A MODEL FOR THE NONDESTRUCTIVE EVALUATION OF HOST MATERIAL AROUND A BUSHING-FASTENER SYSTEM

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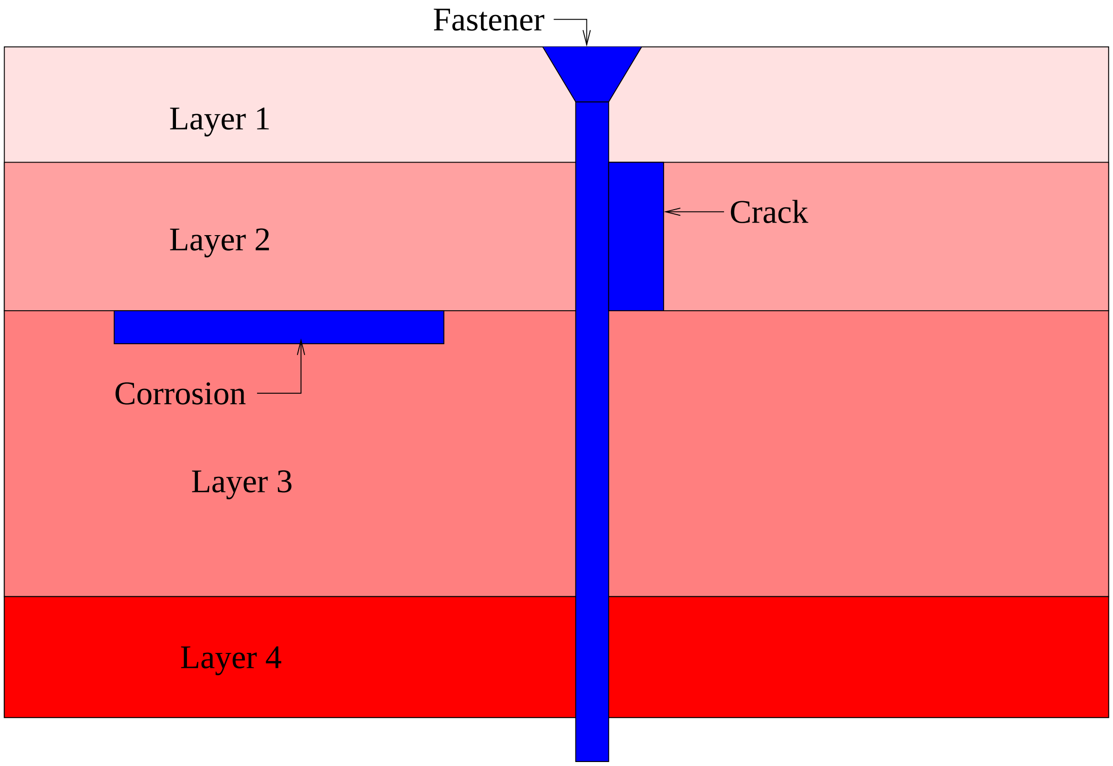
IDENTIFICATION OF THE PROBLEM

- flawed fastener holes are a common defect encountered during aircraft structural repair operations
- flaws are inititated in a fastener hole due to a variety of factors
  - corrosion growth
  - fatigue cracks
  - manufacturing errors
- typical repair strategy for a flawed fastener hole
  - ream the fastener hole until the defect is removed
  - install a bushing (or bushings in a multi-layer stack)
  - install a repair member to help carry the load for the damaged structure
- this effectively encapsulates the bushing and removes the ability to inspect the hole for damage

TECHNICAL OBJECTIVES

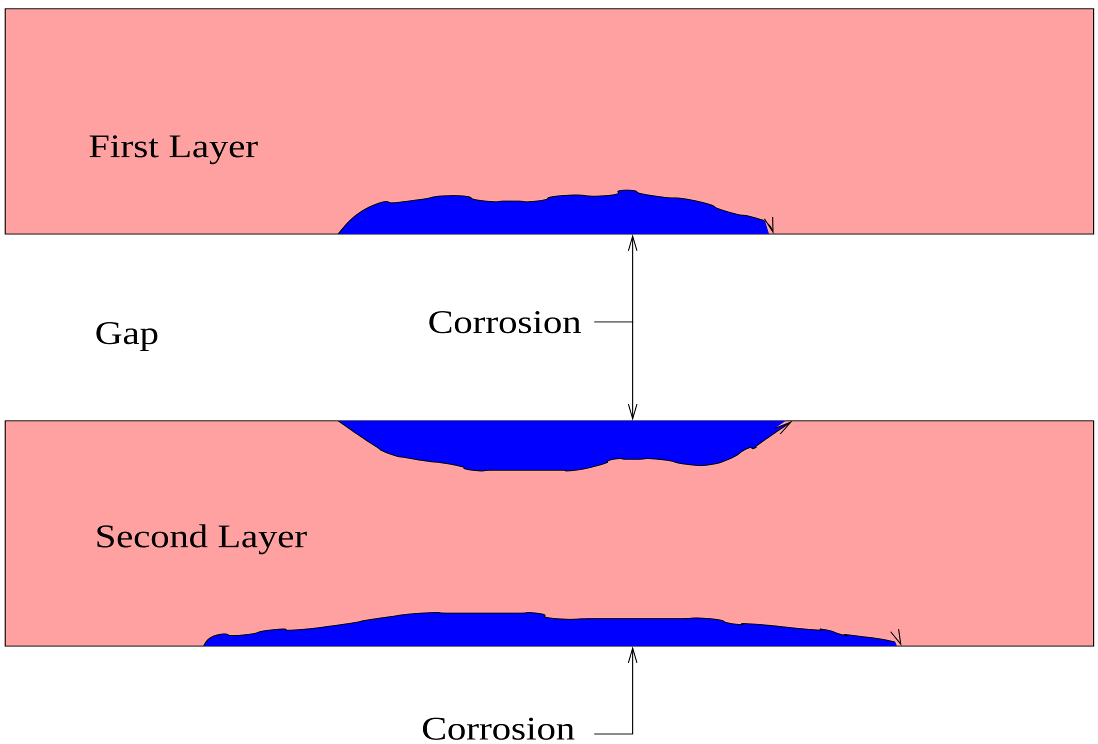
- detect a 0.020-inch anomaly in an aluminum structure through ferrous or non-ferrous bushings
  - bushing wall thickness lies between 0.032 inch and 0.150 inch
  - system to be inspected may contain two to six layers in a multi-layer stackup
  - method does not require removal of repair members
- use **VIC-3D©** as the analysis engine

SOME PROBLEMS IN NONDESTRUCTIVE EVALUATION (NDE)



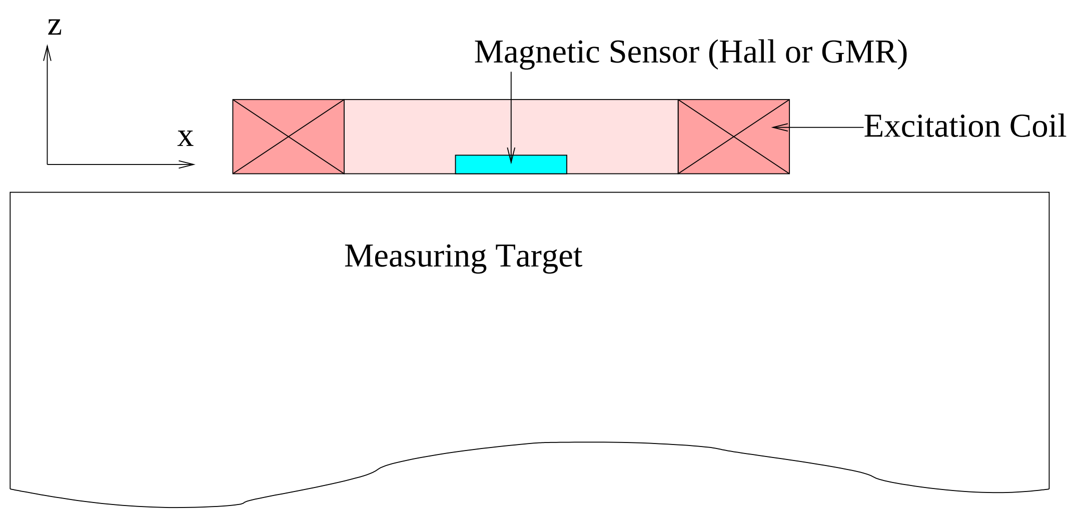
Illustrating a problem in which the anomalies, the fastener, flaw and corrosion, are widely distributed and extend through several layers of host material.

