Pulsed Eddy Current Inspection of Support Structures in Steam Generators

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***Abstract*— Degradation and fouling of support structures in nuclear steam generators (SGs) can lead to SG tube damage and loss of SG efficiency. Inspection and monitoring of support structures combined with preventative maintenance programs can alleviate these effects and extend SG life. Conventional eddy current inspection technologies are extensively used for detecting and sizing indications from wall loss, frets at supports, cracks and other degradation modes in the tubes, as well as assessing the condition of support structures. However, these methods have limited capabilities when more than one degradation mode is present simultaneously, or when combined with fouling. Pulsed eddy current combined with principal components analysis (PCA) was examined for inspection of 15.9 mm (5/8″) Alloy-800 tubes and surrounding stainless steel (SS410) support structures. Clear separation of PCA scores associated with tubes from those associated with ferromagnetic SS410 supports permitted measurement of tube-to-support gaps, in either the presence of tube fretting or variation of relative position of the tube within SS410 supports. For concentric tubes, frets could be sized independently of SS410 hole diameter variations, which in other materials could represent support corrosion. Capability to clearly separate scores was attributed to large differences in relaxation times for diffusion of transient fields through the tube compared with diffusion into the ferromagnetic support structure.**

***Index Terms*— Alloy 800, nondestructive testing, principal components analysis, pulsed eddy current, SS410, steam generator tube.**

I. Introduction

STEAM generators (SGs) are critical components for most thermal power reactors. In nuclear reactors such as PWR and CANDU the SG tubes are the thinnest barrier [1] between the irradiated, primary heat transport system and the secondary heat transport system. To ensure continuing safe operation of nuclear reactors, life management strategies are implemented. These strategies involve regular inspections of SG tubes to detect and monitor flaws such as tube fretting wear, corrosion of support structures, and stress corrosion cracking, to name a few [2]. Eddy current testing (ET) and ultrasonic testing (UT) are used to detect and size flaw indications, and are important for providing the necessary information for condition assessments, predicting flaw growth and determining how long components can operate safely. Fretting wear occurs primarily at support structure locations in the pre-heater and U-bend of the SG [3], [4]. Degradation of SG tube supports leads to enhanced flow induced vibration causing further fretting at these and other locations [3], [4]. Currently, ET is used to inspect SG tubes and to characterize both the type and size of tube frets [5]. However, ET has difficulty characterizing support structure degradation in the presence of flaws, such as frets, and the presence of magnetite fouling negatively impacts ET inspection quality [5]. Accurate detection and characterization of frets is important for the life management of the SG, since tubes are 'plugged' once 40% through-wall frets are detected, reducing SG and subsequently, plant efficiency [4].

Pulsed Eddy Current (PEC) is a novel NDT technique that provides some advantages over conventional ET with applications most recently identified in aerospace [6]–[8]. A large lift-off problem was overcome in the inspection of stress corrosion cracking in the inner wing spar of F/A-18 jets [6] and second layer cracks in a thick multi-layer aluminum structure were investigated for CP-140 Aurora [7] using PEC in combination with principal component analysis (PCA). These two techniques have been shown to be effective in detecting surface and subsurface manufactured defects, isolating the effect of lift-off and gap within multi-layer aluminum aircraft riveted structures [9], [10]. PEC has shown potential to identify position and depth of subsurface volumetric flaws in aluminum using an array of Hall sensors [11]. Signals were analysed with PCA, improving on time-domain feature extraction analyses such as peak height and rise time [11]. PEC combined with PCA and support vector machines (SVMs) have shown the potential for automated defect classification in multi-layer aluminum structures [12], [13]. Independent component analysis (ICA) is an alternative analysis technique similar to PCA in that it reduces dimensionality of multivariate data, and is

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beneficial when dealing with noisy, non-gaussian signals using higher-order statistics to generate independent components [13], [14]. Eddy current pulsed thermography, a thermographic inspection technique employing transient eddy current for induction heating, has been shown to produce improved results when subject to PCA and ICA [15].

