Model Validation Protocol toward MAPOD Application*

N. Nakagawa and B. F. Larson
Center for NDE, Iowa State University

J. M. Amos and V. Pendse
Materials & Process Engineering, Cessna Aircraft

D. Raulerson and K. Smith
United Technologies, Pratt & Whitney

*This material is partly based upon work supported by the Federal Aviation Administration under Contract #DTFA03-98-D-00008, Delivery Order #0039 and performed at Iowa State University's Center for NDE as part of the Center for Aviation Systems Reliability program, and partly upon work supported by the Air Force Research Laboratory under contract # FA8650-04-C-5228 at Iowa State University Center for NDE.

Outline

1. **Introduction**
2. Model Validation Protocol
   - Working protocol
   - Salient features
3. Exercising the Validation Protocol
   - Examples
4. Conclusions

Introduction

Objective

– To develop and validate an eddy current (EC) model, aiming toward model applications to airframe inspections.

Scope

– Model development and validation

– Development of a validation protocol = guidelines for validation procedure.

Expected Significance

– The validation procedure will become an integral part of model-assisted POD (MAPOD) methodologies.

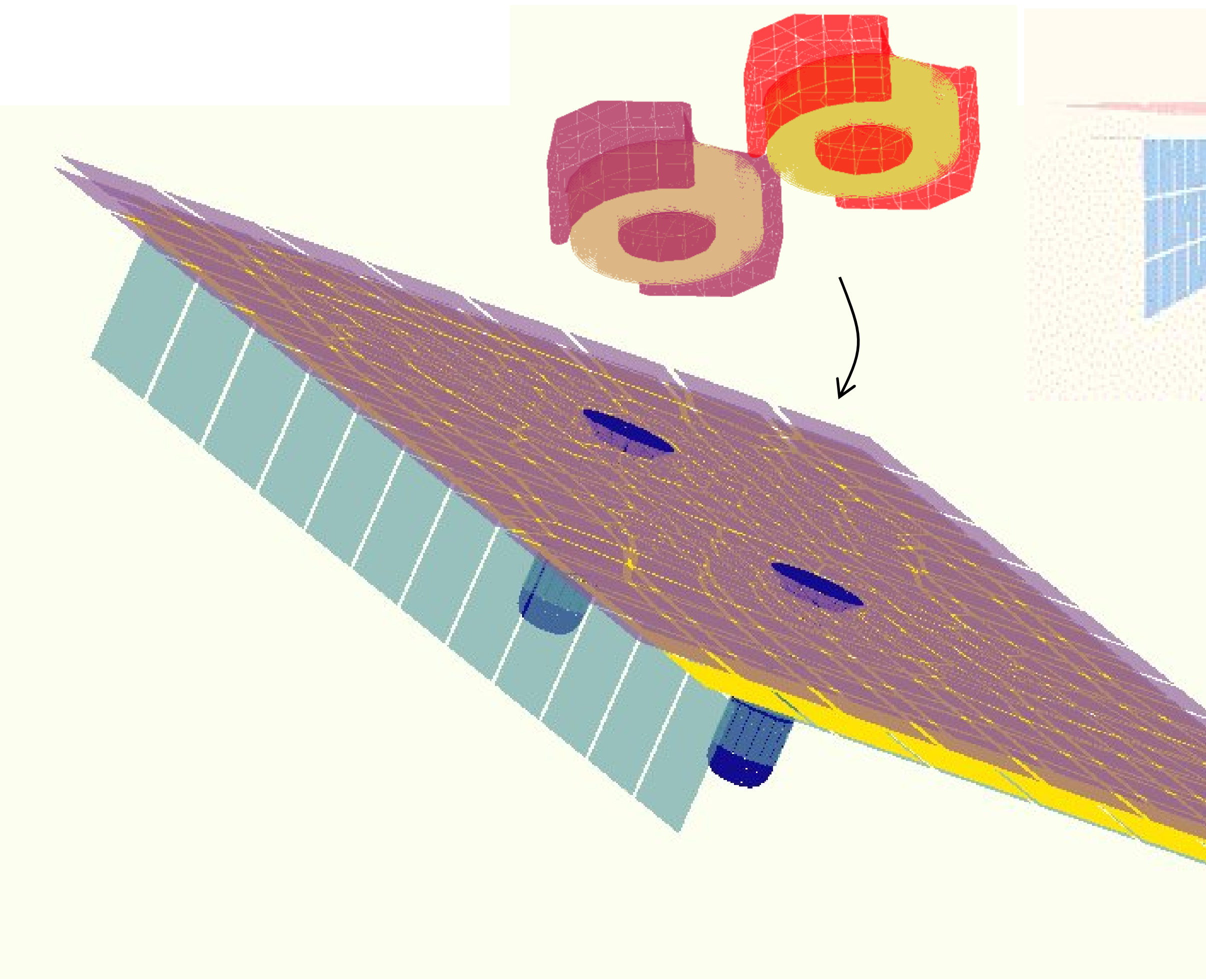
Approach

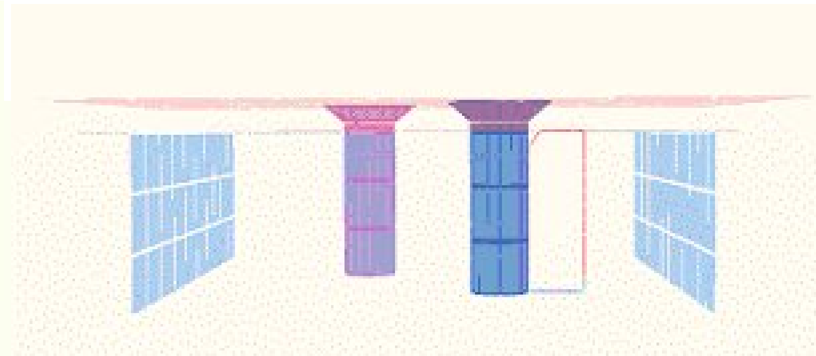
- Develop (draft) validation protocol
  - based on prior experience in industrial inspections and laboratory measurements.
- Exercise the protocol, and refine it through this exercise.
  - Select prototypical airframe eddy current inspections.
  - Select a BEM-based EC model (additional development)
  - Prepare sample (select, fabricate, and characterize)
  - Perform validation measurements & model calculations for comparison

Considerations Prior to Exercising the Protocol

- Select a test problem
  - EC inspections to test
  - Laboratory or Industrial problem
- Select a model to use
  - EC simulation model
  - Based on application requirement
- Determine precision requirements
  - Default accuracy (e.g. "±10%")
  - Based on application scope
    - Ex. MAPOD

Inspection Configuration Example





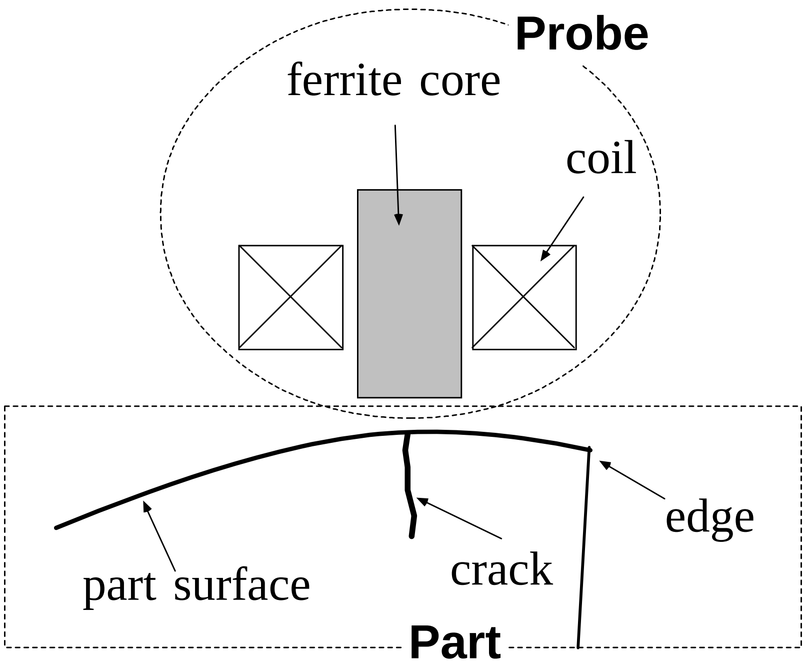
- Complex probe configuration
- (multi-layered) plate geometry