SOME PROBLEMS IN NDE



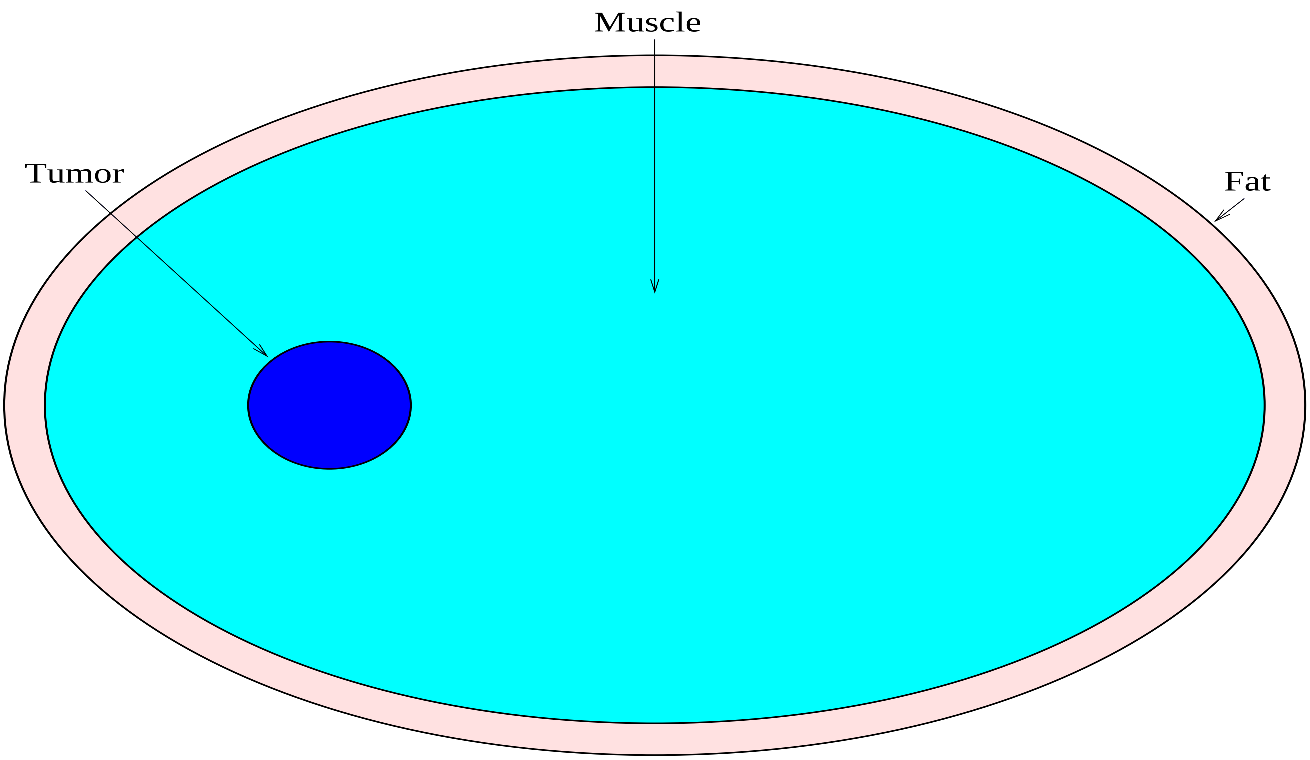
Illustrating a problem in which the anomaly, corrosion, extends through several layers of host material.

SOME PROBLEMS IN NDE



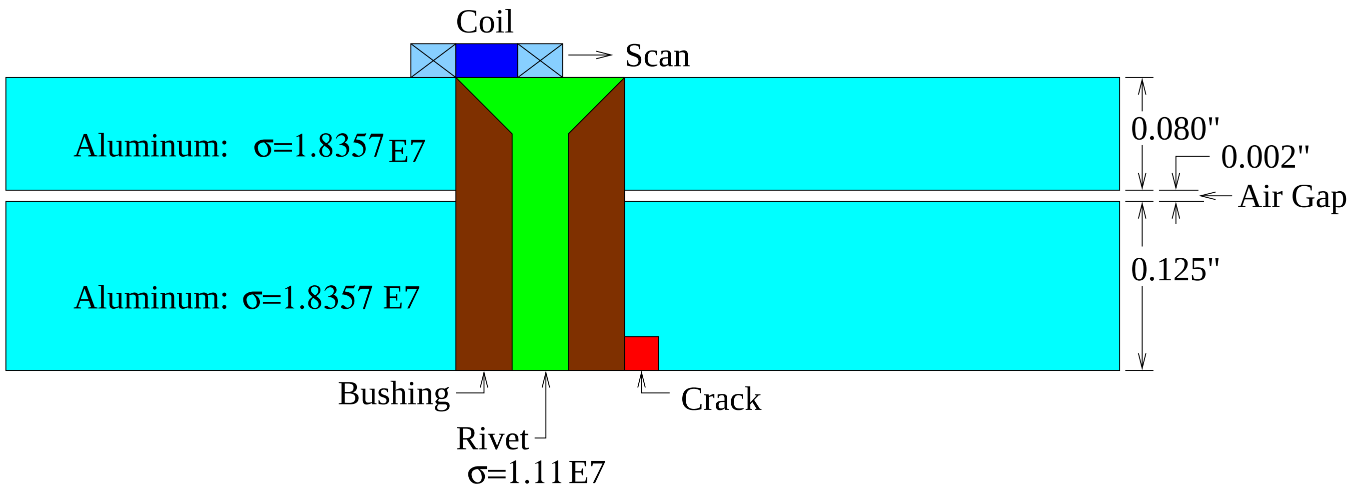
Illustrating a magnetic-field sensor in the vicinity of an exciting coil. Such combinations are useful in low-frequency eddy-current applications, including pulsed eddy-current techniques.

SOME PROBLEMS IN NDE



Illustrating a 'tumor' within a body undergoing hyperthermia treatment. The objective is to remotely measure the temperature of the tumor. Both, the tumor and body are 'anomalous regions,' which require separate grids that can be solved using spatial-decomposition techniques.