PEC differs from conventional ET by utilizing a square voltage pulse as opposed to sinusoidal continuous excitation. The pickup coil transient voltage responses can be considered as a series of discrete frequencies, while the approach to direct current (DC) excitation in the pulse provides magnetization of ferromagnetic materials, enhancing pickup coil responses [16], [17]. PEC has also been shown to be sensitive at higher liftoff when compared to conventional ET [18], indicating potential for the inspection of SG support structures from within tubes.

Conventional ET is sensitive to multiple parameters, and the 2D impedance plane view does not permit examination of multidimensional interactions [8], whereas in PEC, sets of time-voltage data are the focus of analysis. PEC pickup coil responses have been analyzed using Principal Components Analysis (PCA) to reduce the dimensionality of the data [6], [7] and to improve flaw discrimination, when compared to simple time-domain analysis [8].

Results presented here examine a modification of a previously developed PEC probe [19] for its potential to inspect support structures in the presence of frets. Theory, including eddy current diffusion and modified PCA, is examined first in Section II followed by a description of experimental set up and measurement technique in Section III. Results and discussion, presented in Section IV, consider SG tube fret measurements at support structure locations, hole size variations with frets present, and tube position within simple support structure holes of various size without frets, analysed using PCA of PEC signals. The ability to clearly separate SG tube and support structure condition demonstrates the potential of PEC combined with PCA as a novel tool for SG inspection.

II. Theory

A. Eddy Current Diffusion

The use of a square voltage pulse induces transient eddy currents in conductive media surrounding the drive coil via Faraday's law of electromagnetic induction [20], which in turn may be sensed by pickup coils. In addition there is a strong magnetization effect in the presence of ferromagnetic materials. This acts as a secondary change in flux as the magnetic field within the material increases with time, therefore amplifying the resulting emf induced in the pickup coils. Eddy currents decay according to the diffusion equation. A square wave pulse can be decomposed into fundamental and harmonic frequency components and therefore, the response contains additional useful information in the frequency domain, when compared to harmonic excitation ET. The frequency spectrum of the PEC response has also been examined with PCA to improve feature extraction [21]. Diffusion of magnetic flux, $\vec{B}$ as described by Maxwell's equations at low frequencies ($<10^8$ Hz) can be written as [20]:

$$\nabla^2 \vec{B} = \mu\sigma \frac{\partial \vec{B}}{\partial t}. \tag{1}$$

The general solution to the diffusion equation of magnetic fields (1) in conducting media is of the form [22]:

$$\vec{B} = f\left(e^{-t/\tau_D}\right) \tag{2}$$

where the solution can often be expressed as a series of relaxation times, which have a reasonable dependence on the conductivity and permeability. The characteristic diffusion time τ_D for these transient eddy currents in a given material can be described by [20], [22]:

$$\tau_D \sim \mu\ \sigma\ l^2, \tag{3}$$

where σ and μ are the conductivity and permeability of the medium, respectively, and ℓ is a characteristic length of the system. The complete transient response can be understood as a series of relaxation times described by (3), with longer times providing greater depth of penetration by eddy currents. With reference to (3), characteristic lengths, ℓ, between the tube and support structures are not greatly different and as such, the eddy current diffusion time is governed primarily by the $\mu\sigma$ component. The two materials of interest here are Alloy-800 with a $\mu\sigma$ product of 1.0×10^6 S/m^2 [23] and ferromagnetic stainless steel (SS410) with a $\mu\sigma$ product between 1.2×10^9 S/m^2 and 1.8×10^9 S/m^2 [24]. From (3), the diffusion time for eddy currents in SS410 is 3 orders of magnitude longer than in Alloy-800, and is therefore expected to affect the PEC pickup coil response at later times. While it is possible that differences in material diffusion times could be used to analyse rise times of raw signals [8], [9] the focus here is the inspection of support structures and not tube flaws. Rise time information is contained in principal components with earlier time peaks. It should be noted that SS410 supports do not corrode in steam generators; however, these samples, with a $\mu\sigma$ on the same order as that of carbon steel (between 3×10^9 S/m^2 and 7×10^9 S/m^2 [25], [26]), were available to demonstrate the potential of using PEC for inspection of ferromagnetic supports in the presence of SG tube fretting. True corrosion introduces local conductivity and permeability changes that have yet to be investigated in relation to this work, but has been shown to have a quantifiable response on PEC signals in combination with PCA [27], [28].