Cessna Aircraft

Model Example: CNDE EC Models

Physics-based models

– Idealize the system of an EC probe and parts



- Modeling Algorithms
  – **Analytical methods**
    - Dodd-Deeds Solution
  – **Numerical methods**
    - Finite Difference
    - Finite Element
    - Volume Integral
    - ➢ Boundary Element
    - Hybrids

Auld's reciprocity formula

$$\Delta Z = \frac{1}{I^2}\int_S d\vec{S}\cdot\left[\vec{E}\times\vec{H}' - \vec{E}'\times\vec{H}\right]$$

$$= \frac{-1}{I^2}\int_v dV\left[\Delta\sigma\left(\vec{E}\cdot\vec{E}'\right) + i\omega\Delta\mu\left(\vec{H}\cdot\vec{H}'\right)\right]$$

Outline

1. Introduction
2. **Model Validation Protocol**
   - **Working protocol**
   - **Salient features**
3. Exercising the Validation Protocol
   - Examples
4. Conclusions

Model Validation Protocol

- Purpose of the protocol
  - To ensure consistency of model validation procedure by providing guidelines for measurement and computation
- Functions of the protocol
  - "Measurement" protocol: guidelines for
    - Specimens to prepare/procure
    - Instrumentation (instrument & probe) to use
    - Data to acquire/record in what procedure
  - Guidelines to determine
    - What output signals to compute, compare with what data
    - What input parameters are needed, and how to determine
    - How to compare the model output to the data

Validation Protocol, Draft Documents

- Engine Applications
  - 10-page draft document
    - Including 6-page model-to-expt. calibration procedure
  - P&W - EC Model Validation Protocol
- Airframe Applications
  - 2-page draft document
  - Validation Protocol - Cessna

Focal Points of Validation Protocol

- Sample definition, procurement/fabrication
  - **Material property determination**
    - Sample to sample
  - **Defect Characterization**
    - Close to ideal defects
  - **Capture sample geometry/dimension data**
    - With idealization

Focal Points of Validation Protocol (contd.)

- Selection and characterization of instrumentation
  - Instrument parameter/output determination
  - **Probe Characterization**
- Data acquisition by experiment
  - **Motor-controlled mechanical scans**
    - **“Stop-and-Go” scan preferred**
  - Digital data acquisition
    - **No saturation**
  - **Multiple-pass acquisitions with averaging**

Focal Points of Validation Protocol (contd.)

- Data simulation by modeling
  - What output signals to compute
  - How to determine input parameters
    - Probe geometry and parameters
    - Sample geometry and parameters
  - How to use simulation output
- Mapping predictions to experimental data space
  - From impedance plane to horizontal-vertical plane
    - Transfer function = complex number ("gain & phase")
    - Determined by calibration (e.g. notch, controlled lift off)

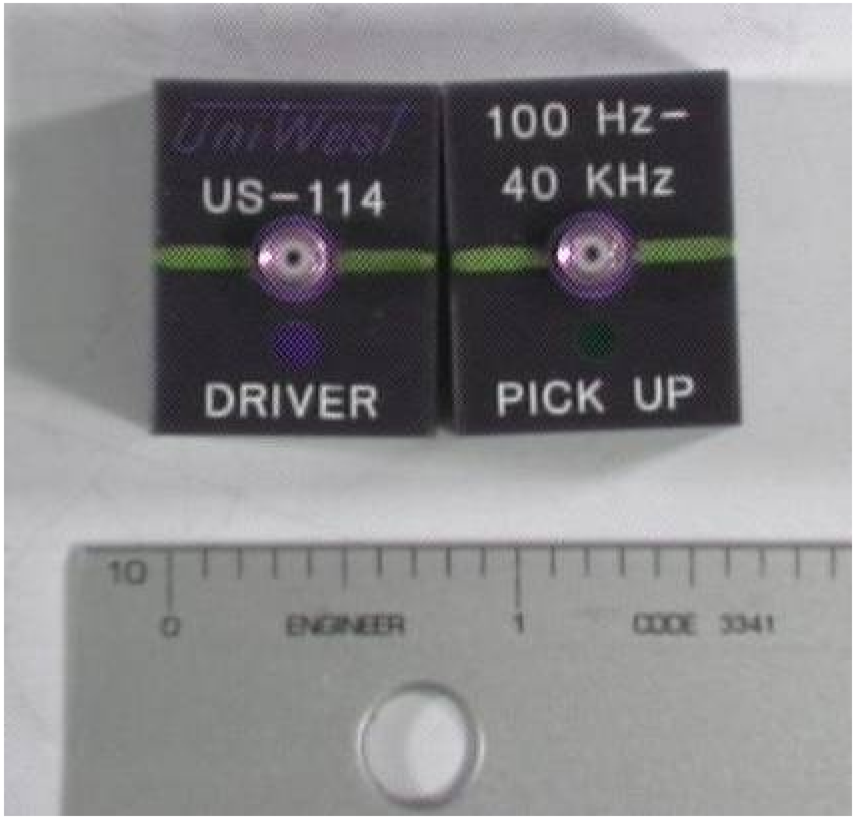
Outline

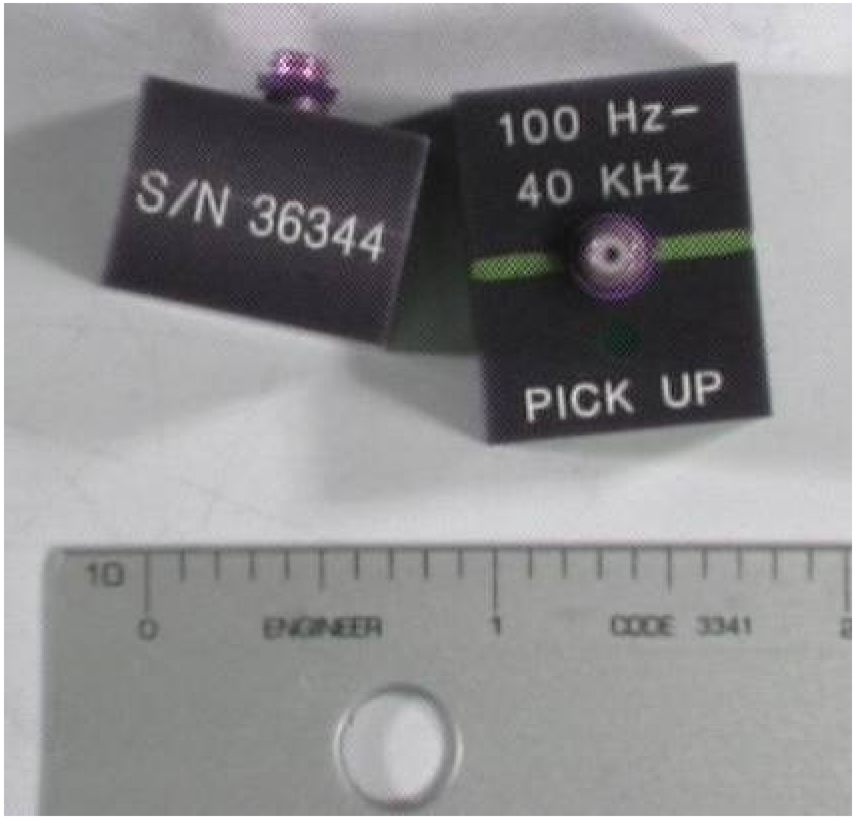
1. Introduction
2. Model Validation Protocol
   – Working protocol
   – Salient features
3. **Exercising the Validation Protocol**
   – **Examples**
4. Conclusions