TWO PROBLEMS INVOLVING FERROUS AND NONFERROUS BUSHINGS

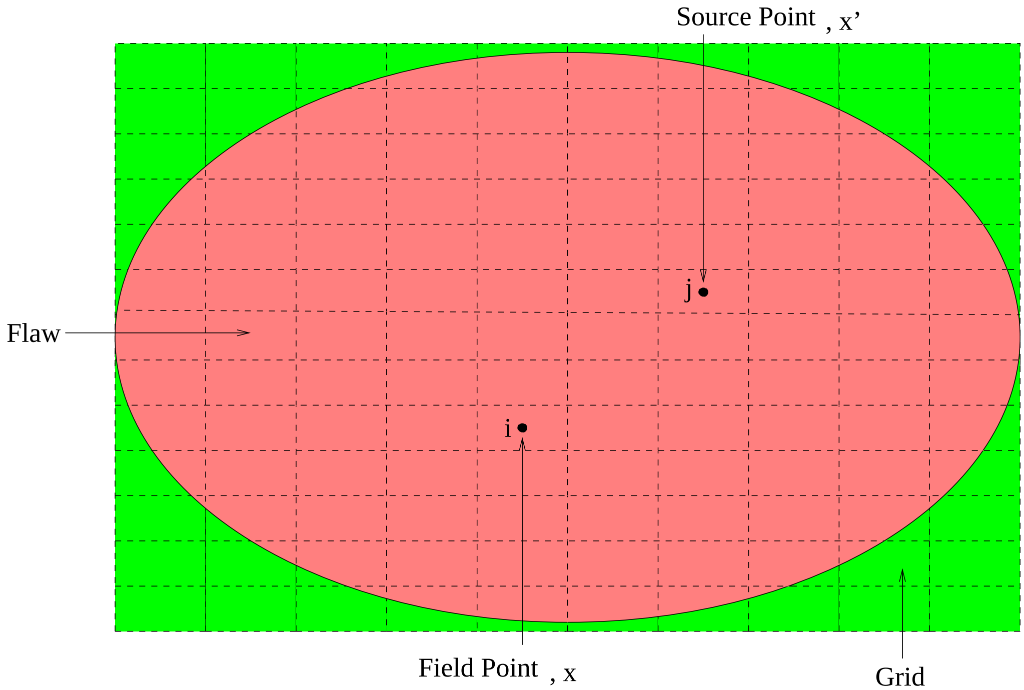


TWO PROBLEMS INVOLVING FERROUS AND NONFERROUS BUSHINGS

Data for both problems:

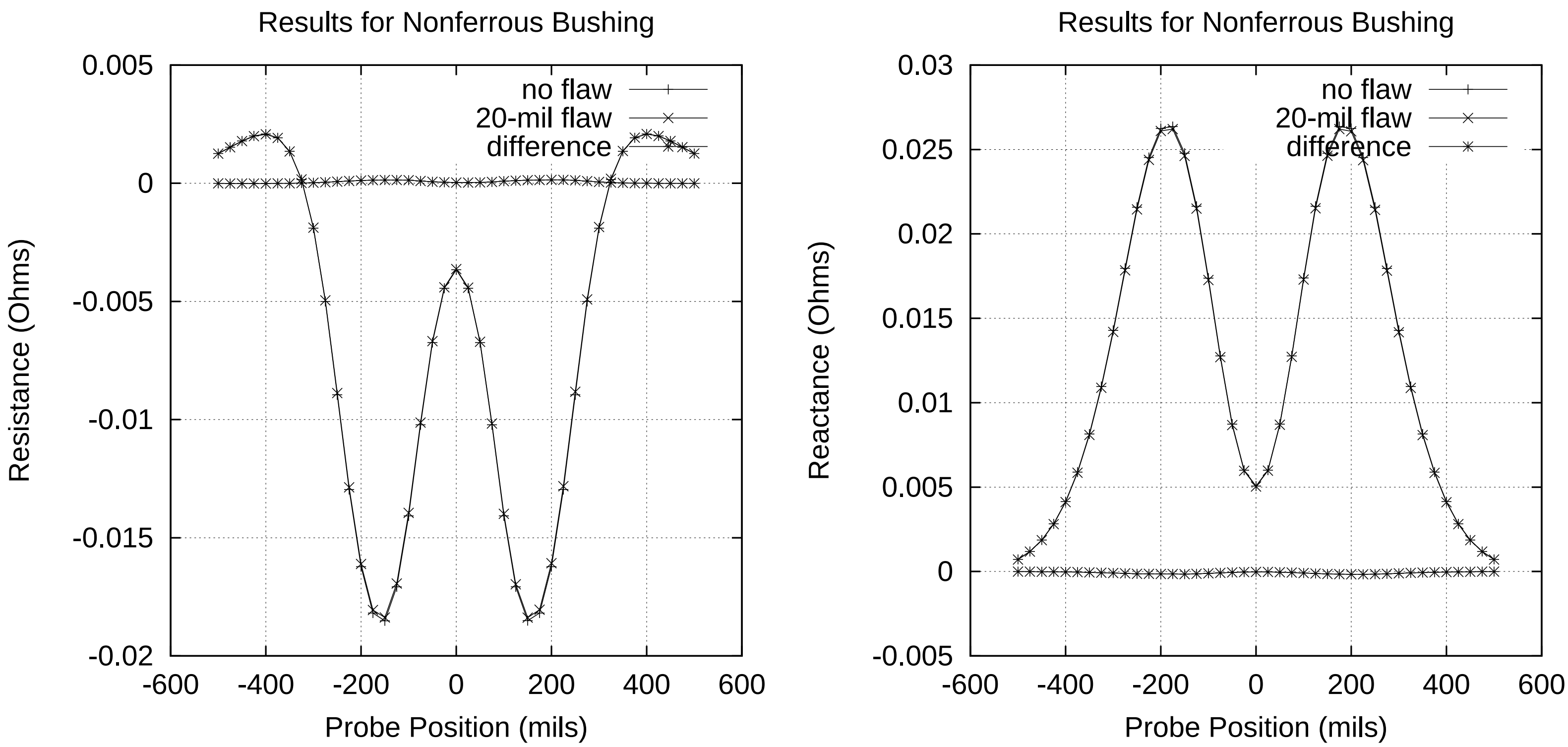
- rivet head has a radius of 0.1 in.
- shank has a radius of 0.05 in.
- bushing is 0.050 in. thick
- crack is a nonconducting cube of 0.020 in. on a side
- conductivity of the bushing is 1.45×10^6 S/m in both cases
- magnetic permeability of ferrous bushing is 70
- frequency of excitation of the coil is 1 kHz for both problems

THE VOLUME-INTEGRAL METHOD (VIM)



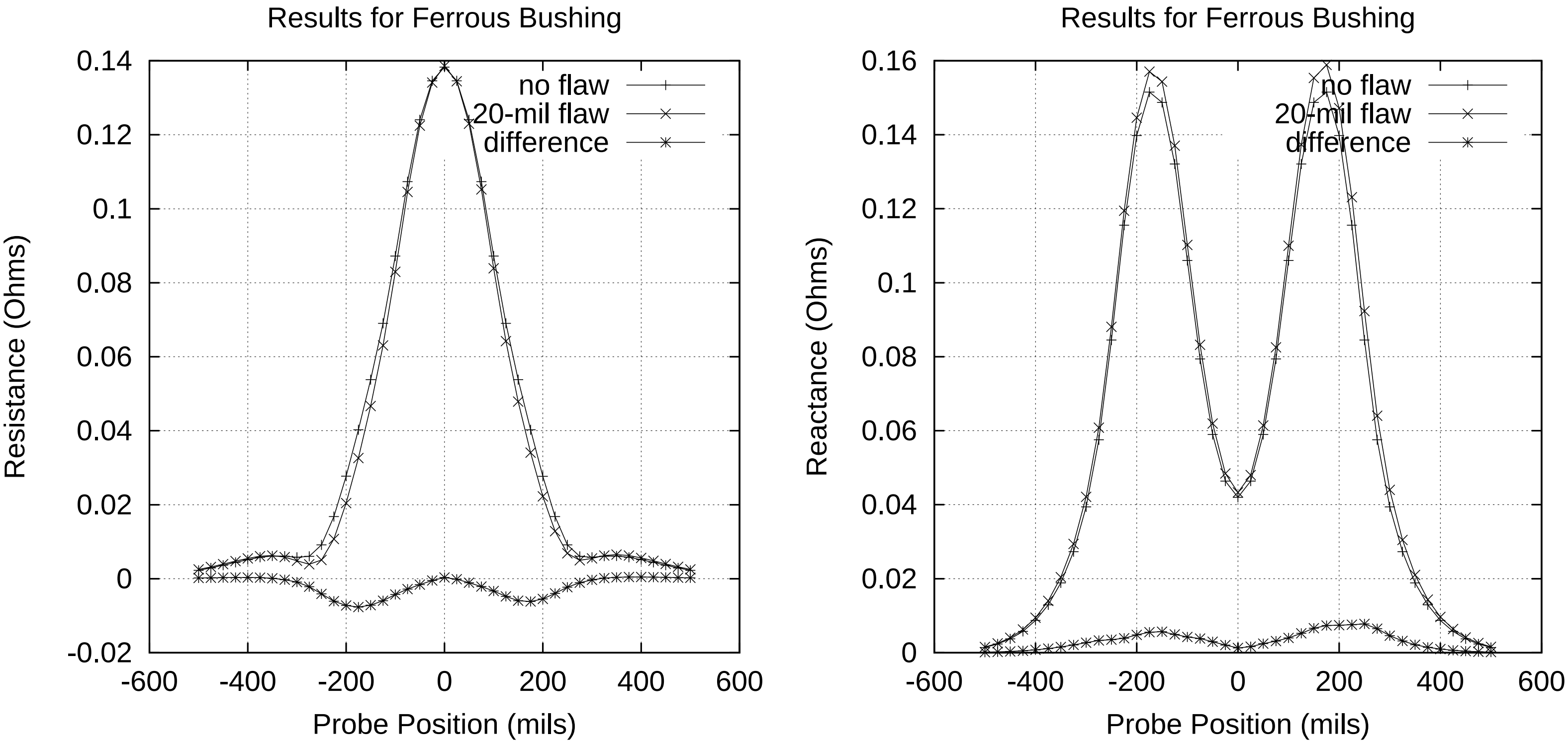
- Anomalous currents, not fields, are the unknowns
- Anomalous currents are confined to the flaw region
- Only flaw region needs to be gridded
- Green's function matrix, $\mathbf{G_{i,j}} = \mathbf{G_{i-j}}$ and/or $\mathbf{G_{i+j}}$
- Much faster solution times than the finite-element method (FEM)
- VIM: 5-10 minutes; FEM 48-100 hours

