AFRL-RX-WP-TM-2014-0064

SPLIT D DIFFERENTIAL PROBE MODEL VALIDATION USING AN IMPEDANCE ANALYZER (PREPRINT)

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February 2014
Final Report

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MATERIALS AND MANUFACTURING DIRECTORATE
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

NOTICE AND SIGNATURE PAGE

AFRL-RX-WP-TM-2014-0064 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YY)***
February 2014

2. REPORT TYPE
Final

3. DATES COVERED ***(From - To)***
12 November 2009 – 12 January 2014

4. TITLE AND SUBTITLE
SPLIT D DIFFERENTIAL PROBE MODEL VALIDATION USING AN IMPEDANCE ANALYZER (PREPRINT)

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62102F

6. AUTHOR(S)
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Ryan D. Mooers and Shamachary Sathish, University of Dayton Research Institute
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5d. PROJECT NUMBER
4349

5e. TASK NUMBER

5f. WORK UNIT NUMBER
X08J

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials State Awareness Branch (AFRL/RXCA)
Wright-Patterson AFB, OH 45433-7734

See back

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
Wright-Patterson Air Force Base, OH 45433-7750
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RXCA

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RX-WP-TM-2014-0064

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PA Case Number: 88ABW-2013-4411; Clearance Date 17 Oct 2013. Conference paper to be published in QNDE 2013 Conference Proceedings. This is a work of the U.S. Government and is not subject to copyright protection in the United States. This document contains color.

14. ABSTRACT (*Maximum 200 words*)
Benchmark and validation studies are presented that quantify the accuracy of computational models. An important factor in these studies is the ability to compare simulated impedance results with experimental data. In a majority of differential benchmark studies the data acquisition is handled by a commercial eddy current instrument which allow for only a relative comparison of the data. In this study a novel data acquisition system allows for the collection of impedance data for differential probes. Details about the data collection, experimental procedure, model construction, and data comparison will be presented.

15. SUBJECT TERMS
Split D, differential probe, validation, impedance values

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Mark P. Blodgett
Unclassified	Unclassified	Unclassified	SAR	12	**19b. TELEPHONE NUMBER** *(Include Area Code)* (937) 255-9799

REPORT DOCUMENTATION PAGE Cont'd

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Split D Differential Probe Model Validation Using an Impedance Analyzer

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Abstract. Benchmark and validation studies are presented that quantify the accuracy of computational models. An important factor in these studies is the ability to compare simulated impedance results with experimental data. In a majority of differential benchmark studies the data acquisition is handled by a commercial eddy current instrument which allow for only a relative comparison of the data. In this study a novel data acquisition system allows for the collection of impedance data for differential probes. Details about the data collection, experimental procedure, model construction, and data comparison will be presented.

Keywords: Split D, Differential Probe, Validation, Impedance Values.
PACS: 02.70.-c, 81.70.Ex

INTRODUCTION

Benchmark and validation studies in eddy current NDE are needed to understand and quantify model discrepancy between computational models and experimental data. While the majority of benchmark studies are performed with absolute probes, there is a need to better address models for differential probes, which are mostly used for eddy current inspections of aerospace components. However, this leads to a problem with data comparison. In order to truly validate a model, the simulated impedance response should be compared directly with impedance measurements. For differential probes this can be difficult since most impedance analyzers are not configured to accept inputs from differential probes. Often, commercial eddy current instruments are used, but these only give a voltage representation of the response change due to a defect and only support relative comparisons with respect to a calibration standard. This paper will detail a validation study using a representative split D differential probe. However, in this paper a specially designed data acquisition system is used that enables an impedance analyzer to collect data from a differential probe. This connector was built in-house and the construction and operation will be discussed. In addition detail about the validation experiment, the construction of the simulation model and the data analysis will be given. Finally the major results of the validation study will be highlighted.