Instruments and Specimen

- Instrumentation: A commercial sliding probe (UniWest US-114) attached to EC instrument (US-454)
- Specimen: a custom-made double-layer specimen.
  - The top layer = a 1.016 mm (0.040”) thick Al2024-T3 sheet
    The bottom layer = a 6.350 mm (0.250”) thick Al 7075-T76 plate
  - The conductivities, 19.31 MS/m (top), 23.77 MS/m (bottom)
  - Two rows of EDM notches in the bottom (Al 7075) plate.
    - 0.127 mm (0.005”) opening width, 2-to-1 (L-to-D) aspect ratio
    - Three semi-elliptical notches
      length = 1.524 mm (.060”), 2.540 mm (.100”), 3.810 mm (.150”)
    - Four square notches
      length = 1.524 mm (.060”), 2.540 mm (.100”), 3.810 mm (.150”), 5.080 mm (.200”) (through thickness)

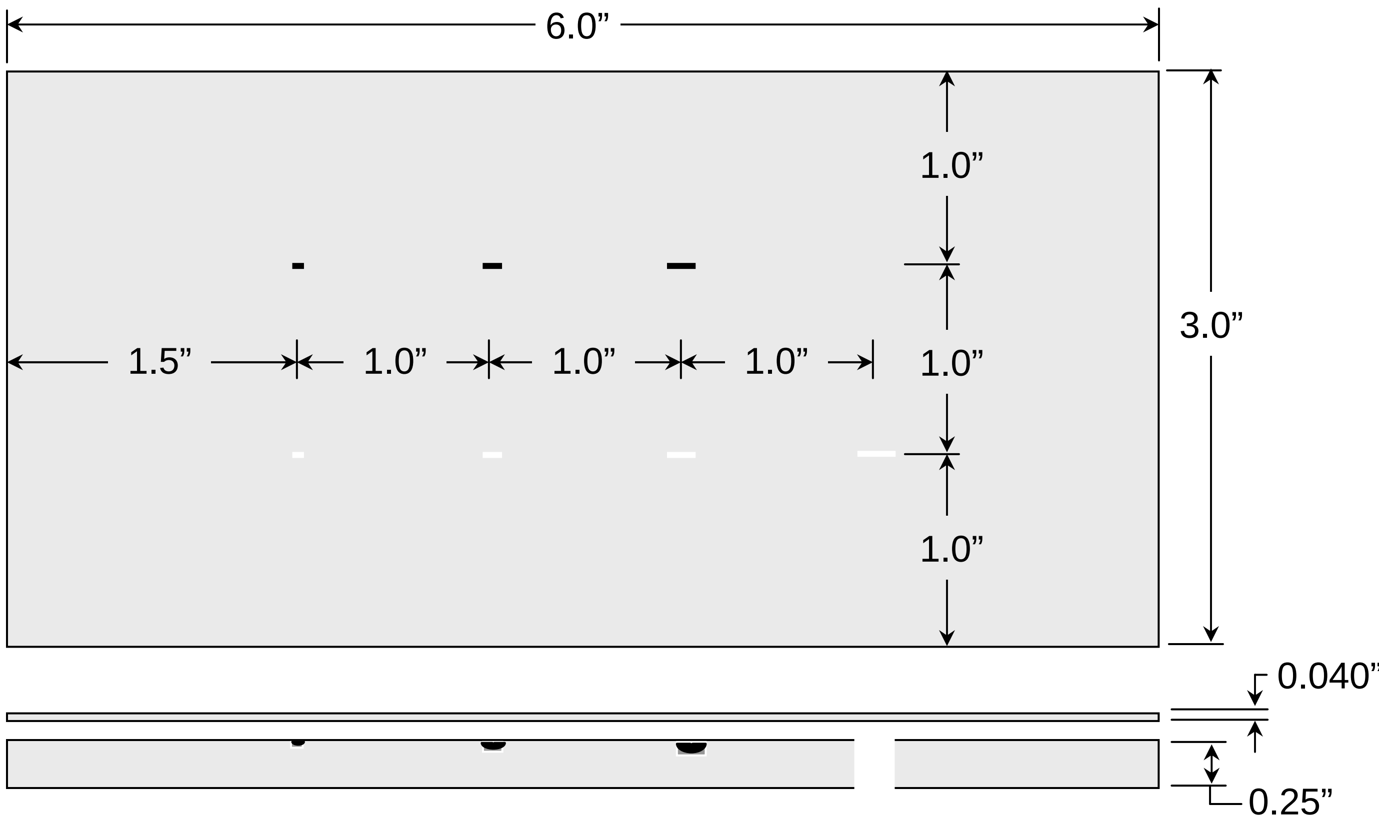
Sliding Probe





Case II Specimen

Material: 2024-T3 Sheet and 7075-T76 Plate

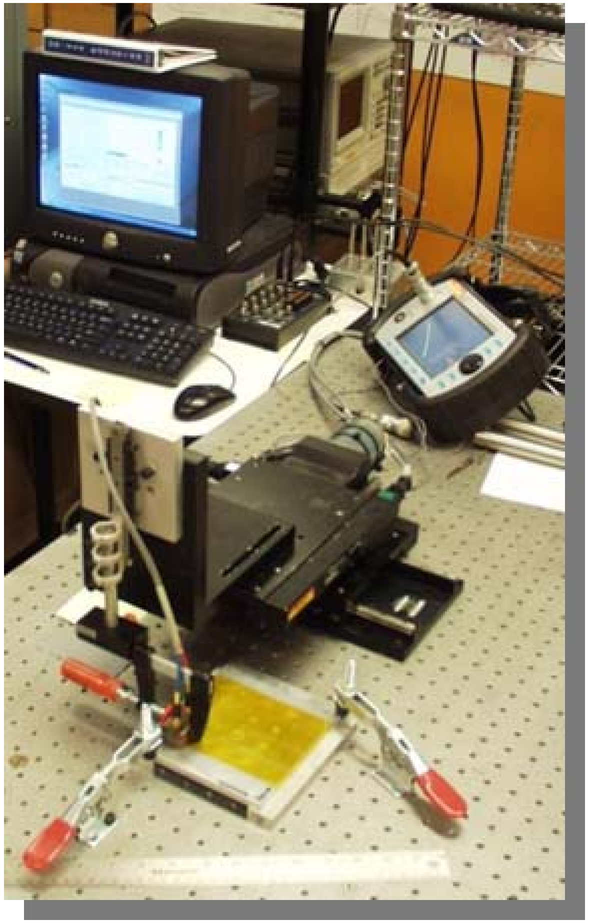


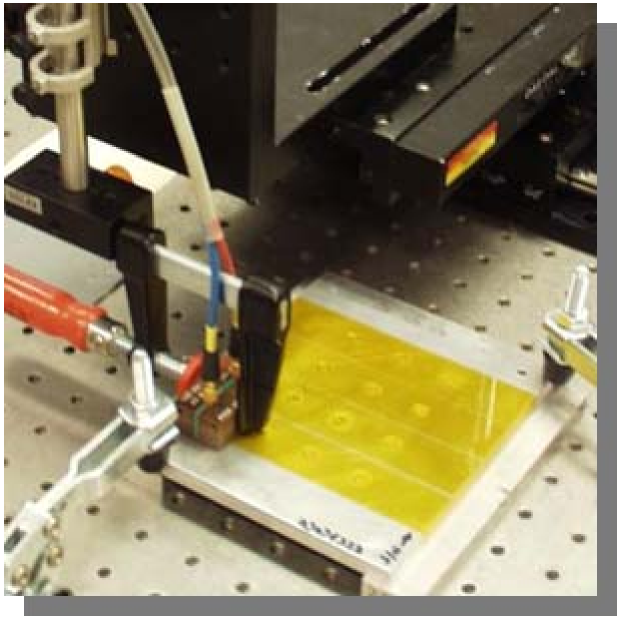
	Notch 1	Notch 2	Notch 3	Notch 4
Row 1 (Semi-elliptical)	0.060” long x 0.030” deep	0.100” long x 0.050” deep	0.150” long x 0.075” deep	
Row 2 (Square)	0.060” long x 0.030” deep	0.100” long x 0.050” deep	0.150” long x 0.075” deep	0.200” long x 0.25”