B. Modified PCA

Principal components analysis (PCA) is a statistical method of separating large highly correlated data sets into a combination of linearly uncorrelated principal components and associated scores. The data is assumed to be represented by a sum of a small number of eigenvectors (principal components) such that a column vector $\boldsymbol{Y}$ can be written as [6], [29]:

$$\boldsymbol{Y} = \sum s_i \boldsymbol{V}_i \tag{4}$$

where $\boldsymbol{V}_i$ are the eigenvectors and s_i are the principal component scores. In modified PCA the mean has not been subtracted

TABLE I
IDs OF SS410 COLLAR HOLES USED TO SIMULATE VARYING GAP WITHIN FERROMAGNETIC DRILLED AND BAFFLE SG TUBE SUPPORT STRUCTURES

Collar Number	Hole ID [mm]	Radial Gap [mm]
1	16.5	0.3
2	17.0	0.6
3	18.8	1.5
4	20.3	2.2
5	21.8	3.0

TABLE II
FRET DEPTHS IN ALLOY-800 TUBE

Fret Number	Fret Depth [mm]
1	0.65
2	0.74
3	0.87
4	1.00
5	1.11

from the original data [6]. In this case the eigenvector with the largest eigenvalue is the best possible choice of basis vector (in a least squares sense), accounting for the largest amount of variation in the original data. The second largest eigenvalue indicates the vector that accounts for the largest variation in the remaining data once the first has been removed, and so on. This method effectively allows for a complete reproduction of the original signal, while significantly reducing its dimensionality. This is accomplished through determination of the scores s_i, for each data set, reducing the amount of data from potentially hundreds of points for each measurement to 3-5 scores. By retaining the data mean, the results are less susceptible to instrumentation changes that could result in systematic offsets, which would occur if the average signals were not the same. The modified PCA presents a minimization of the sum square residuals interpretation of the results, instead of a variance minimization interpretation [6].

III. EXPERIMENTAL SETUP

A. Apparatus

Four 25 mm long SS410 samples, simulating ferromagnetic drilled supports or baffle plates, with hole inner diameters (IDs) as shown in Table I, were used to simulate uniform tube-to-support gaps, which in other materials such as carbon steel can represent corrosion of the SG tube support structure. All of the samples were cylindrical and had an outer diameter (OD) of 32 mm and will be referred to simply as collars for the remainder of this work. Two 15.9 mm (5/8″) OD, 46.1 cm long Alloy-800 tubes, with a wall thickness of 1.2 mm (0.05″), were used in this investigation. One of the tubes was as manufactured and the other contained 5 flat frets of successively increasing depth as shown in Table II. The tube frets were 25 mm in length, the same as the length of the SS410 collars used during testing and are shown schematically in Figure 1. Note that this arrangement was selected to demonstrate the capabilities of PEC in a complex flaw/support combination. Only the 4 largest hole IDs, representing increase in ID from the as-installed condition (collar 1) were considered in this study.

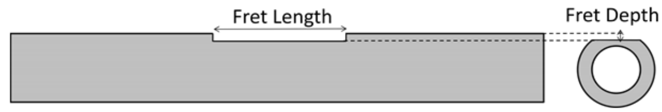

Fig. 1. Schematic of rectangular tube frets including indications of 25.4 mm fret length and fret depth.

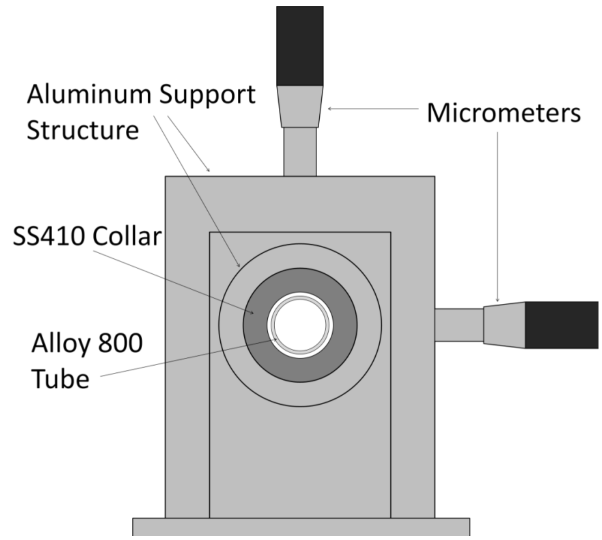

Fig. 2. Schematic of micrometer apparatus used to position Alloy-800 tube within a SS410 collar.