TWO PROBLEMS INVOLVING FERROUS AND NONFERROUS BUSHINGS



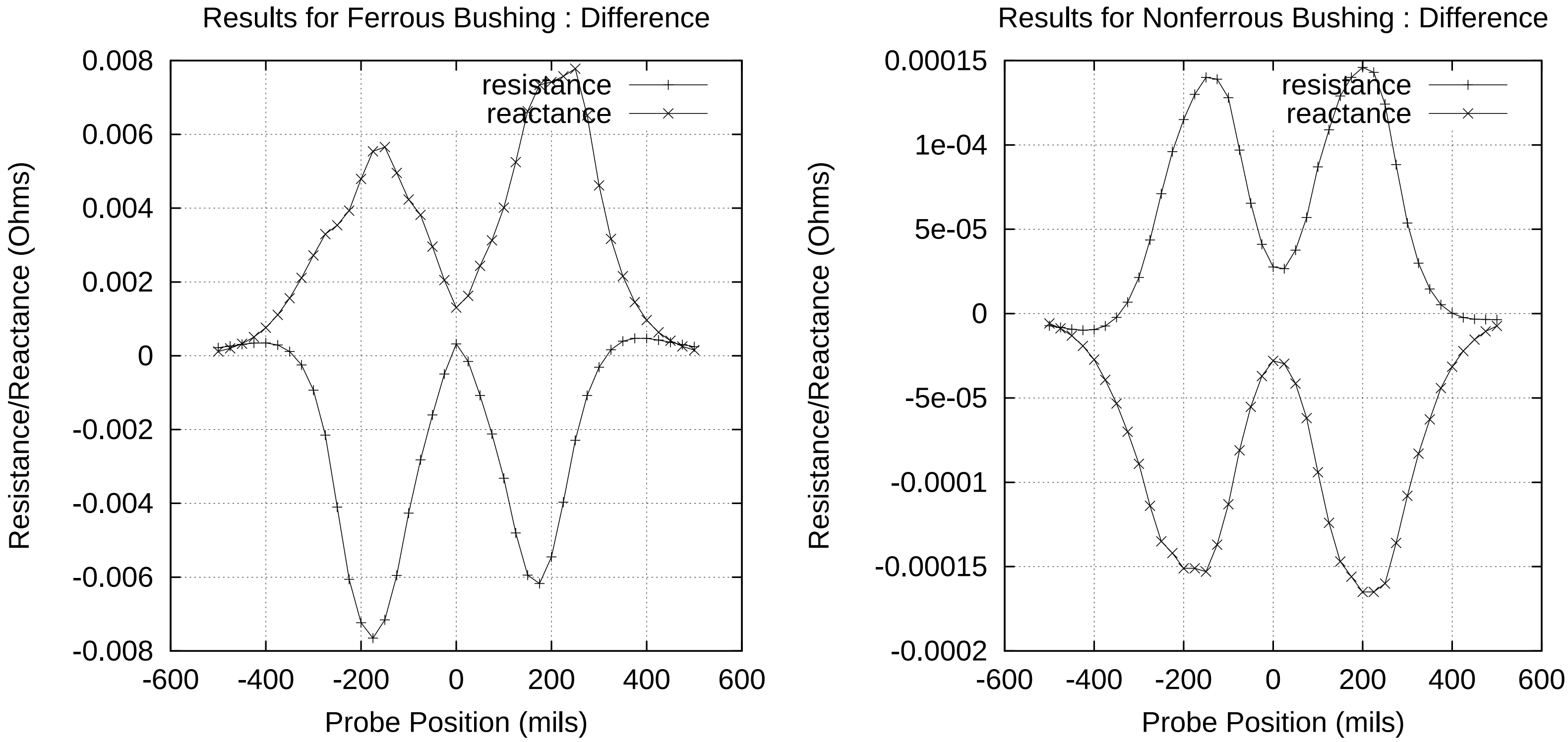
Impedance calculation using **VIC-3D©** for a nonferrous bushing with and without the crack. Left: resistance; right: reactance.

TWO PROBLEMS INVOLVING FERROUS AND NONFERROUS BUSHINGS



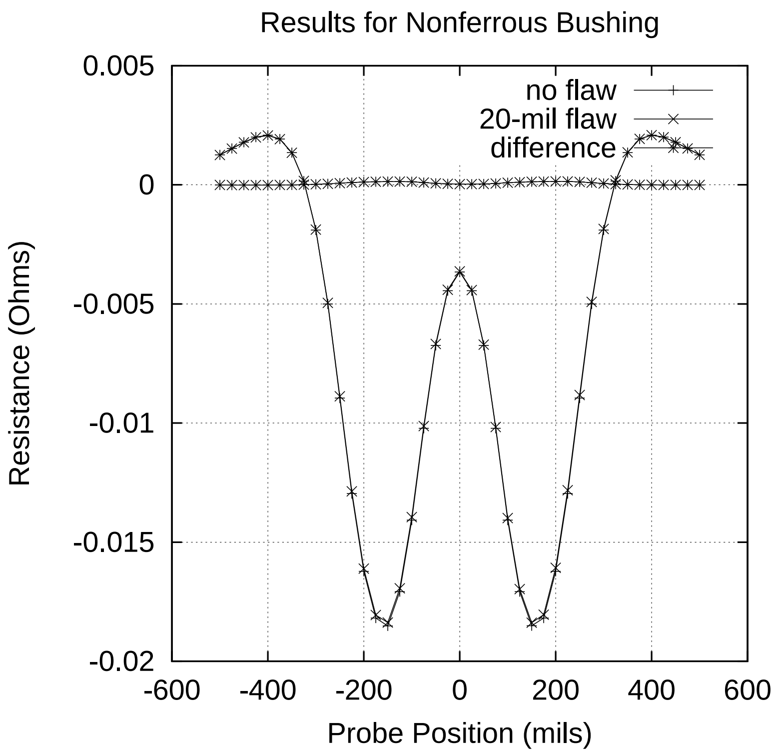
Impedance calculation for a ferrous bushing with and without the crack. Left: resistance; right: reactance.