PREVIOUS WORK

Overall the number of validation studies performed using differential probes is much smaller than those using absolute probes. Differential bobbin probe used for pipe inspections are one design of differential probe that has been modeled in the past. These probes are composed of two circular coils set on a former. In these probes the coil normal axis is parallel to the scan axis, see Figure 1a. A large number these studies are based on a problem known as the TEAM Workshop Problem 8 [1-5] which is part of a collection of problems to test electromagnetic models. For this problem, a probe composed of 3 circular coils, an outer drive and differential receiving pair, is scanned across a notch in a conductive plate. A diagram of the probe can be seen in Figure 1b. This problem is relatively simple to solve with today's state-of-the-art modeling software due to the circular nature of the coils and the absence of ferrite cores. However there have been attempts at validating more complex probe designs. By adding ferrite cores but retaining the circular coil shape the level of model complexity can be increased. A probe of this design is modeled in [6, 7] for pipe inspections, a diagram of the probe is shown in Figure 1c. Changing the shape of the coils and including ferrite cores and shields adds another level of complexity. Split D probes have this design. A diagram of these probes can be seen in Figure 1d. Nakagawa et al. has run validation exercises on split D style probes [8-10]. In the probe diagram images the coils are gray with a black outline, non-ferrite cores are shown white with a black outline, and ferrite cores and shields are shown black.

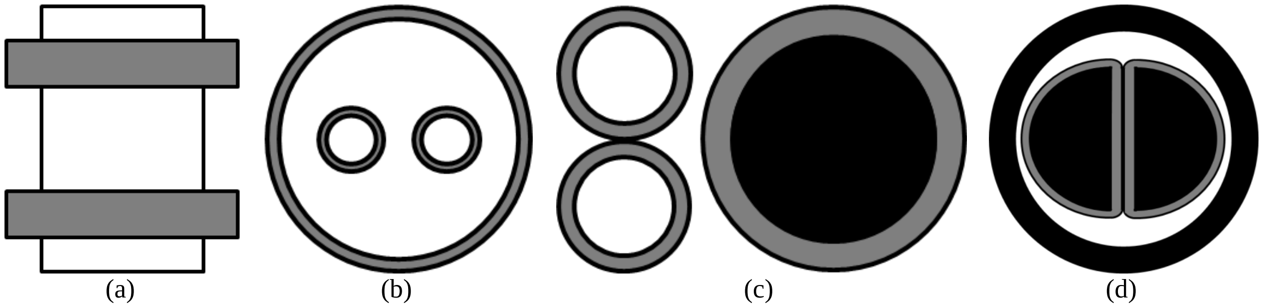


FIGURE 1. Probe diagrams for the various probe types used in differential benchmark studies: a) Differential bobbin probe, b) TEAM Workshop Problem 8, c) reflection differential probe composed of circular coils, d) Split D Differential Probe

EXPERIMENTAL DETAILS

Validation studies rely on a very rigorously controlled scan where as much variability between scans is removed. It is also necessary to have a very well characterized probe. The scanning system, the probe, and the specimen used in the study have been used for various benchmark and validation studies in the past. The next few sections will provide some details about the test problem and the data collection including the new cabling system that was employed.

Test Problem Description

A representative split D differential probe as shown in Figure 1(c) is scanned over a surface breaking electric discharge machining (EDM) notch in a conducting plate. The probe has a center frequency of 2 MHz, an outer ferrite shield, and has ferrite cores within the D-coils. The test specimen is Ti-6Al-4V with an assumed conductivity of 0.58 MS/m (1.00% IACS) [11]. The specimen has five rectangular notches running down the center with lengths ranging from 0.100" (2.5 mm) to 0.020" (0.5 mm). All notches have a 3:1 length to depth aspect ratio and a constant width, 0.005" (0.125 mm). Only the longest two notches (0.100" and 0.080") were scanned for this exercise. Images of the specimen and probe can be seen in Figure 2. Two scan directions were used, corresponding to the *x* and *y* axis in Figure 2a. Scans along the *x* axis were 6 mm total in length while those along the *y* axis were 12 mm. Both used a scan increment of 0.1 mm and were centered over the notch. The scan lengths were chosen to ensure that the extremes of the scans were sufficiently far from the defect as to produce no response signal. In each scan the probe was oriented with the scan direction parallel to a line connecting the centers of the D shape cores; the probe orientation for scans in the *x* direction is presented in Figure 2c.