A micrometer apparatus, a schematic of which is shown in Figure 2, was used to hold the Alloy-800 tube within the hole of the SS410 collar. The apparatus held the SS410 collar fixed, but permitted independent control of horizontal (x) and vertical (y) positions of the tube within the hole.

B. Probe

The probe design, based on previous work [19], was modified to include an additional array of 4 pickup coils rotated 90° from the original and is shown schematically in Figure 3. The length and outer diameter of the probe were 77.6 mm and 13.5 mm, respectively. A central drive coil was wound coaxially on the probe body with 127 turns of 36 AWG wire. The two arrays of 4 pickup coils were located in front and behind the drive coil, each wound with 360 turns of 42 AWG wire. The pickup coils were arranged at 90° intervals around the probe in their respective arrays, with all of the axes perpendicular to the drive coil. The signals from the pickup coils were carried by shielded twisted pair wire to a purpose-built amplification circuit. Pickup coil responses were collected separately and were amplified 100 times. Signals were then digitized at 1 MHz using a NI6356 USB DAQ, which was connected to a desktop computer. Opposing coils, at 180°, were matched as closely as possible for signal response in order to enhance sensitivity to the presence of single-sided frets and relative distance from collar ID.

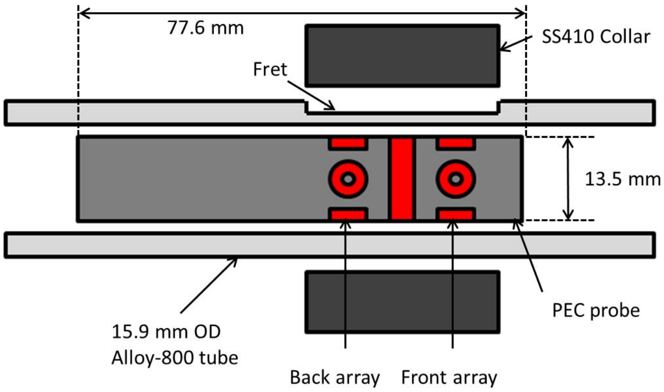

Fig. 3. Schematic of PEC probe inside an Alloy-800 tube with fret located at the SS410 collar.

TABLE III
SUMMARY OF MEASUREMENTS PERFORMED FOR THE PRESENTED RESULTS

Test	Number of measurements	Probe motion per measurement relative to collar center [mm]
Translation	142	2
Centered fret	24	0
Tube off-centering	63	0.25

The excitation pulse was generated by the NI6356 USB DAQ at 1000 Hz and 50% duty cycle ratio, with subsequent current amplification resulting in a 2.5 V square wave pulse, 0.5 ms in duration, and carried to the drive coil with a coaxial cable.

PCA requires inputs spanning all possible flaw arrangements and types such that there is sufficient data for statistical analysis and so that resulting eigenvectors are not restricted to a particular set of measurements. A summary of the measurements obtained for each experiment is presented in Table III.

Translational measurements along tube axis were performed by positioning the probe axially at 2 mm increments within the Alloy-800 SG tube, while a timed LabView program generated excitation pulses and collected pickup coil voltage responses. Each experiment translated the probe by 80 mm, through the tube, past collar and fret location.

Stationary measurements were performed by centering the drive coil of the probe within the SS410 collar. For measurements examining probe response with fret depth, data was collected for frets aligned with the collar and the probe center. To examine the effect of tube movement away from the hole center, the nominal Alloy-800 tube was shifted horizontally across the full hole ID in 0.25 mm increments, with the drive coil centered vertically within the collar, as shown in Figure 3. The latter set of measurements was performed with no fret present.

