Regression Analysis of Pulsed Eddy Current Signals for Inspection of Steam Generator Tube Support Structures

J. Buck[1, 2], P. R. Underhill[2], S. G. Mokros[1, 2], J. Morelli[2] and T. W. Krause[1, 2]
V. K. Babbar[3], B. Lepine[3]
[1] Royal Military College of Canada, Kingston, Ontario, Canada
(j.buck@queensu.ca)
[2] Queen's University, Kingston, Ontario, Canada
[3]Canadian Nuclear Laboratories, Chalk River, Ontario, Canada

A Master's Level Submission

Summary

Nuclear steam generator (SG) support structure degradation and fouling can result in damage to SG tubes and loss of SG efficiency. Conventional eddy current technology is extensively used to detect cracks, frets at supports and other flaws, but has limited capabilities in the presence of multiple degradation modes or fouling. Pulsed eddy current (PEC) combined with principal components analysis (PCA) and multiple linear regression models was examined for the inspection of support structure degradation and SG tube off-centering with the goal of extending results to include additional degradation modes.

1. Introduction

Nuclear power reactor the steam generator (SG) tubes are the thinnest barrier between the secondary and radioactive primary heat transport systems [1]. Regular inspections of the SGs search for tube flaw using non-destructive evaluation (NDE) techniques [2]. Ultrasonic testing (UT) and conventional eddy current testing (ET) are used to accurately detect and size flaws, with ET being the more commonly employed method, due to its rapid volumetric inspection capability. While ET is capable at dealing with single degradation modes it has reduced functionality when multiple degradation modes overlap or tube fouling is present [3]. Degradation of SG tube supports can lead to enhanced flow-induced vibrations [4] causing fretting wear, and the position of the tube within the support structure changes the local water flow, which results in additional degradation modes.

Pulsed eddy current (PEC) is a novel NDE technique that uses a square wave excitation to induce eddy currents. PEC can more readily inspect ferromagnetic materials in which the approach to a DC current results in magnetization of the sample [5]. PEC signals are commonly analysed using a technique called principal components analysis (PCA), which is a statistical method that reduces large amounts of data to a series of discrete scores at each measurement location [6-8]. In order to relate the obtained PCA scores to physical measurements, a multiple linear regression model was considered. As a first step toward independent feature extraction, the effect of varying the inner diameter (ID) of holes in a simple drilled support structure (simulating uniform corrosion) and varying SG tube position within the holes was examined. This examination is a necessary first step towards including additional parameters such as tube fretting wear and, more importantly, fouling in the vicinity of support plates.

2. Theory

In PEC a square voltage excitation of a drive coil is used to generate electromagnetic field interactions in surrounding conducting and ferromagnetic media [9]. Pickup coils can be used to investigate the local electromagnetic field interactions that decay according to the diffusion equation [9]. In addition, ferromagnetic materials are magnetized with the approach to the DC level of the pulse. Sensitivity to these combined effects gives PEC a unique capability unavailable in conventional ET [10].

Principal components analysis (PCA) is a statistical tool that separates large highly correlated data sets into combinations of linearly uncorrelated principle components and associated scores. Using PCA the data can be written as a linear combination of eigenvectors (principal components) and associated scores s_i [6]. In this modified PCA the mean is not subtracted from the original signal [6]. This method allows for incremental reproduction of the original signal while significantly reducing the dimensionality of the data.

3. Experimental Setup

Four 25 mm long SS410 samples, simulating ferromagnetic drilled supports or baffle plates, with hole IDs as shown in Table I, were used to simulate uniform tube-to-support gaps. The sample SG tube was a nominal 15.9 mm (5/8") OD, 46.1 cm long Alloy 800 tube, with wall thickness of 1.2 mm. Although SGs are vertical structures in this experiment the tube was horizontal. A custom apparatus permitted accurate horizontal and vertical positioning of the tube within the hole of the simulated support structure using micrometers. While both horizontal and vertical variation in position was examined, for conciseness only horizontal position results are presented here.

Support hole ID [mm]	Radial gap [mm]	Number of unique tube positions measured
17.1	0.6	9
18.7	1.4	19
20.1	2.1	24
21.8	3.0	43

Table I Number of unique tube positions within each hole for which measurements were taken.

