on data analysis have dealt primarily with the implementation of multivariate regression and neural network models to establish more robust correlations for characterizing of tubing defects. Empirical models that describe potential relationships between EC probe response and tube structural integrity are also being studied. Both linear and nonlinear multivariate analysis methods have been evaluated. For linear models, standard multivariate regression and factor-based algorithms have been utilized. Neural networks, on the other hand, have been applied for nonlinear modeling studies. Both modeling approaches consist of two stages referred to as calibration and prediction. The calibration stage produces a model that relates the probe response to known values of the desired parameters to be estimated. In the prediction stage, the matrix of coefficients and weights describing the system response (input-output relations) is used to estimate the parameters of interest in other measurement test sets.

Various studies on the correlation of bobbin and RPC signals with defect depth have been carried out with data sets collected from tubes with various laboratory-grown and field-induced cracking. Figure 6 shows sample results on prediction of degradation extent for patch-like intergranular attack on field data collected from bobbin coil inspection of once-through steam generator tubes. The regression model was developed from NDE and destructive examination results on pulled tubes from operating plants. Figure 6(a) is a plot of measured versus estimated depth based on conventional phase angle analysis. Clearly, no obvious trends can be observed from this plot. A least-squares linear fit to this data resulted in a correlation coefficient $R < 0.3$. The results of analysis using a factor-based multivariate regression model are shown in Fig. 6(b). A correlation coefficient of $R \approx 0.81$ was calculated in this case. For comparative studies, neural network analysis of the same data base was also evaluated and suggests comparable prediction accuracy of the nonlinear model. Such models could be incorporated into automated EC data analysis software for improved sizing of complex degradation morphologies.

V. Concluding Remarks

Under a U.S. NRC funded program on steam generator tube integrity, argonne national laboratory is carrying out research on the impact of advanced eddy current inservice inspection technology. An overview of studies was presented on various areas of research associated with 3-D finite-element modeling (FEM), signal processing, and data analysis. The numerical simulation studies carried out so far have contributed to validation of FEM accuracy and to acquiring a better understanding of the complex nature of the interaction between induced eddy currents with difficult flaws. Reliable simulation results can be utilized as costeffective and realistic training sets for software-based data calibration, detection, and characterization algorithms and to further help reduce the subjectivity of EC data analysis. Sample calculations were also provided on the application of digital filters and automated data analysis algorithms. Finally, test case results were provided on the application of multivariate data analysis algorithms for construction of improved correlation between nondestructive evaluation parameters and flaw size.

VI. Acknowledgments

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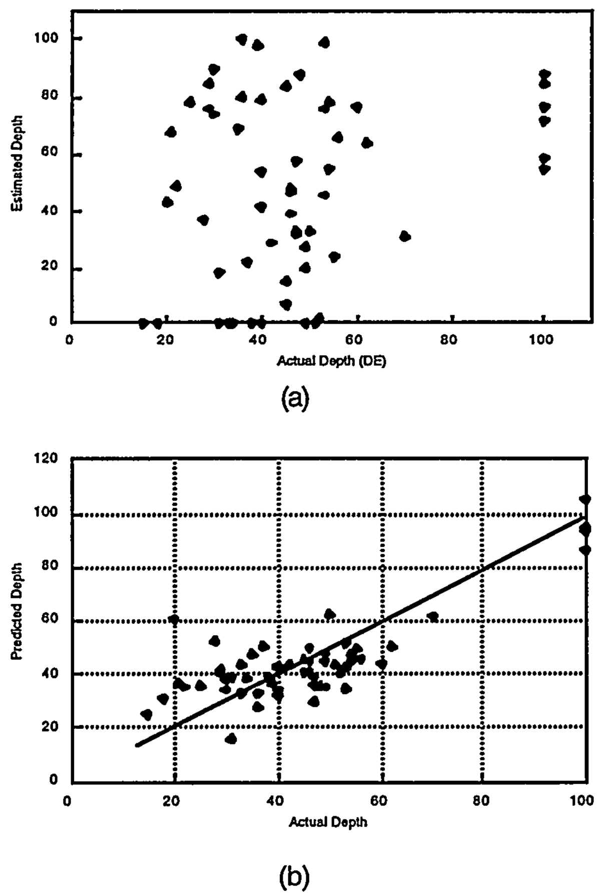

Fig. 6. Measured (by destructive evaluation) vs. predicted depth of intergranular attack in percent wall loss with (a) conventional phase angle analysis of bobbin coil data (R < 0.3, and (b) multivariate regression analysis (R ≈ 0.81).

VII. References

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