IV. RESULTS AND DISCUSSION

A. Probe Response

The transient response of the probe demonstrated sensitivity to both the presence of ferromagnetic materials and volumetric tube flaws such as frets, as shown in Figure 4. The amplification of the eddy currents due to magnetization in the presence of a ferromagnetic SS410 collar, made it relatively easy to distinguish it from the signal obtained with only the as-manufactured tube present. However, the free span fret had a subtler impact on the transient response, which could not be as easily identified without a more sophisticated analysis.

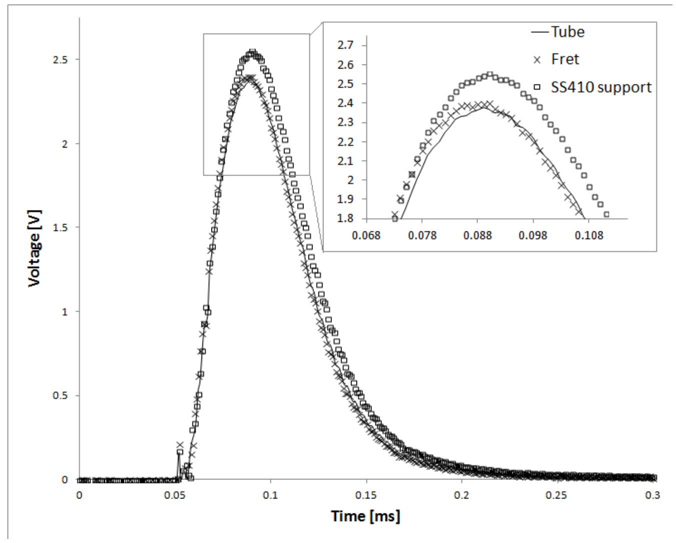

Fig. 4. Transient voltage responses of the PEC probe in an Alloy-800 tube (solid line), an Alloy-800 tube with a fret (x's), and Alloy-800 tube in a ferromagnetic SS410 collar (squares).

The variation in pickup coil response caused by effects in either tube or support structure material, due to the differences in relaxation times as discussed in Sect. II.A, is expected to be readily separable through a signal decomposition technique such as PCA [29] (see Sect. II.B).

B. PCA

PCA was applied to the complete data set once all measurements had been performed. The first four principal components were selected for signal reproductions (using equation 4) resulting in an average reproduction error of the as-measured signal of 0.15%. Higher order principal components were not considered as the reproduction was considered sufficiently accurate for analysis. As appended data sets contained different types of measurements (probe translation, tube translation, and variable fret depth and hole ID) different combinations of generated principal components were used to extract desired information from the results.

Sample normalized eigenvectors for PCA reproduction of the translational data are shown in Figure 5. The shape of the vectors provides some insight as to the physical effects individual vectors are expected to be associated with. The first principal component (V_1) has a shape very similar to the original data, and represents average response of the data. The scores associated with this vector tend to be two orders of magnitude larger than any other score, indicating that it accounts for the largest amount of variation [29]. Voltage amplification due to production of a secondary magnetic field in ferromagnetic materials is expected to have

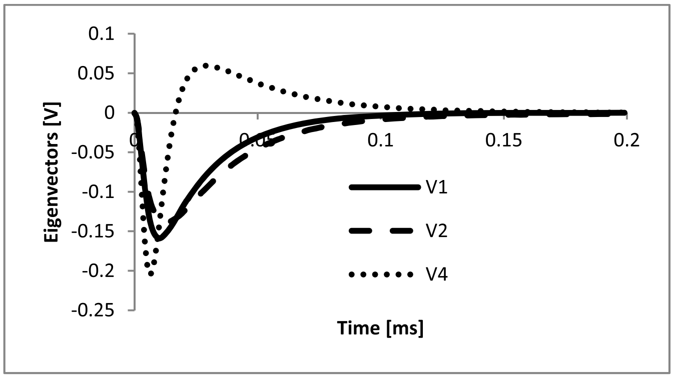

Fig. 5. Eigenvectors V_1 (V1), V_2 (V2), and V_4 (V4) generated from a global data set for the reproduction of signals collected for this work.