The PEC probe [10] consists of a 127 turn, 36 AWG, excitation coil wound coaxially with the probe body, and 2 arrays of 4 360 turn, 42 AWG, pickup coils placed at 90° intervals around the surface of the probe both before and after the excitation coil as shown in Figure 1. Excitation pulses were generated in LabView and output from a NI6356 USB DAQ at 1000 Hz and 50% duty cycle resulting in a 2.5 V pulse after current amplification. Pickup coil responses were carried by shielded twisted wire pairs to a custom amplification system before being digitized by a NI6356 USB DAQ at 1 MHz. The resistance, inductance and positions of the surface pickup coils were matched for opposite pairs such that the residual between them was minimized while subject to nominally identical sensing conditions.

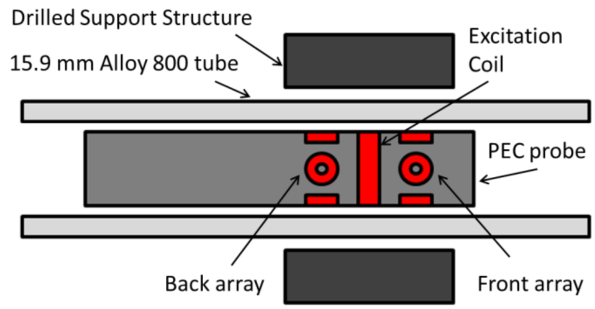

Figure 1 Schematic of the PEC probe inside an Alloy 800 SG tube and drilled support structure viewed horizontally. 4 of the vertically aligned coils can be seen side-on and 2 of the horizontal coils face-on.

4. Results and Discussion

To examine the effect of varying both hole ID and position of tube within the hole a map of points was randomly generated for tube positions given a particular radial gap. Table I shows, for each hole ID, radial gap between tube OD and hole ID and the number of discrete tube positions for which measurements were obtained. Once data was collected at all positions for each hole it was aggregated into a single data set for a PCA performed in LabView. Scores output from PCA were then used as inputs for a multiple linear regression model created in MATLAB, targeting either the support structure hole ID or the horizontal position of the SG tube. Six principal components were retained for each differential coil pair (diametrically opposed coils) resulting in 24 predictor variables for every measurement. A stepwise linear model was created in MATLAB, with a different subset of input PCA scores for each model. PCA score subsets were chosen, exploiting the probe geometry, to remove inputs that were either redundant or lacking information. The fitting equation of the multiple linear regression models can be described as:

$$y \sim A + \sum_{i=1}^{n}\left(B_i s_i + C_i {s_i}^2 + \sum_{j=1}^{n} D_{ij} s_i s_j\right) \quad (1)$$

where A is a constant, s_i are the PCA score inputs, B_i, C_i and D_{ij} are their regression coefficients and n is the number of predictor PCA scores chosen for the particular model.

It is important from an inspection perspective to accurately indicate the amount of support structure degradation that has occurred. The model created to determine the SS410 hole ID was generated from the PCA scores of only the front array of 4 coils as the back pair would add redundant predictors. Only linear and purely quadratic terms of Eqn. (1) were retained in this model as an excellent fit was obtained without interaction terms of Eqn. (1). A comparison of the predicted to measured hole IDs is shown in Figure 2. The best fit line has a slope of 1 with R^2 = 0.9994, demonstrating the predictive capability of the regression model. These results demonstrate that PEC, in combination with PCA and linear multiple regression, can be used to determine the hole size of a ferromagnetic SG support structure independently of the position of tube inside that support.