Make notch width as narrow as possible but 0.007” Max.

Case II Specimen Overall Photo

Automated Scanner-DAQ Station





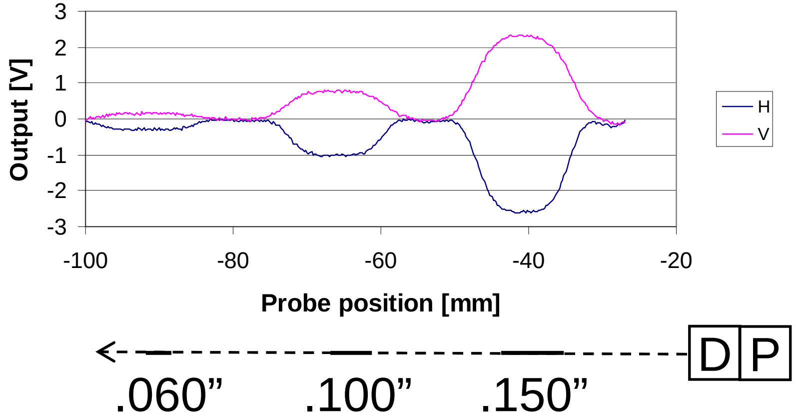
Scan Setup for Validation Specimens

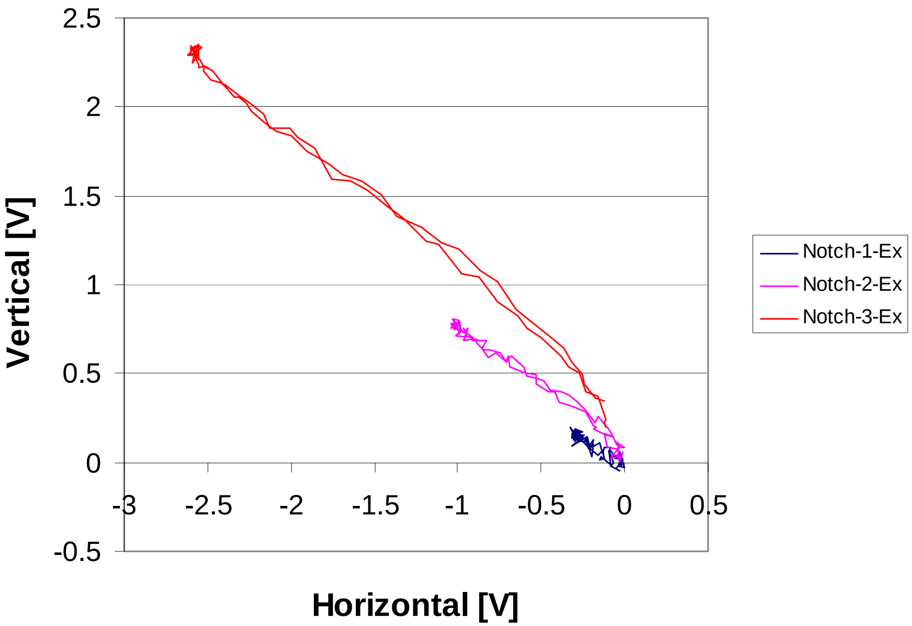
Experiment

- The physical probe was
  - connected to the eddy current instrument (UniWest US-454)
  - mounted to our computer-controlled scanning system
  - and scanned over the notches, with the output voltages being digitized and acquired.
- The data were acquired for all the four possible plate configurations
  - notches on the probe side or the opposite
  - with or without the top sheet.
- Two data sets used
  - the notches on top, without the top sheet.
    - the instrument settings = 1 kHz, 65.0 dB, and 55°
  - the notches on top, with or without the top sheet.
    - the instrument settings = 1 kHz, 69.0 dB, and 30°

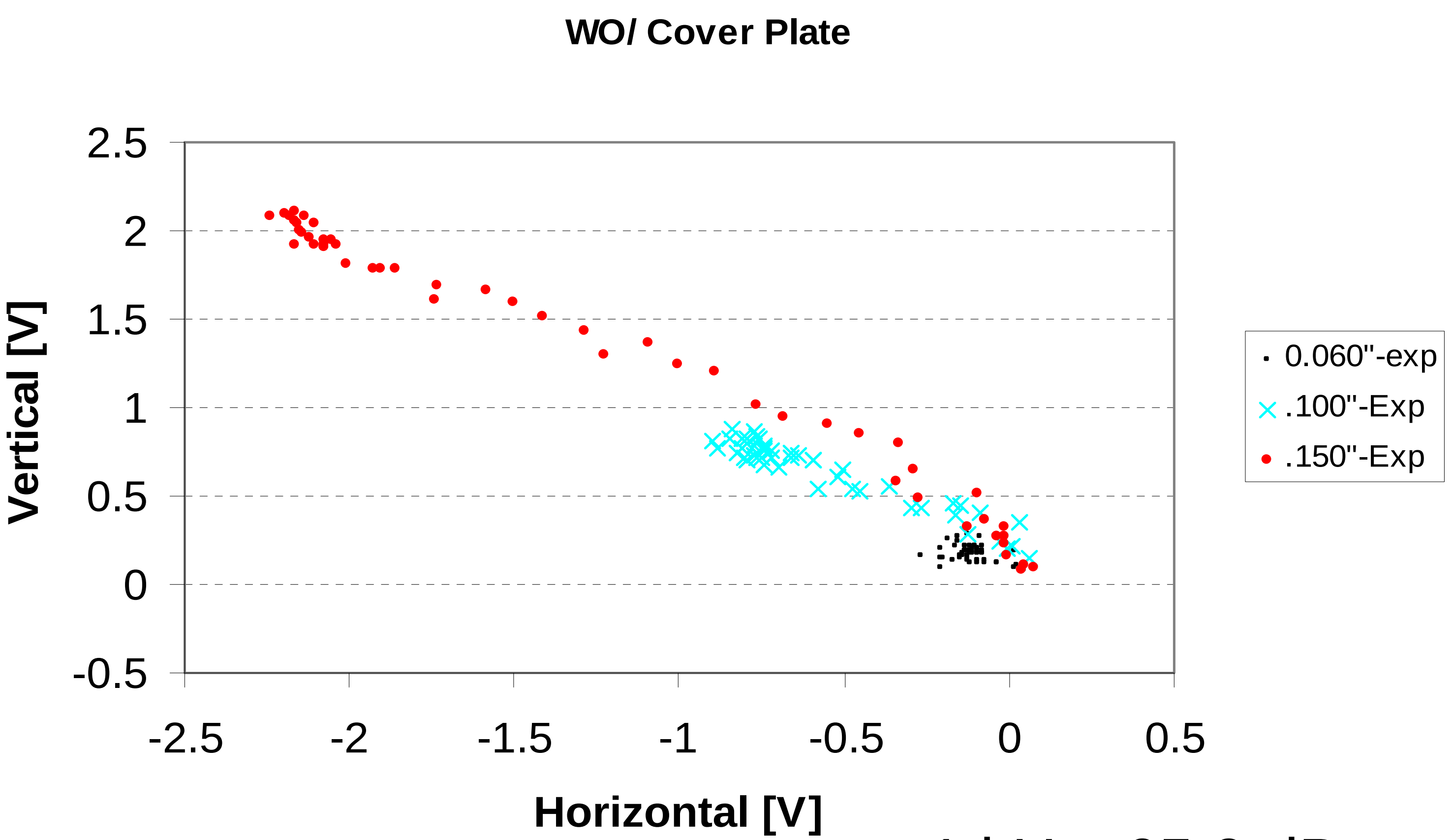
Typical Experimental Data, Case II Sample