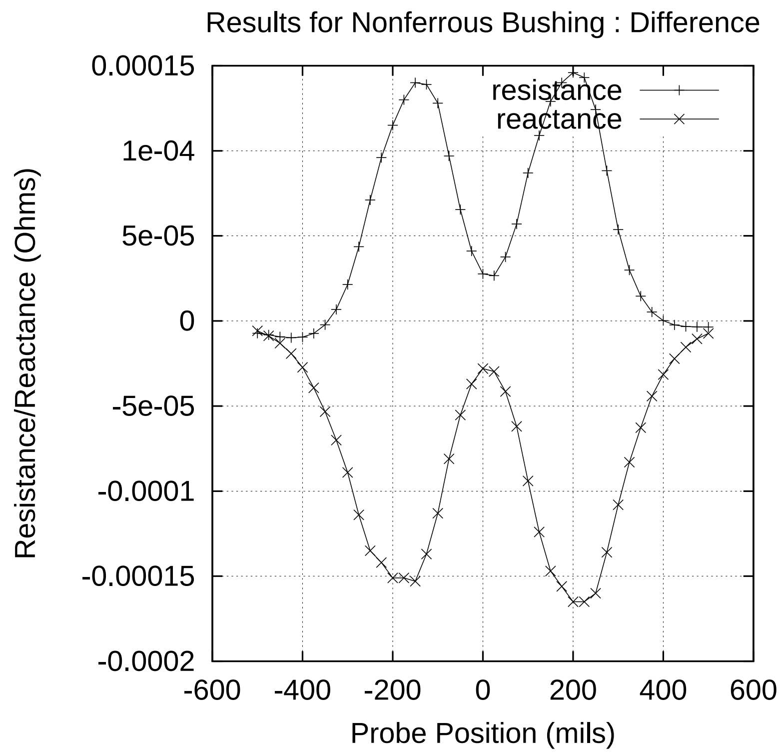
TWO PROBLEMS INVOLVING FERROUS AND NONFERROUS BUSHINGS



Difference curves for ferrous (left) and nonferrous bushing (right).

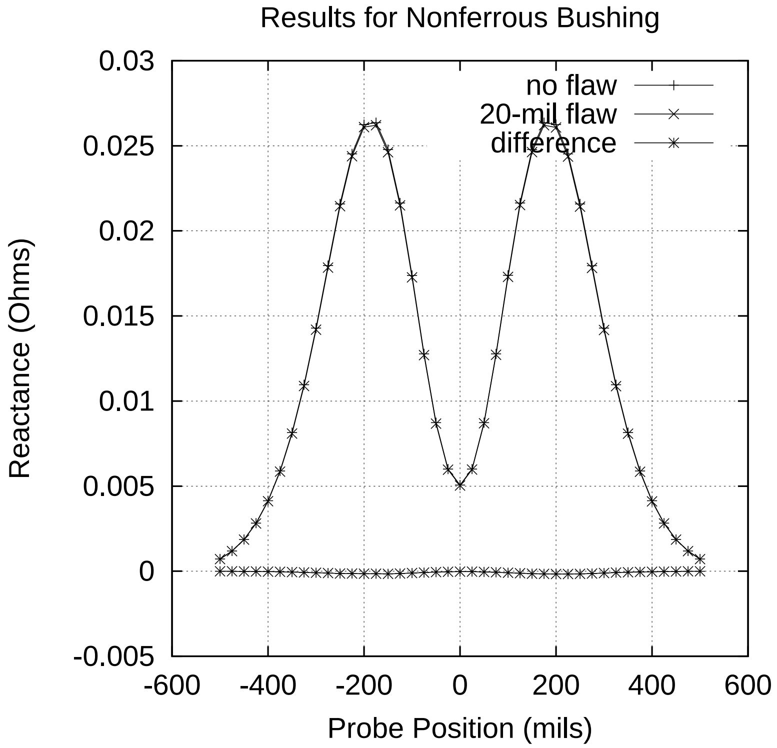
DYNAMIC RANGE OF INSTRUMENTS: NONFERROUS (RESISTANCE)

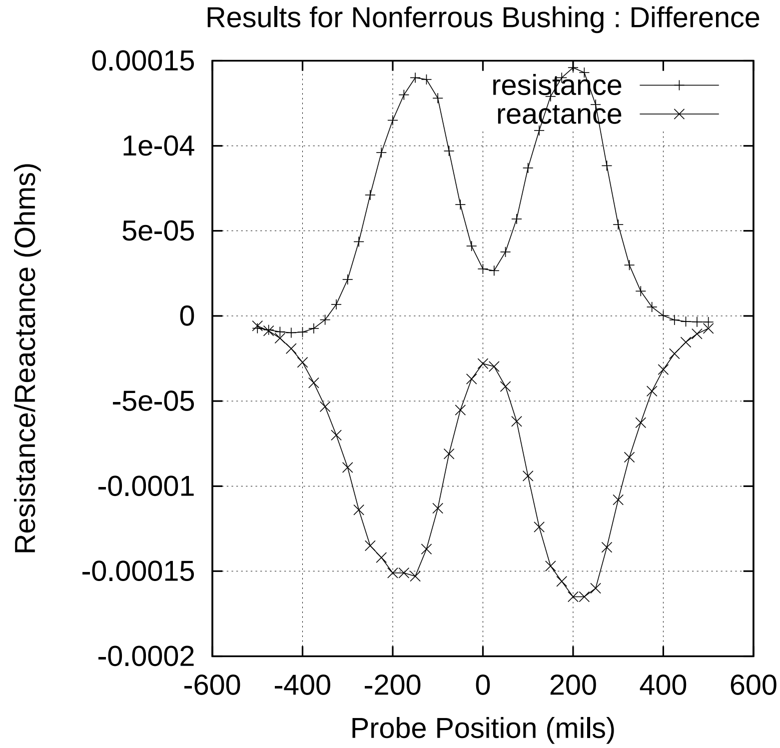




- background resistance value ('host only') is 0.39731Ω
- δ difference-resistance in one scan interval $\sim 5 \times 10^{-5}\Omega$
- dynamic range required to measure resistance is $20 \log(0.39731/5 \times 10^{-5}) =$ 78dB.

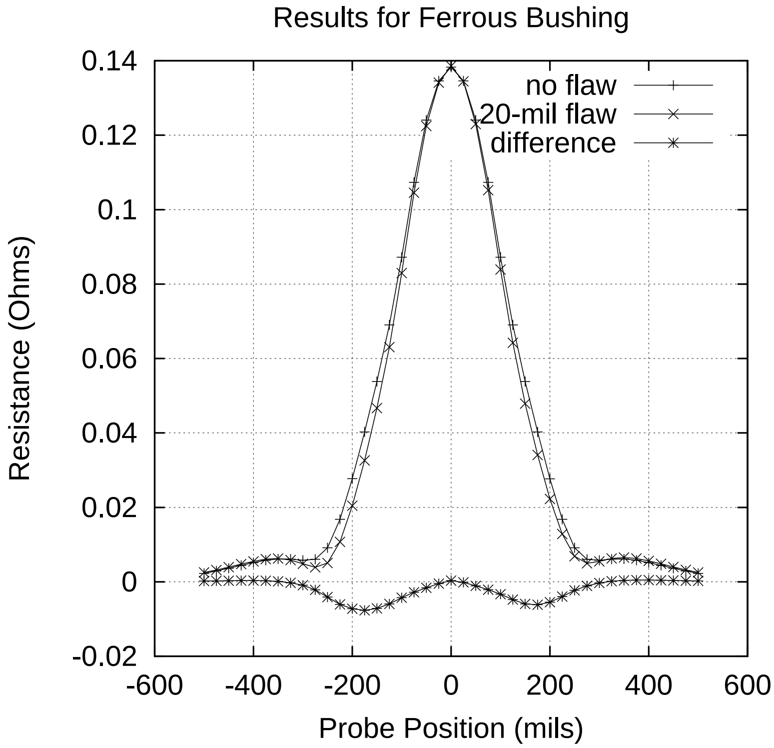
DYNAMIC RANGE OF INSTRUMENTS: NONFERROUS (REACTANCE)