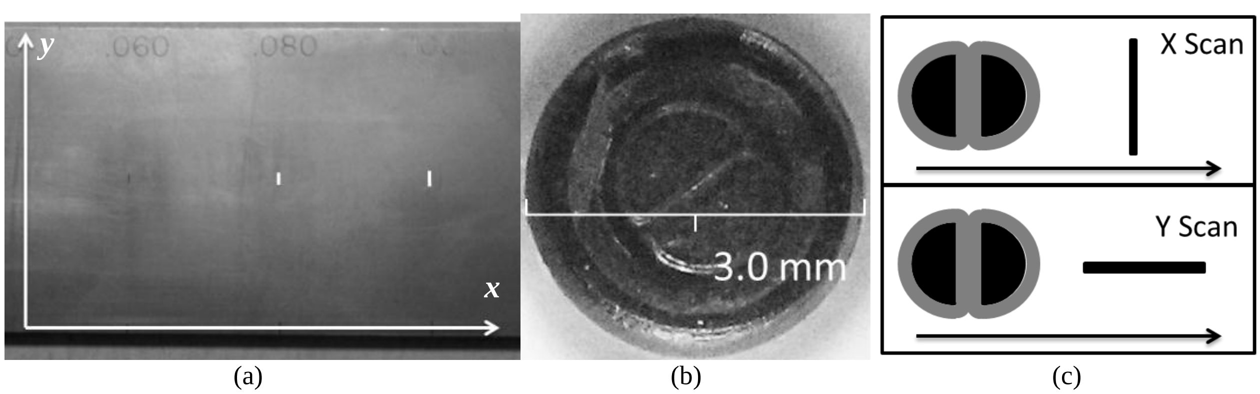


FIGURE 2. a) Specimen showing 2 largest EDM notches scanned in exercise, b) Image of the face of probe used in the study, c) Image showing the orientation of the probe when scanned.

(a) (b) (c)

FIGURE 3. a) Images of the Impedance Spectroscopy System (ISS), and the two data collection instruments used in the validation experiments: b) Agilent 4294A Impedance Analyzer, c) Nortec 2000D Eddy current meter

Experimental Data Collection

Specimen position and data collection was performed using an in-house scanning system called the Impedance Spectroscopy System (ISS). The ISS consists of three stages, two of which are used for specimen motion, and a tilt stage for specimen alignment. The system is controlled by custom developed LabVIEW programs. The tilt stage, along with a second custom LabVIEW program, is used to level the specimen to the scan plane. By moving over the specimen and adjusting the tilt stage the specimen can be effectively leveled. This reduces the need for external methods for controlling liftoff. Data collection can be handled by either an Agilent 4294A impedance analyzer or through a commercial eddy current meter (for example a Nortec 2000D or 19e[II]). Both the Agilent and the Nortec 2000D were used for data collection. The Nortec is used to verify that the impedance data collected by the Agilent is accurate in terms of shape. Images of the scanning system and the two data collection instruments can be seen in Figure 3. A total of 5 data sets were collected with each of the instruments. For the data taken with the impedance analyzer this means a total of 10 scans were needed. This is a result of the custom cabling system. Each experimental scan with the impedance analyzer only collects data from one coil in the probe. Consequently this means two scans are needed to collect a full impedance analyzer data set.

Data was taken at only 2 MHz to speed data collection. The impedance analyzer was set up in its most accurate configuration with a bandwidth setting of five and both point and sweep based averaging. The Nortec signal was set with zero phase offset to maintain an unaltered signal from the probe. The magnitude for each notch was set to be 80% full screen height and width for all data sets. For experimental scans conducted with the Nortec, the system was nulled at the starting point of the scan to provide the response change due to the defect.