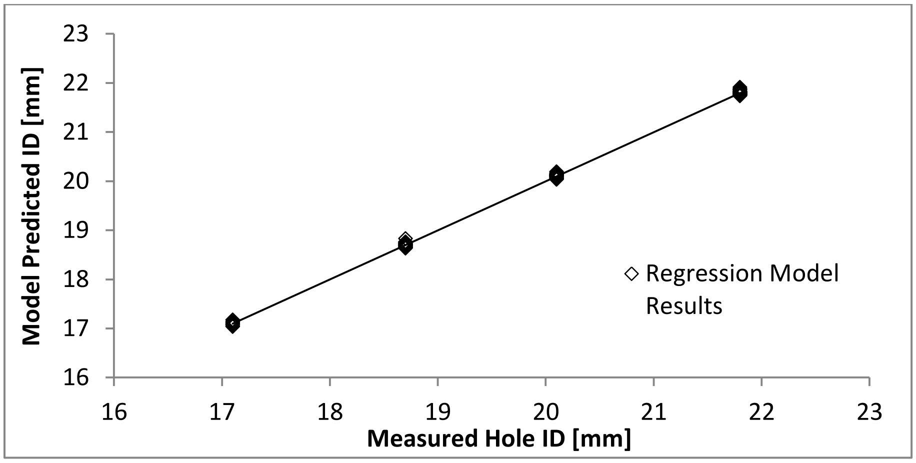

Figure 2 Comparison of regression model results against measured hole ID plotted with best fit line.

The position of SG tubes relative to sides of support structure holes can be used as an early indicator of flaws that may stem from changes in water flow through the support. Locations within the support hole can be mapped to horizontal and vertical positions relative to a nominally centered tube. Exploiting the orthogonal arrangement of coils, only coils aligned with the plane of interest (horizontal in the experimental configuration) were retained for analysis. Horizontal location for 95 tube positions has been compared directly to micrometer measurements in Figure 3, such that data sets with different positions within the hole could be plotted together. The best fit line with slope of 1 and R^2 = 0.9987 again demonstrates the predictive capability of the regression model. Vertical model results demonstrate the same trend as seen in Figure 3, but with a slightly larger spread attributed to more unbalanced coils of the vertical array (R^2 = 0.9784). Determination of position has been shown to be independent of hole ID in this unflawed case.

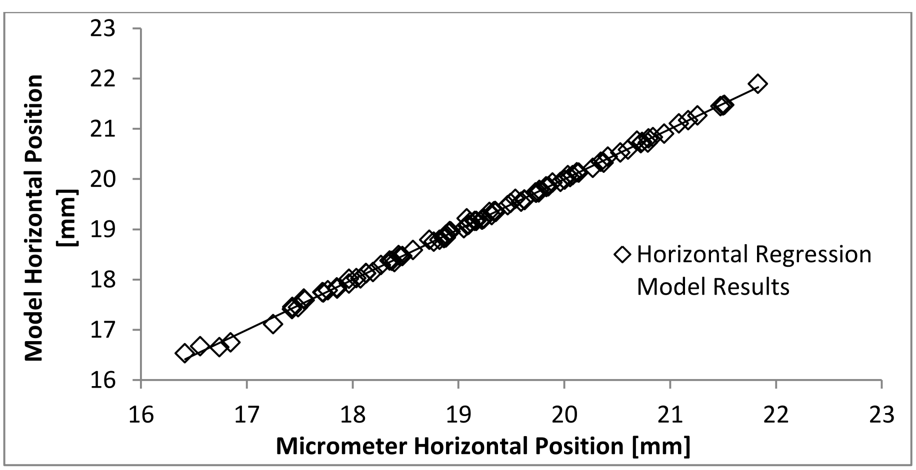

Figure 3 Horizontal tube position predicted by the regression model compared to horizontal micrometer measurements presented with best fit line through the data at 95 different locations.

5. Conclusion

A PEC probe was examined for the inspection of support structures from within Alloy 800 SG tubes. The time-voltage responses of the pickup coils at 95 different random tube locations spanning the 4 hole IDs were subjected to a PCA. The obtained PCA scores were used as inputs to a set of multiple linear regression models created to independently determine the horizontal and vertical positions of a SG tube within a simulated support structure hole as well as measure the size of that hole. Following this work, models will be applied to secondary and tertiary data sets to examine if a generalized model can be created and used as a basis for a SG tube support structure inspection. These preliminary results demonstrate the power of PEC combined with PCA to inspect ferromagnetic materials from within conducting tubes.

6. Acknowledgements

The authors would like to thank Vijay Babbar and Brian Lepine at Canadian Nuclear Laboratories (CNL) for useful discussions. This work has been supported by University Network of Excellence in Nuclear Engineering (UNENE) and Natural Sciences and Engineering Research Council (NSERC).

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