- Without top sheet
- Sliding probe data
- US-454, Gain = 65dB, Phase = 10°





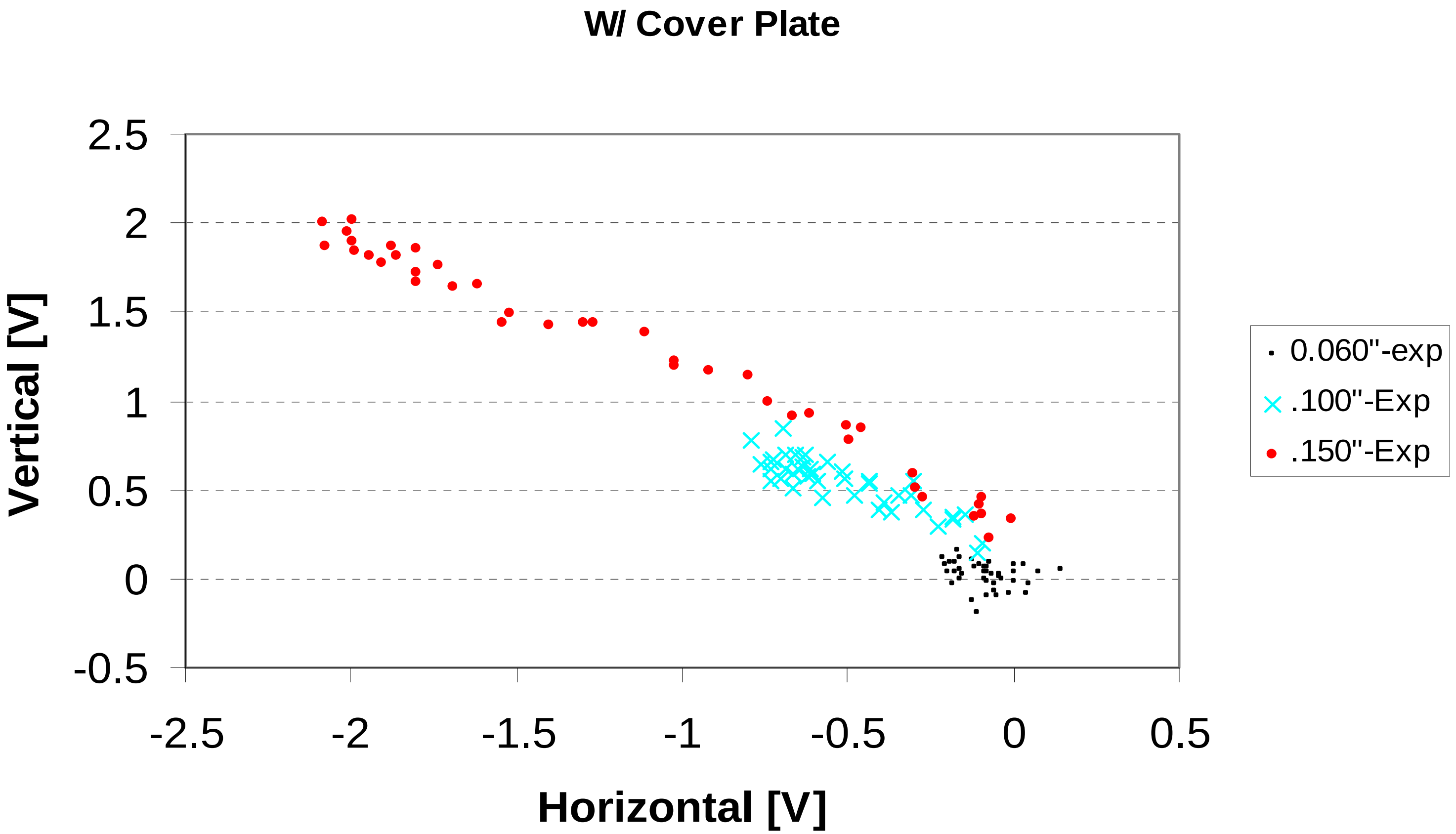
Data, No Top Sheet



1 kHz, 65.0 dB, and 55°

CENTER FOR NDE

Data, with Top Sheet



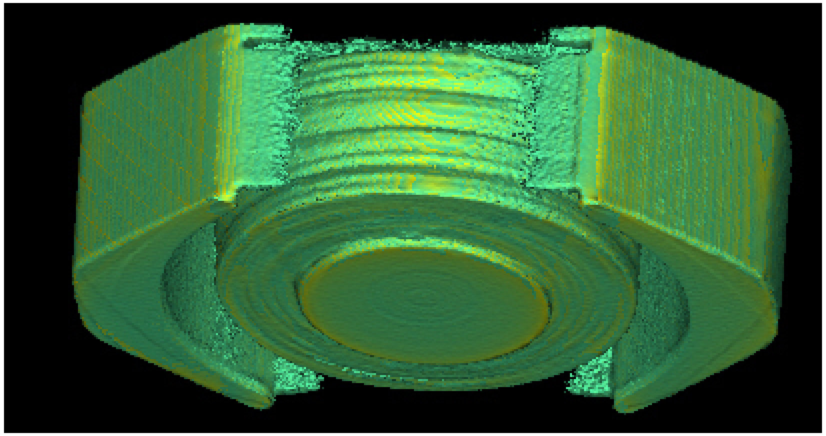
1 kHz, 69.0 dB, and 30°

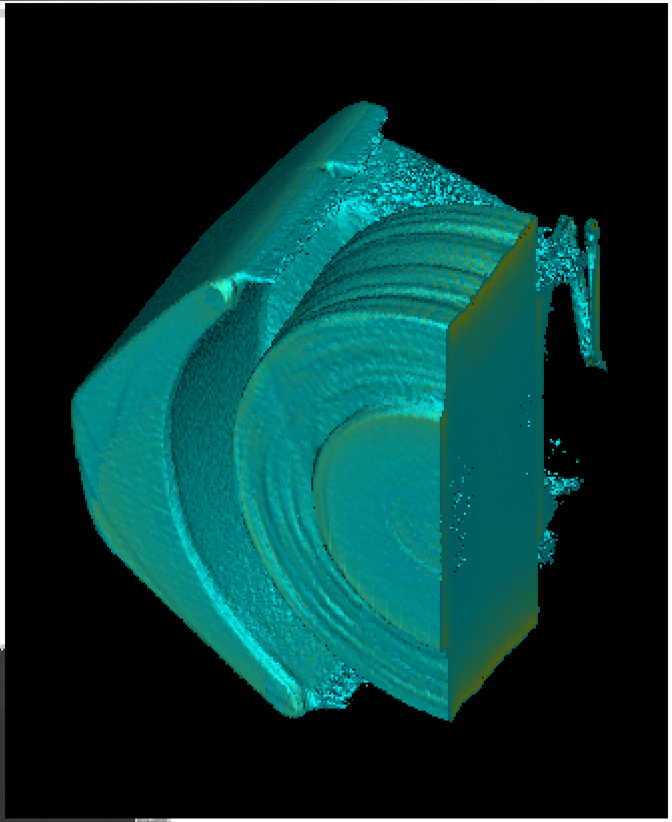
CENTER FOR NDE

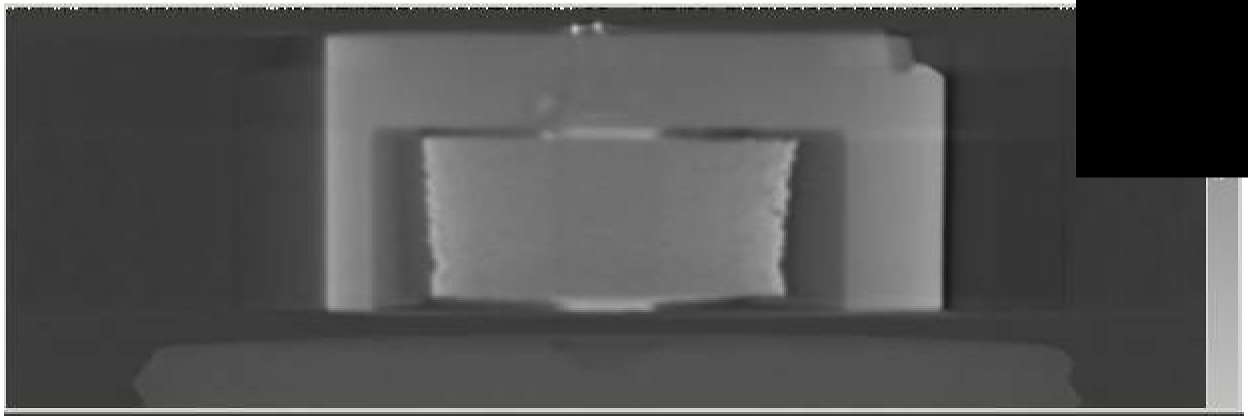
Computations

- The impedance predictions via PLATE07
  - The two corresponding configurations of the plates and notches
  - A CAD model of the probe obtained from the x-ray images
  - The other specimen parameters as input
    - Ex. the overall lift off = 0.53 mm
- The model output are complex impedance values
  - Need to be mapped to the vector-voltage values to compare the experimental data.
  - A single, multiplicative transfer function
    - for a given frequency (e.g. 1 kHz) and for a given lift-off value (e.g. 0.53 mm).
  - The single multiplicative complex factor can be determined by calibration.
    - In this example; calibration via the maximum of the .150” notch signal
    - The single (complex-valued) scaling factor was used in what follows.