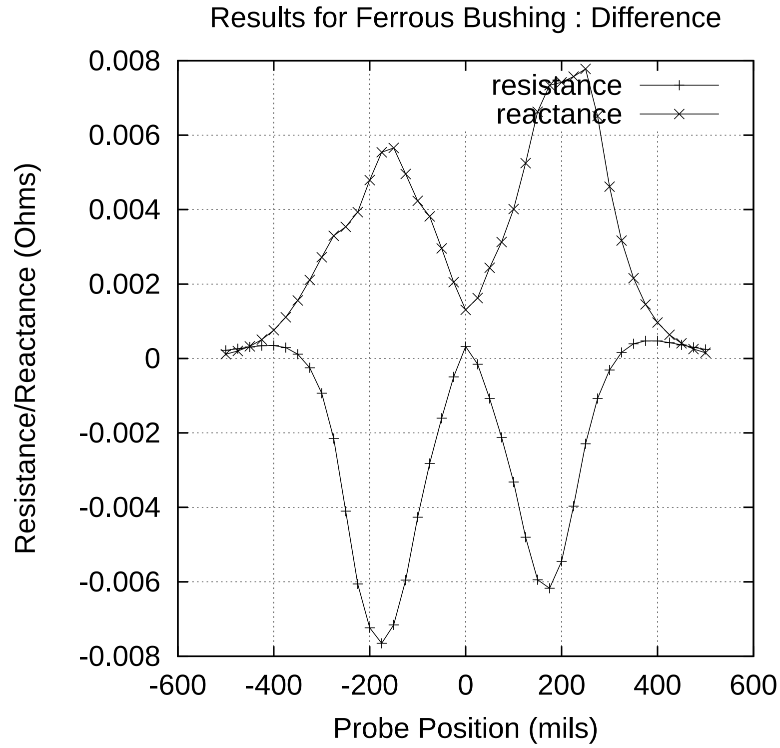




- background reactance value ('host only') is 5.7979Ω
- δ difference-reactance in one scan interval $\sim 5 \times 10^{-5}\Omega$
- dynamic range required to measure reactance is $20 \log(5.7979/5 \times 10^{-5}) = 101.3\mathrm{dB}$.

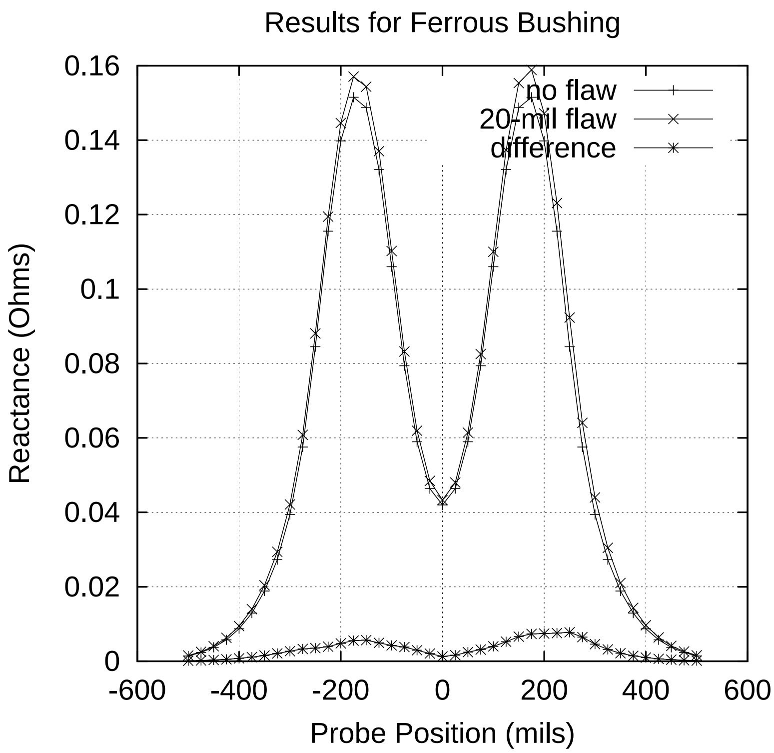
DYNAMIC RANGE OF INSTRUMENTS: FERROUS (RESISTANCE)

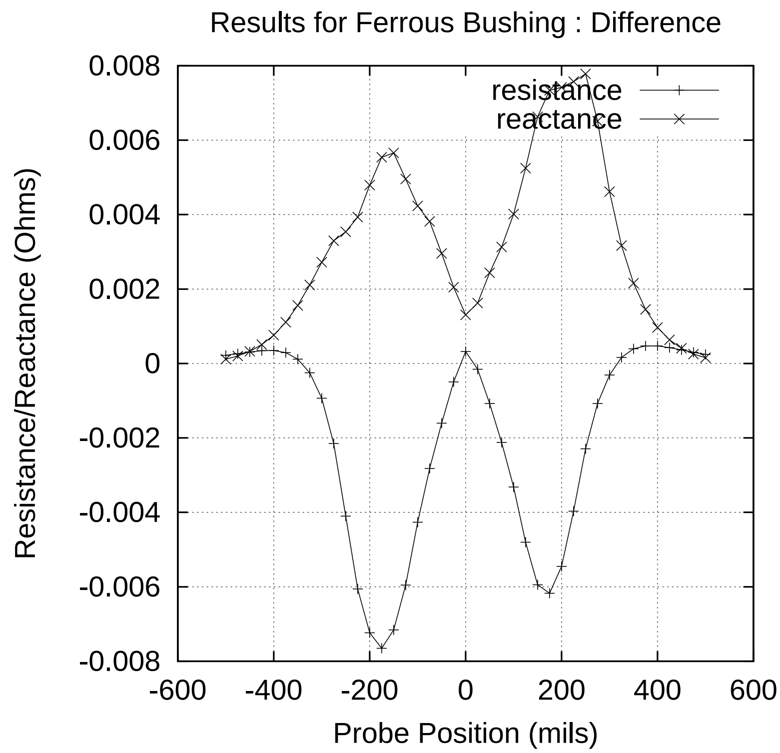




- background resistance value ('host only') is 0.39731Ω
- δ difference-resistance in one scan interval $\sim 1 \times 10^{-3}\Omega$
- dynamic range required to measure resistance is $20 \log(0.39731/1 \times 10^{-3}) =$ 52dB.

DYNAMIC RANGE OF INSTRUMENTS: FERROUS (REACTANCE)





- background reactance value ('host only') is 5.7979Ω
- δ difference-reactance in one scan interval $\sim 1 \times 10^{-3}\Omega$
- dynamic range required to measure reactance is $20\log(5.7979/1 \times 10^{-3}) = 75.3\text{dB}$.

DYNAMIC RANGE OF INSTRUMENTS

Commercial impedance/network analyzers that

- operate over a frequency range of 5 Hz to 200 MHz
- have a resolution of six significant digits
- have a dynamic range of 100-120 dB

already exist, and are routinely found in undergraduate electrical engineering laboratories. For example, the Hewlett-Packard HP 3577A network analyzer.

CONCLUSIONS FROM MODEL STUDIES

- presence of ferrous bushing reduces dynamic range requirement for detection of small flaw by 26dB
- similar results are seen for ferrous rivet (no bushing) and flaw
- ferromagnetic steels behave very much like a ferrite core in a probe; they enhance the effect of the normal electric currents in producing a flaw signal

PROPOSED DESIGN CRITERION

When designing for inspectability

- use ferrous rivets in the original structure
- use ferrous bushings in the reworked structure

when the host material is nonferrous (such as aluminum).