Custom Cabling System

A new data acquisition system was constructed to allow for collection of the impedance data using the Agilent. The probe is connected to the impedance analyzer through standard and custom cabling and connection devices. A triax cable (with two separate shielded conductors) is used to connect the probe to the new system. The first component, Figure 4a, is a custom cable composed of two coaxial cables terminated by a standard 8 pin Burndy connector. This cable effectively splits the signals from the two coils. Each conductor in the triax cable is diverted into the center conductor of one of the coaxial cables. The shield from the triax cable is connected to the outer conductor of the coaxial cables. Each of the coaxial cables is labeled with information relating to which coil the data is collected from, which is important for post-processing. These coaxial cables are connected to the impedance analyzer through a custom wired box, Figure 4b, that transfers the signal for the cable to the appropriate connectors on the impedance analyzer. The center pin on the input BNC is connected to the center pins of the high current and potential output BNC's. The input BNC's outer pin is connected to the center pins on the low current and potential BNC's. The connecting wires are connected to the outer pins on the output BNC's, and the ground plane is established by soldering the shields of the wires together. During experimental scans each of the coaxial cables is connected to the box for a predefined number of scans then switched. After post processing, discussed later, this gives the predefined number of data sets, in this case five.

(a) (b)

FIGURE 4. Images of the custom connector system used to collect impedance data: a) custom cable for splitting signal, b) connection box for impedance analyzer

SIMULATION DETAILS

The simulations were run in VIC-3D® [12-14] which is a volume integral code developed by Victor Technologies. VIC-3D® begins with the sinusoidal steady state form of Maxwell's Equations given below (1 and 2) where **E** is the electric field intensity, **B** is the magnetic induction, **M** is the magnetization, and **J** is the true electric current density.

$$\times \boldsymbol{E} = -j\omega\boldsymbol{B} \tag{1}$$

$$\times \boldsymbol{B} = j\omega\mu_0\epsilon_0\boldsymbol{E} + \mu_0 \quad \times \boldsymbol{M} + \mu_0\boldsymbol{J} \tag{2}$$

VIC-3D® solves for the necessary fields by calculating the anomalous currents in the coil and the anomalous magnetism in the core and shield, if present. VIC-3D® meshes only the defect and the cores and shield, if present; the rest of the computational domain is computed through the use of Green's Functions. For this problem the iterative solver is employed due to the computational complexity of the cores and shield. The mesh used for the probe was 32x32x32 (in *x*, *y*, and *z*) while the defect mesh was 32x2x16. The defect mesh resolution is setup such that the dimensions of the volume elements are roughly equal along the three axis direction. Simulated scans followed the experimental scans shown in Figure 2c in scan length (*x*: 6mm, *y*: 12 mm), frequency (2 MHz), and orientation (scan direction parallel to a line running between D core centers). The specimen conductivity was set to be 0.58 MS/m and the relative permeability (μ_r) of the ferrite cores and the shield was 2000.

Model Construction

The specimen was modeled as a semi-infinite plate surrounded by air on both free surfaces. The EDM notch is modeled as rectangular region with zero conductivity. Dimensions for the probe model were found through images shown in Figure 2b, a scale bar was included to give a size reference. The dimensions are representative of a split D differential probe. By using pixel values and a known dimension it was possible to work out all necessary dimensions for the probe model. However due to the quality of some of the images certain approximations were necessary, namely the internal liftoff of the probe. The internal liftoff was approximated through a series of simulations with varying total liftoff. These results were then compared to the results of the first experimental data set. By matching the magnitude with the best case the internal liftoff can be determined. This value was then set as a constant for all other simulations. As with all models in VIC-3D®, construction order is crucial to producing an accurate model. With the probe having an outer ferrite shield this must be modeled first. The shield is modeled first as a circular cylinder with a diameter equal to the outer diameter of the shield and the desired relative permeability value. This is hollowed out using a second circular cylinder with a diameter equal to the shield inner diameter and a relative permeability of one. The cores are modeled using a circular cylinder that is offset in the *x* direction by an amount equal to half the core gap; they are then clipped in half, along the *yz* plane, using a clip plane to create the D shape. VIC-3D® already has a provision to model D shaped coils [14], which makes the process straight forward. The important factor when modeling the different objects is ensuring they are located vertically in the coordinate system correctly relative to each other for setting liftoff. The total liftoff is set for the whole probe after modeling all the necessary components.