CT Images of Driver Coil

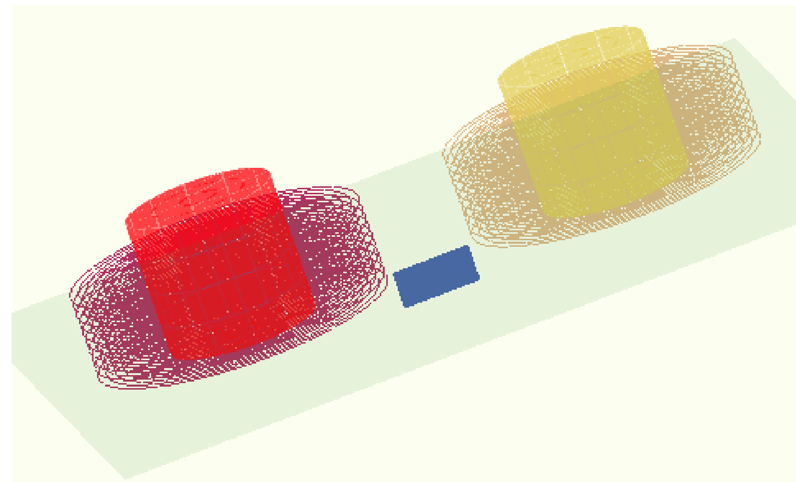


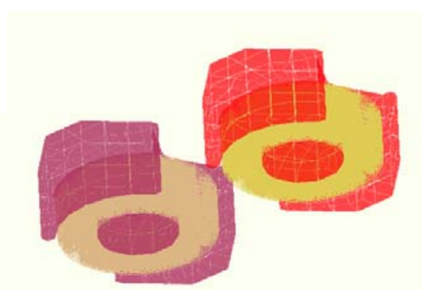




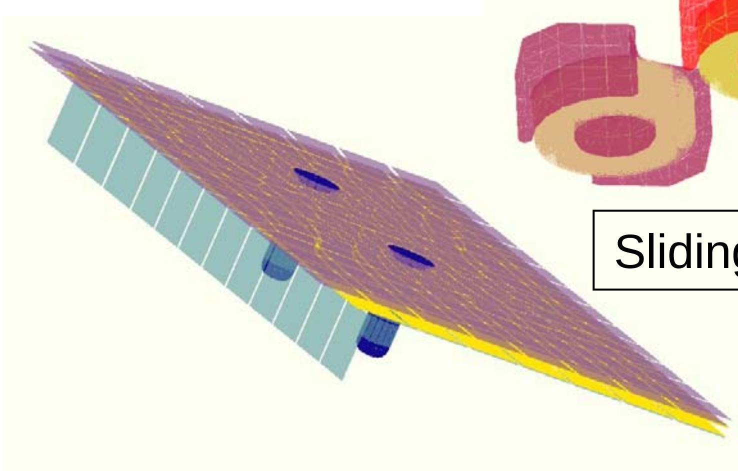
CAD Model of the Probe

Capture geometry/dimension data

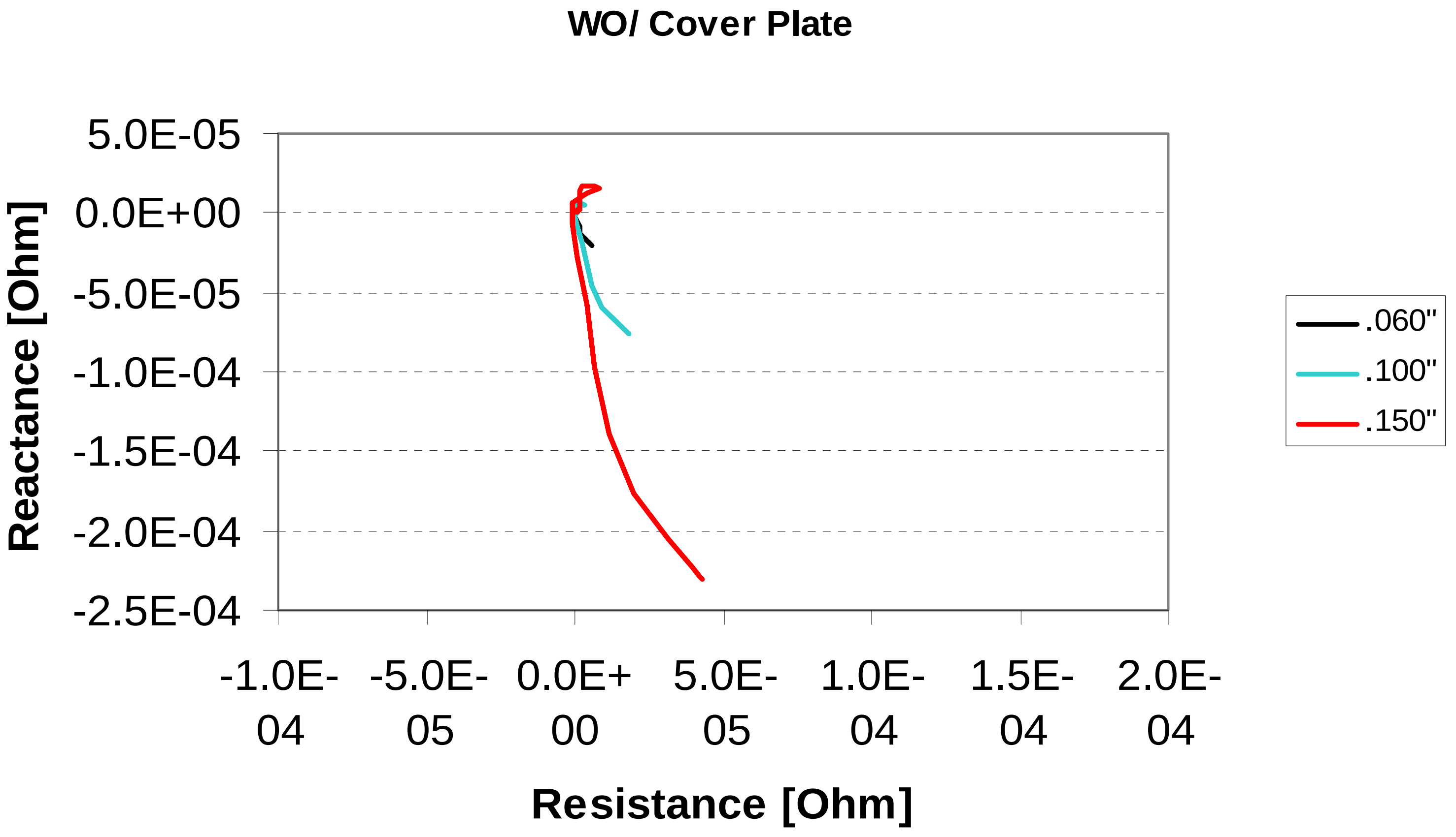




Sliding Probe

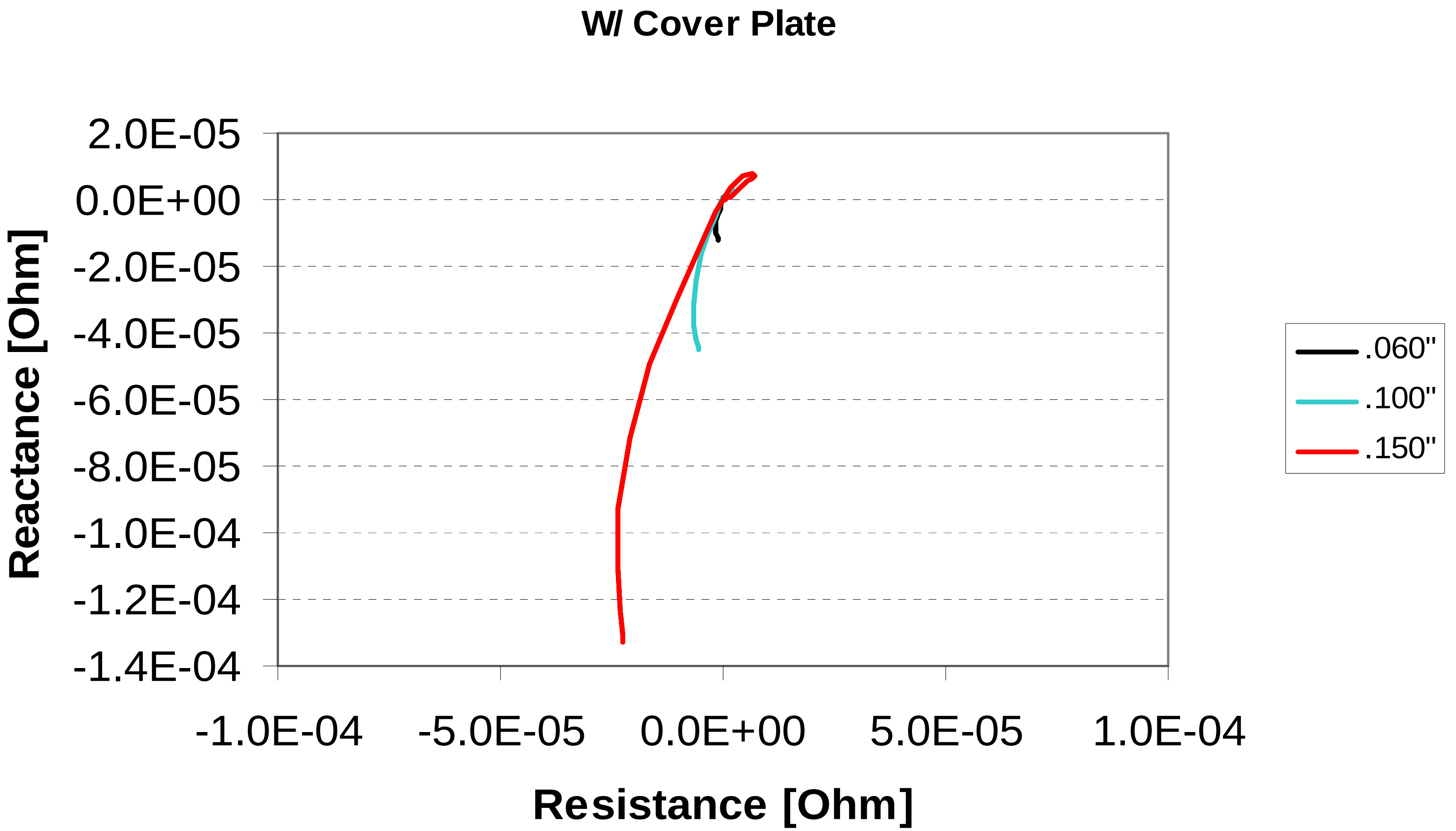


Signal Prediction, no Top Sheet

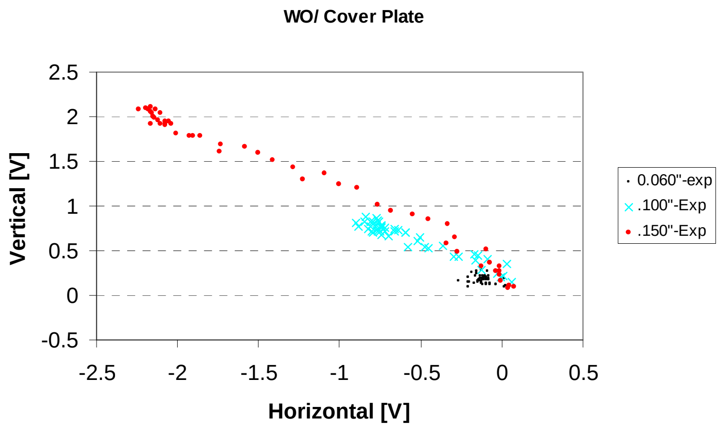


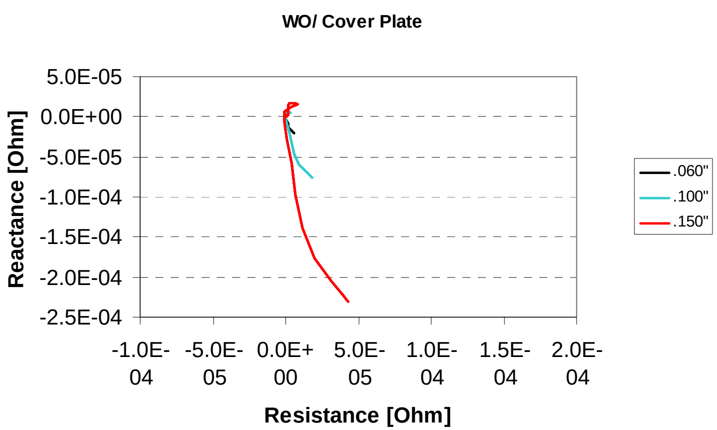
CENTER FOR NDE

Signal Prediction, with Top Sheet

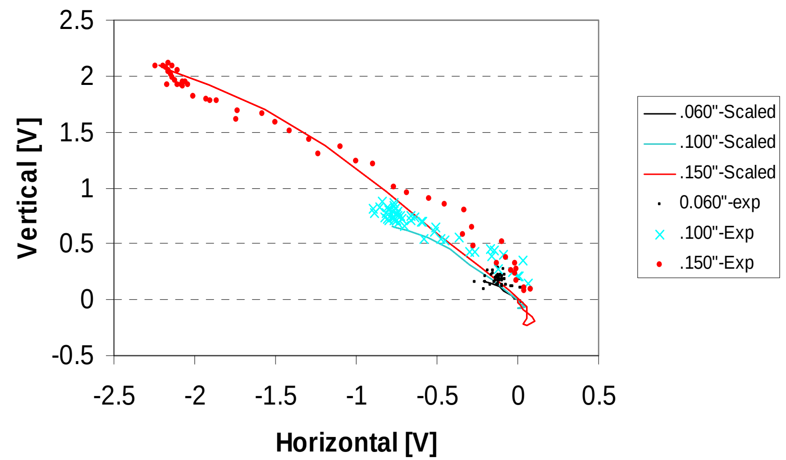


Mapping Theory to Instrument Output

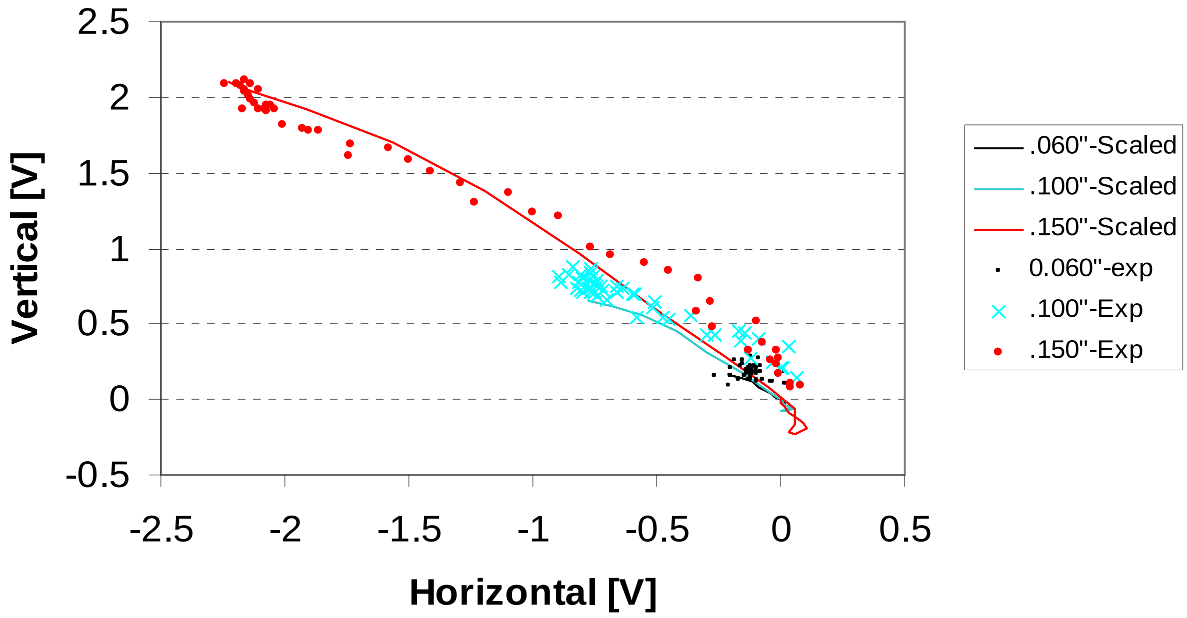




- Calibration-based approach