NONLINEAR LEAST-SQUARES INVERSION ALGORITHM:NLSE

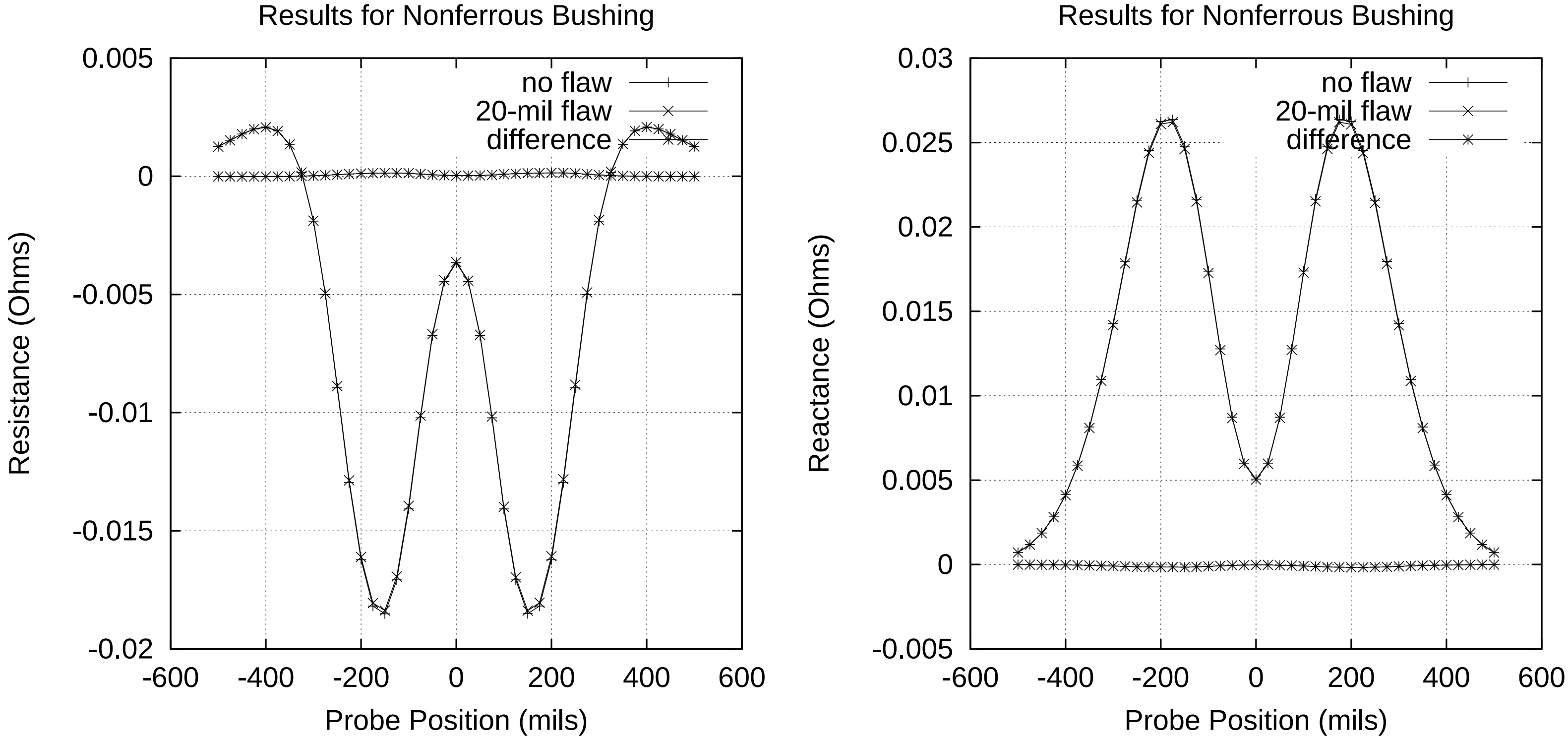
$$\begin{array}{rcl} \text{Measured Data} & & \text{Model Data} \\ R_1 + jX_1 & = & f_1(p_1, p_2, p_3, \ldots, p_M) \\ R_2 + jX_2 & = & f_2(p_1, p_2, p_3, \ldots, p_M) \\ R_3 + jX_3 & = & f_1(p_1, p_2, p_3, \ldots, p_M) \\ & \vdots & \\ R_N + jX_N & = & f_N(p_1, p_2, p_3, \ldots, p_M) \end{array} \tag{1}$$

$p_1, \ldots, p_M$ are parameters to be determined; e.g., length, width, height

NLSE: Minimize $\|\mathbf{R} + j\mathbf{X} - \mathbf{f}(\mathbf{p})\|$ over $\mathbf{p}$ Using Gauss-Newton

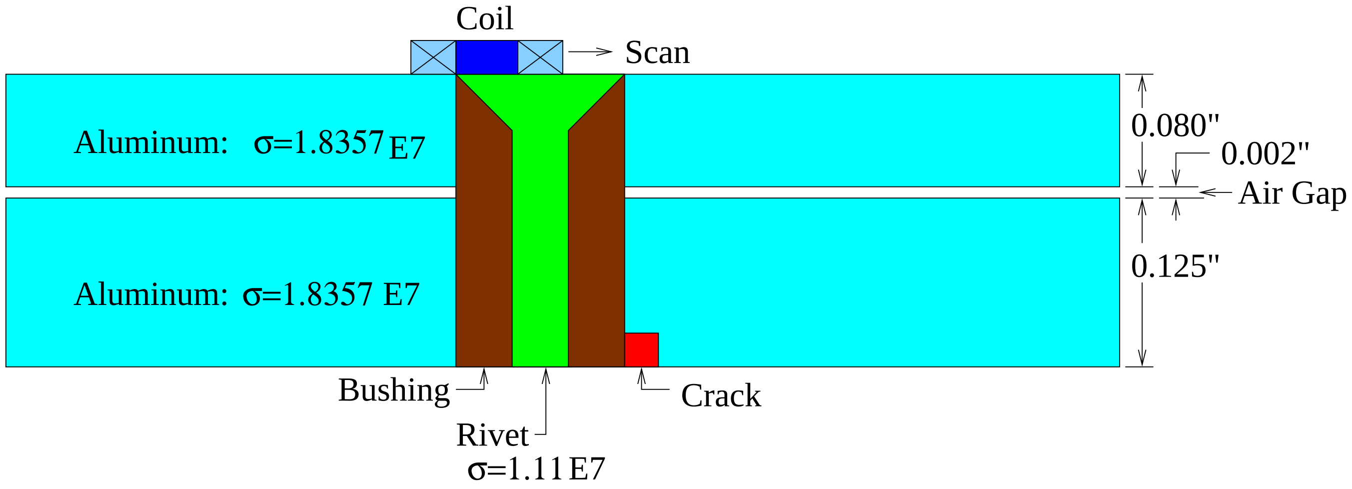
VIC-3D© generates the Model Data based on an interpolating 'look-up' table for $\mathbf{p}$.

TWO PROBLEMS INVOLVING FERROUS AND NONFERROUS BUSHINGS:CAN YOU DETERMINE IF A CRACK IS PRESENT?



Impedance calculation using **VIC-3D©** for a nonferrous bushing with and without the crack. Left: resistance; right: reactance.

AN INVERSE PROBLEM TO AUTOMATICALLY DETERMINE CRACK HEIGHT



Procedure

- Use **VIC-3D©** to generate a five-point interpolation table for crack height: 20, 22.5, 25, 27.5 and 30 mils at 1kHz.
- Use model-generated input ('measured') impedance data for HT = 25 mils at 1kHz, with and without noise.
- One DOES NOT make a decision by observing the measured data.
- Apply NLSE to this system with interpolation orders of 1-4.