4-Coil Construction Method

The 4-coil construction method models each coil in the probe as both a transmit and a receive coil occupying the same space. This method was determined to be best after running a series of simulations with various coil construction methods. In each of the following construction methods only D shaped coils are used. The different constructions methods were: 1) shaped drive coil, 2) drive/ receive, 3) 2 drive coils, 4) 4-Coil Method. The single D case is a transmit coil positioned in one of the probe locations while the two drive case uses transmit coils in both probe locations. The drive/ receive case uses a transmit coil in one location and a receive coil in the other. In previous split D validation studies [15] the drive/ receive method was also used for coil modeling. One key benefit to using the 4-coil method in VIC-3D® is that post processing is not needed for the data, which isn't the case for the single drive and drive/ receive cases.

DATA ANALYSIS

Data analysis for this study was very minimal. The goal was to minimize post processing of the data to preserve whatever trends and agreement was seen from the raw data. That being said there were some areas where analysis was needed. In the case of the simulated data, there was a slight asymmetry to the data; the main peaks had slightly different magnitudes. The overall difference was under 1% but this was still a concern. This was removed by averaging the eddy current response around the origin point at the center of the notch.

Experimental Data Analysis

The experimental data analysis was more involved than for the simulated results, but it was still rather straightforward. To be able to compare the data from the impedance analyzer directly to the simulated results it was necessary to find the response change due to the defect. VIC-3D® produces change in resistance and reactance values while the impedance analyzer gives raw impedance values. To compare these results, the unflawed impedance data must be removed. This step was accomplished by fitting a 3rd order polynomial model to a portion of the data far from the notch, roughly the first and last 20% of the scan. In this area the signal should be from the base material and have no response due to the flaw. Each of the components is fit with a different polynomial model. This fit line is then subtracted from the component to produce the necessary change in impedance response. Because data from only one coil is collected during a scan post processing is used to create a differential data set. The differential data sets are created by sequentially subtracting the components from one cable from the other. This reduces the number of data sets by half. It was found that the agreement was best when the drive cable was subtracted from the sense cable. These are then averaged into a single data set for comparison with the simulated data. The five data sets collected from the Nortec were averaged into a single set as well then they were normalized such that the maximum value for each component matched that from the impedance analyzer data.