an amplification effect on first principal component scores. The second principal component (V_2) peaks later in time and rises more slowly when compared to V_1, suggesting a representation of long relaxation time transients associated with the ferromagnetic collar (see Sect. II.A). The fourth principal component (V_4) has two peaks of opposite sign initially rising much faster than V_2. It represents a shift of intensity from later times to much earlier times. Hence, it is associated with the shorter diffusion times within the Alloy-800 tube (see Sect. II.A). The third principal component (V_3) is not shown as its scores were not used in the analysis. Although the vectors are not generally utilized in the end-state analysis of PCA results, they are useful for providing an insight into physical parameters associated with the resultant principal component scores.

C. Fret Signal Separation and Sizing

The effect of the presence of a fret on principal component scores was investigated. Figure 6 shows three scores as a function of translational position in the tube a) with a fret present, followed further down the tube by a ferromagnetic support structure (collar 2 in Table I) and b) with support structure aligned with the fret. The scores associated with the first principal component (s_1), which multiply V_1 to produce the general trend of the data, are observed to remain constant, while the probe translates through the Alloy-800 tube and fret, only decreasing in the presence of the collar. In both cases the magnitude of change in s_1 appears independent of the presence of tube flaws (frets). The second principal component score (s_2) appears to have a slight dependence on the fret and a stronger opposing dependence on the support structure as shown in Figure 6(a). The opposing response of s_2 is evident as a reduced signal response to the fret and collar at the same location as shown in Figure 6(b). Finally, the fourth principal component score (s_4) is only sensitive to position of the 43% through-wall rectangular fret, displaying the same characteristic shape and peak-to-peak magnitude of 0.9 in Figures 6a) and b). The clear independence of s_1 from the effect of frets and independence of s_4 from the effect of the ferromagnetic collar may be related to relative dependencies arising at later and earlier times, of eigenvectors V_1 and V_4, respectively, as discussed in Sect. IV.B.

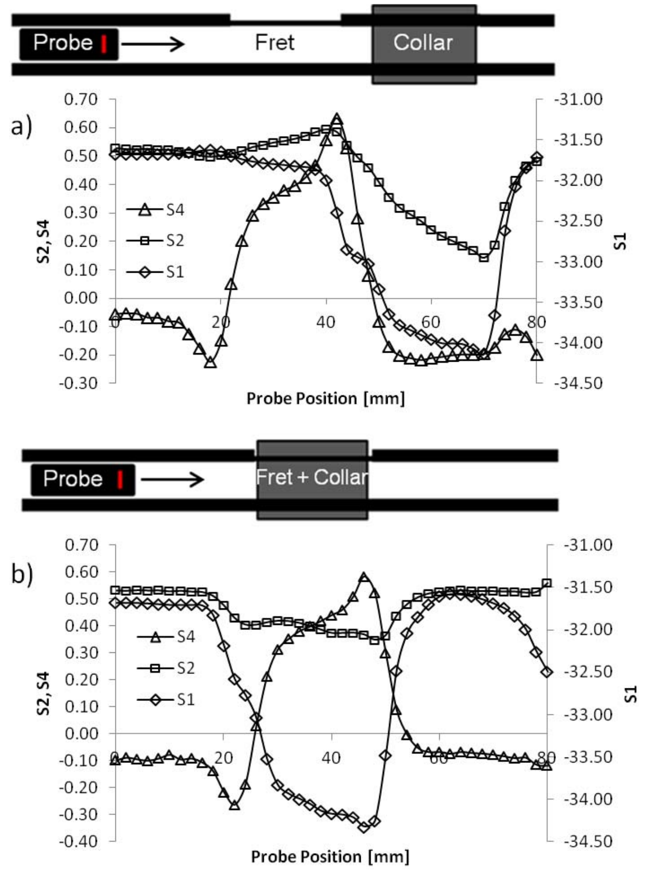

Fig. 6. First three principal component scores along an Alloy-800 SG tube, s_1 (S1) on right vertical axis, s_2 (S2) and s_4 (S4) on left: a) for 43% through-wall fret and SS410 collar at different positions and b) fret and collar at the same position.