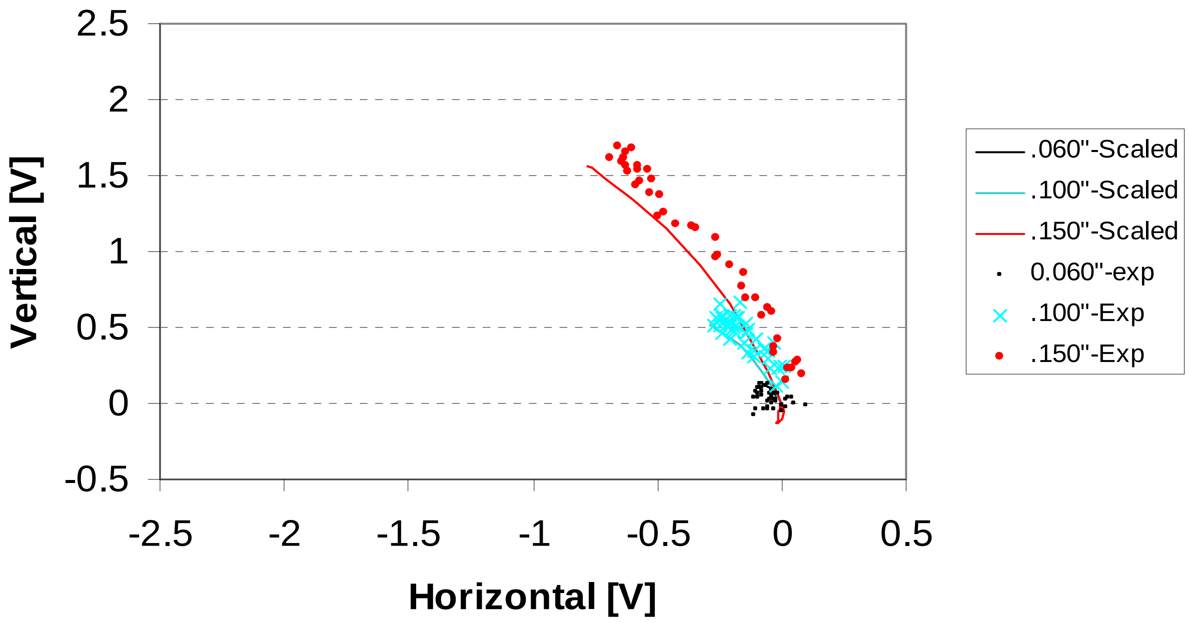


Model vs Data, No Top Sheet



Vector-voltage plane plots of the three 2-to-1 notch signals without the top sheet. The dots represent measured values (the instrument settings of 1 kHz, 65.0 dB, and 55°). The lines represent scaled model predictions. A single complex number (i.e. magnitude and a phase) was determined so that the maximum .150" signal matches the corresponding experimental maximum, and used to map the predicted impedance to the voltage plane.

Model vs Data, with Top Sheet



Vector-voltage plane plots of the three 2-to-1 notch signals with the .040" top sheet. In plotting the measurement data (dots), the acquired data at 1 kHz, 69.0 dB, and 30° were scaled/rotated by 4dB and 25° to match the 65.0 dB, and 55° settings. For the theory curves, the same complex scale factor determined previously was used to map the impedance prediction to the plotted voltage curves, as represented by the lines.

Conclusions

- A version of model validation protocol document has been developed.
  - Eddy current inspection and modeling
  - Draft
- A case study of exercising the draft validation protocol has been shown.
- Explicit validation results are emerging
  - Ex. Case II sample with sliding probe scans