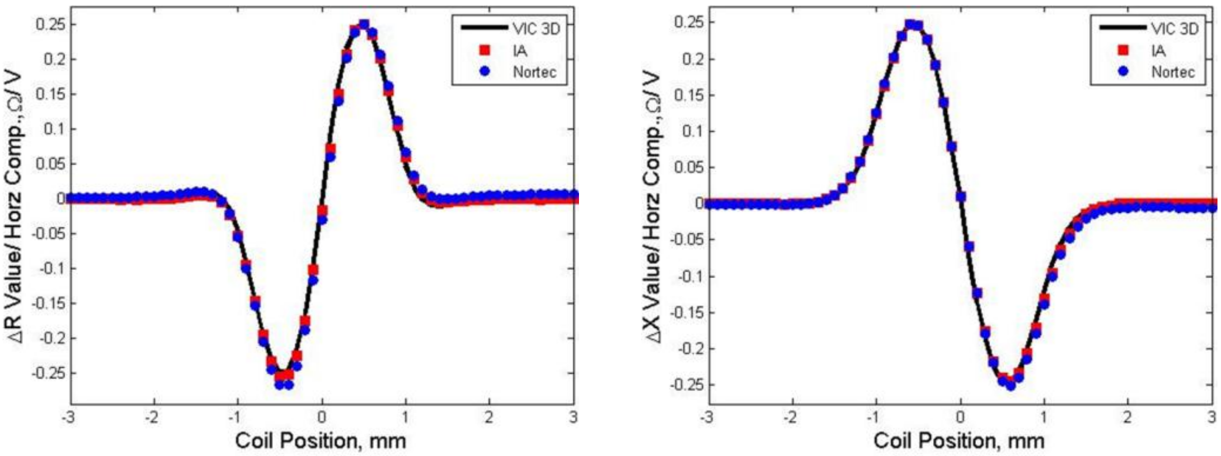
RESULTS AND DISCUSSION

The validation results will be divided in to groups by scan direction and notch length. In all cases both the resistance and reactance components will be displayed for all data sets (impedance analyzer, Nortec, simulation). In each plot the simulated results will be presented as a line, while the experimental data is shown as points. Again the results are an average of five data sets.

X Direction Results

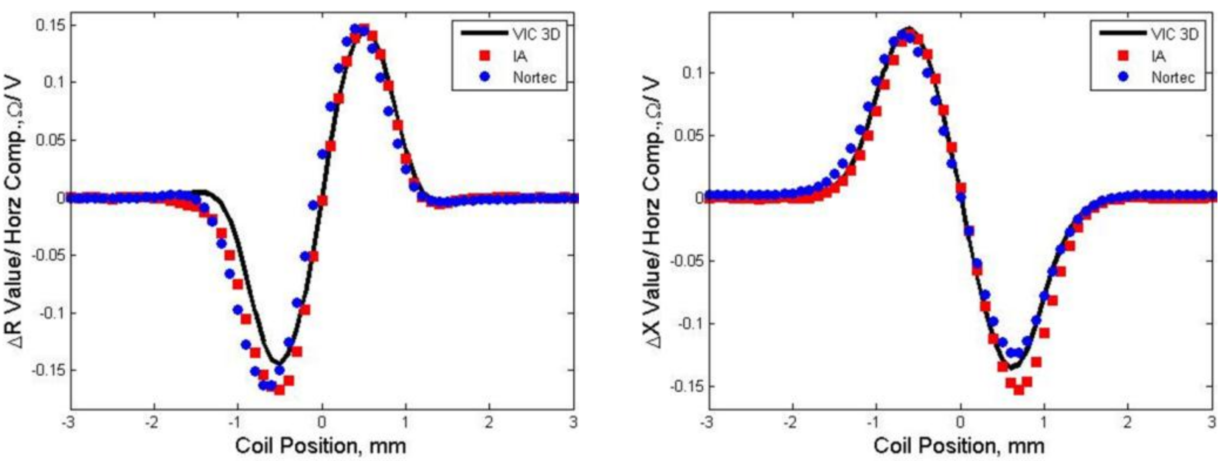
Figure 6 shows the results for the 0.100 in notch which has by far the best agreement. Overall the results are excellent in both shape and magnitude agreement. The experimental percent difference is 0.4% for the resistance and 0.38% for the reactance. There is a slight over shoot in the minimum peak in both components but overall the magnitude agreement is excellent. Moreover, the shape agreement is excellent with the small perturbations at the beginning of the ΔR data sets matching well. In terms of response shape the impedance analyzer results agree slightly better than the Nortec data. There is a slight difference in the end slope for the Nortec data, but overall these differences are negligible.