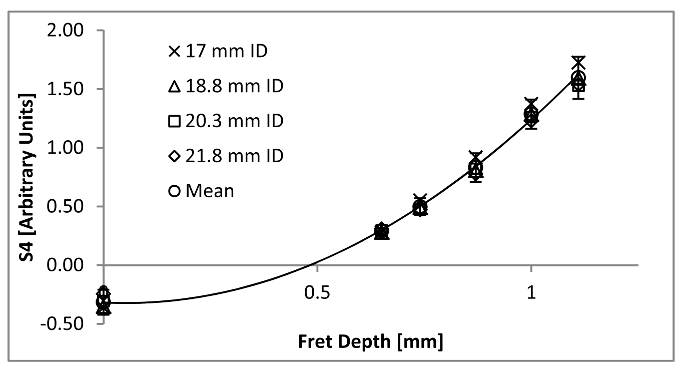

Fig. 7. Relation of s_4 (S4) and fret depth for various ferromagnetic collar hole IDs, best fit with a quadratic polynomial.

To further investigate the effect of tube frets on the PEC response, measurements with a stationary probe were conducted, while both through-wall fret depth as well as collar hole ID were varied. The tube was centered within the hole for this experiment. A clear trend is observed in Figure 7, for s_4 with fret depth largely independent of collar ID. Data has been best fit with a quadratic polynomial. Clearly, PCA provides good separation of tube fret response from ferromagnetic support structures, facilitated by the large relative difference in characteristic diffusion times (see (3) in Sect. II.A).

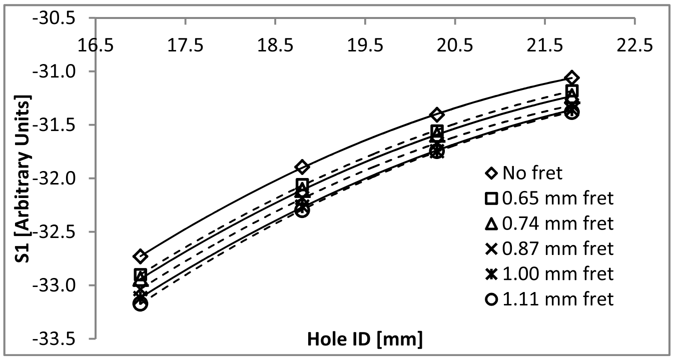

Fig. 8. s_1 (S1) as a function of hole ID for each of the fret depths. Solid and dashed curves are quadratic polynomial best fit to the data.

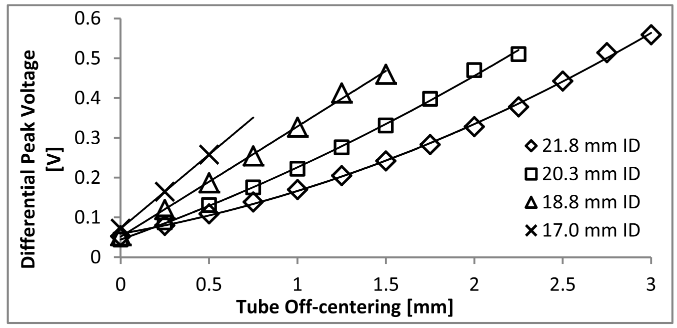

Fig. 9. Differential peak voltages of coils 4 and 8 plotted against horizontal tube off-centering for each collar (IDs in legend). Solid curves are quadratic polynomial best fits to the data.

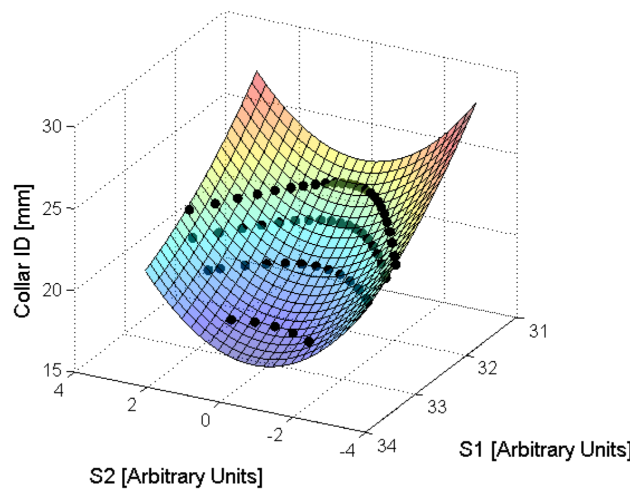

Fig. 10. Surface plot of s_1 (S1), s_2 (S2) and collar ID demonstrating use of PCA scores to determine both horizontal tube position and SS410 support structure hole ID, simultaneously.