Figure 7 shows the results for the 0.080 in notch and it is clear that the agreement is not as good as the larger notch. The overall experimental percent difference increased to 1.46% for the resistance and 3.94% for the reactance. There is also much more overshoot in the experimental data at the minimum peak. This could be caused by dimensional asymmetry in the coil, an issue with unflawed data removal, or due to some unseen issue with the notch. As for the shape, there is a difference in the slope at the beginning of the experimental resistance data. The curious thing is that it only affects the beginning of the scan as the other extreme shows nearly perfect agreement in both experimental data sets. In addition, this is the only data sets where this kind of trend is observed. The reactance data does show better shape agreement, but the small slope difference is still present.



(a) (b)

FIGURE 6. Results for the 0.100 in notch scanned in the X direction: a) resistance data, b) reactance data



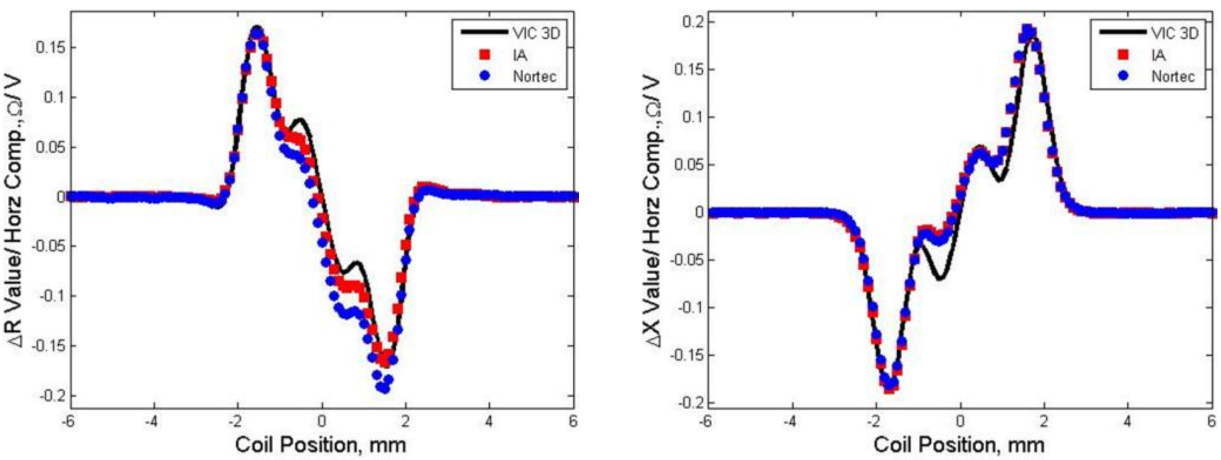
(a) (b)

FIGURE 7. Results for the 0.080 in notch scanned in the X direction: a) resistance data, b) reactance data