As the depth of a fret increases for a given collar hole ID, there is an increase in magnitude of s_1, as shown in Figure 8. This can be attributed to less material at the fret, which reduces the shielding effect of SG tube and thereby increases probe response to the collar. The increase in magnitude is a consistent trend between collar sizes and therefore, once fret depth is known, the collar can be sized by comparing s_1 to the appropriate curve shown in Figure 8.

Relative independence between hole ID and fret response in the PCA scores s_1 and s_4, respectively, was associated with the 3 order magnitude smaller diffusion time through the SG tube wall compared with diffusion into surrounding support structure as estimated in Sect. II.A. These independent effects were also reflected in the difference between orthogonal eigenvector V_1, associated with the large signal response due to support structure and variations therein, and V_4, which exhibited an early time peak associated with the short diffusion time penetration of fields through the SG tube wall and thereby, sensitivity to the presence of fret depth variations. With increasing fret depth these diffusion times become shorter in amplitude along with the removal of shielding effect of the SG tube on support structure electromagnetic field interactions.

D. Tube Shift and Collar Hole ID Sizing

Proximity of PEC probe pickup coils to the ferromagnetic samples being inspected has a significant effect on response signals. By combining data from two coils on opposite sides of the probe differentially, this proximity effect becomes apparent in the peak response voltages as seen in Figure 9 for coil pairs 4 and 8. This is consistent with previous FE model results obtained over a wider range of tube positions within the SS410 hole [19]. Although the results of Figure 9 show a consistent trend for tube shift quantification, the peak height varies with collar hole ID. PCA has been used here to extract tube off-centering and collar hole ID, simultaneously. The first two principal components should contain enough information within them to reproduce signals in the presence of tube shift and hole ID variation.

Figure 10 illustrates a calibration surface that is constructed by plotting s_1, s_2 and collar ID under these conditions. s_2 provides a good estimate of horizontal position of the tube within the ferromagnetic collar, while the combination of s_1 and s_2 are unique for a given tube position and collar hole ID. By generating s_1 and s_2 from acquired data and comparing it to the calibration surface, collar hole ID can be determined. A best fit surface created for Figure 10 provides a relation between s_1, s_2 and collar ID in the form of:

$$ID = A\,(s_2)^2 - B\,(s_2) + C\,(s_1)^2 - D\,(s_1) + E(s_1)(s_2) + F \tag{5}$$

where A, B, C, D, E, and F are best fit parameters, and s_1 and s_2 are generated from PCA on data using existing calibration eigenvectors.

The results presented here are limited to the horizontal plane, but it is postulated that a similar trend as seen in Figure 10 would appear in s_2 for the vertical plane of coils. By utilizing the full 8 coils of the probe the true position of the tube within the collar could be determined in conjunction with hole ID.

This work has not considered the combination of fret sizing and horizontal shift of the tube, under conditions of varying SS410 hole ID. Magnetic sludge and ID magnetite fouling are encountered in nuclear reactor SGs and their effects on the PEC results also require examination.

V. Conclusion

This paper described the development of a pulsed eddy current inspection method, utilizing principal components analysis (PCA), for the simultaneous determination of tube position and ferromagnetic SS410 support structure hole inner diameter (ID), simulating corrosion, in Alloy-800 SG tube. Depth sizing of rectangular frets was demonstrated as being independent of variations in SS410 hole IDs. PCA was shown to be a robust analysis technique that provided good separation of tube and support structure effects on PEC signals. This independence was associated with the difference in diffusion times through the SG tube wall, compared with diffusion of electromagnetic fields into the surrounding support structure.

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