Y Direction Results

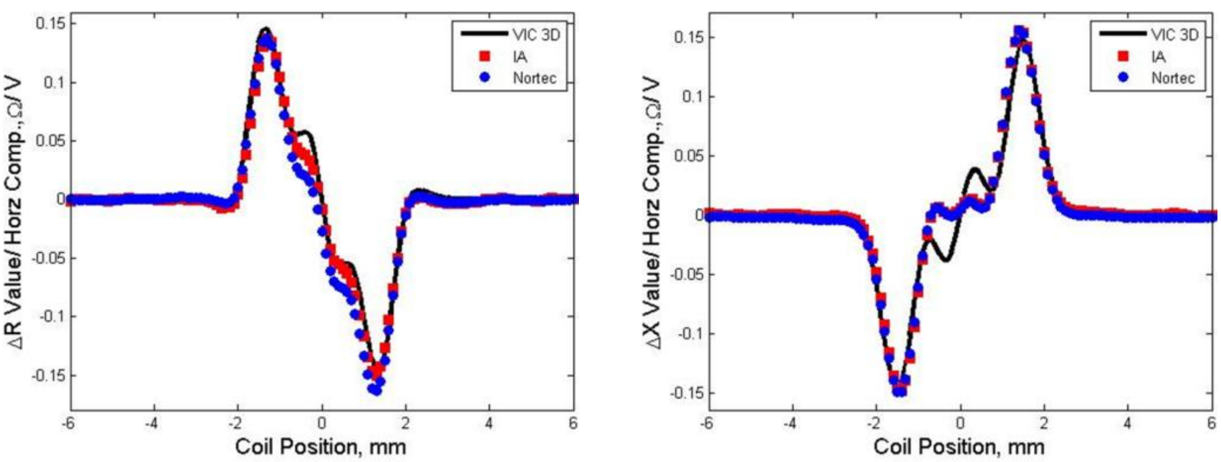
Figure 8 shows the results of the 0.100 in notch for *y*-direction scans. For scans in the y-direction the probe was rotated to maintain scan center. For this orientation, the probe response has a more complex shape. The magnitude agreement is very good, with a percent difference of 3.45% for both components. This error is higher than the *x*-direction scan of the same notch, but it is still very good agreement. Again there is some overshoot in the area of the minimum peak, but this is minor. One significant discrepancy comes in the form of a shift in the experimental secondary peaks. If a line is drawn at y=0 there is clear shift present. The offset in the secondary peaks is most likely caused again by dimensional asymmetry in the coils, where one produces a larger signal than the other. Overall the shape agreement is very good as well, but there are some areas where there are discrepancies in the secondary peaks. For the resistance plot there is a significant difference in the overall shape of the secondary peaks, while in the reactance the main issue seems to be solely in magnitude. A coil dimension difference may explain the shape discrepancy in the secondary peaks.

Figure 9 shows the results for the 0.080" notch y-direction scans. Many of the same trends follow from the larger notch, with very good overall agreement in magnitude and the significant disagreement in the secondary peaks in terms of shape and magnitude. The experimental percent difference is 6.05% for the resistance and 4.93% for the reactance was the highest values of the study. The overshoot at the minimum peak is reduced in the case of the smaller notch and the offset is not a pronounced. Another interesting trend is the decrease in the magnitude of the secondary peaks and the associated decrease in the simulated secondary peaks. In theory, as the notch length continues to approach the width, these peaks will continue to reduce until they reach a point where the scan resembles that of the x-direction scan.



(a) (b)

FIGURE 8. Results for the 0.100 in notch scanned in the Y direction: a) resistance data, b) reactance data



(a) (b)

FIGURE 9. Results for the 0.080 in notch scanned in the Y direction: a) resistance data, b) reactance data

CONCLUSIONS AND FUTURE WORK

Overall the validation results were very good. The agreement in magnitude was slightly better than in shape but both were very good. The *x*- direction scans over the 0.100 inch notch showed the best agreement in terms of both magnitude and shape. There were some shape issues when looking at the scans on the 0.080 inch notch for scans along the *x*-direction, but the magnitude agreement was still very good. The *y*-direction scans showed very good magnitude agreement for the primary peaks; however, there were some significant discrepancies in the secondary peaks. There was a definite offset seen in the secondary peaks of the *y*-direction scan data, which was most likely due to dimensional asymmetry in the probe. This difference in response for the two D coils was likely the cause of some of the overshoot seen at the minimum peaks of all the data sets.

For future work, there are a number of areas that need to be explored that could improve model agreement. The first is to include the possible effects that the cables have on the data. Another idea is to run the same tests but using two impedance analyzers in order to collect data from both coils simultaneously. Using this configuration, mutual inductance effect between the coils could be better studied. A final experimental idea is to run the tests for smaller notches to see how the secondary peaks change and eventually vanish. In terms of the future simulated studies, it is important to get precise probe dimensions especially where they were approximated. Investigating the effect of small changes in probe model parameters, modeling probe asymmetries, and increasing the mesh size in the model should help determine the source for error in modeling the secondary peaks.

ACKNOWLEDGMENTS

The authors would like to thank Hal and Elias Sabbagh for their modeling expertise and Rick Reibel and Ray Ko for their work on the data acquisition system. This work was done under Air Force contract FA8650-09-D-5224.

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