RESULTS OF INVERSE PROBLEM TO DETERMINE CRACK HEIGHT

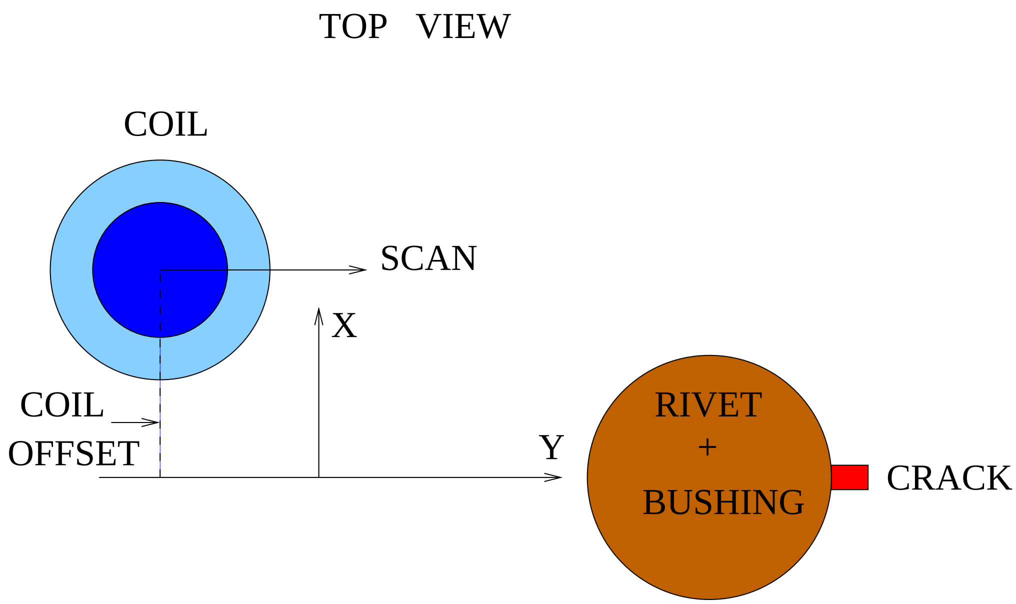
Table 1: Results of Inversion Without Noise

ORDER	Φ	HT/Sensitivity
1	0.1517(-8)	25.00/0.1312(-3)
2	0.1517(-8)	25.00/0.1968(-3)
3	0.1516(-8)	25.00/0.1997(-3)
4	0.1516(-8)	25.00/0.1981(-3)

Table 2: Results of Inversion With Noise

ORDER	Φ	HT/Sensitivity
1	0.1135(-3)	30.00/0.1223(2)
2	0.1094(-3)	22.78/0.9213(1)
3	0.1106(-3)	24.31/0.1009(2)
4	0.1420(-3)	23.43/0.1099(2)
AVG		25.13

A TWO-PARAMETER INVERSE PROBLEM: CRACK HEIGHT + COIL OFFSET



Procedure

- Use **VIC-3D©** to generate a five-point interpolation table for crack height: 20, 22.5, 25, 27.5, 30 mils, and coil offset: -30, -15, 0, 15, 30 mils at 1kHz.
- Use the same model-generated input ('measured') impedance data for HT = 25 mils and OFFSET=0 mils, at 1kHz, with and without noise, as before.
- One DOES NOT make a decision by observing the measured data.
- Apply NLSE to this system with interpolation orders of 1-4 for each variable.

RESULTS OF TWO-PARAMETER INVERSE PROBLEM TO DETERMINE CRACK HEIGHT + COIL OFFSET

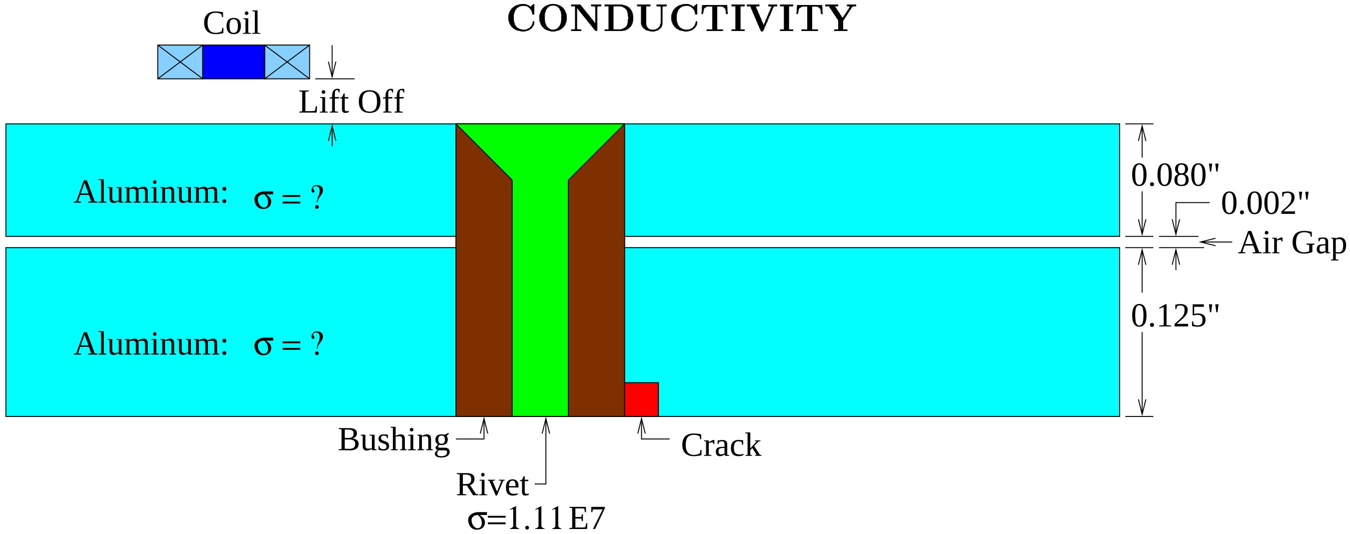
Table 3: Results of Inversion Without Noise

ORDER	Φ	HT/Sensitivity	OFFSET/Sensitivity
1	0.1515(-8)	25.00/0.1310(-3)	0./0.1624(-5)
2	0.1506(-8)	25.00/0.1954(-3)	0.4069(-3)/0.7224(-3)
3	0.1505(-8)	25.00/0.1982(-3)	0.3684(-3)/0.3798(-3)
4	0.1505(-8)	25.00/0.1967(-3)	0.3875(-3)/0.3358(-3)

Table 4: Results of Inversion With Noise

ORDER	Φ	HT/Sensitivity	OFFSET/Sensitivity
1	0.1394(-3)	24.41/0.1206(2)	-0.3149/0.1762(1)
2	0.1704(-3)	23.92/0.8393(1)	-1.6050/0.6632(1)
3	0.9034(-4)	23.51/0.7062(1)	0.1435/0.6335(2)
4	0.1257(-3)	23.86/0.1036(2)	-0.2967/0.3878(2)
AVG		23.93	-2.0731

A TWO-PARAMETER INVERSE PROBLEM : LIFT-OFF + HOST CONDUCTIVITY



Excite coil at 21 equispaced logarithmic frequencies between $1\text{x}10^5$ and $1\text{x}10^7$ Hz

True Data: $\sigma = 1.8357 \text{ x } 10^7$ S/m, Lift−Off = 30 mils

Procedure

- Use **VIC-3D**© to generate a five-point interpolation table for lift-off: 0, 10, 20, 30, 40 mils, and and host conductivity: 1×10^7, 1.25×10^7, 1.5×10^7, 1.75×10^7, 2×10^7, at 21 frequencies.
- Use model-generated input (‘measured’) impedance data for LO = 30 mils and host $\sigma = 1.8357 \times 10^7$S/m, at the same 21 frequencies, with and without noise
- One DOES NOT make a decision by observing the measured data.
- Apply NLSE to this system with interpolation orders of 1-4 for each variable.

RESULTS OF TWO-PARAMETER INVERSE PROBLEM TO DETERMINE LIFT-OFF + HOST CONDUCTIVITY

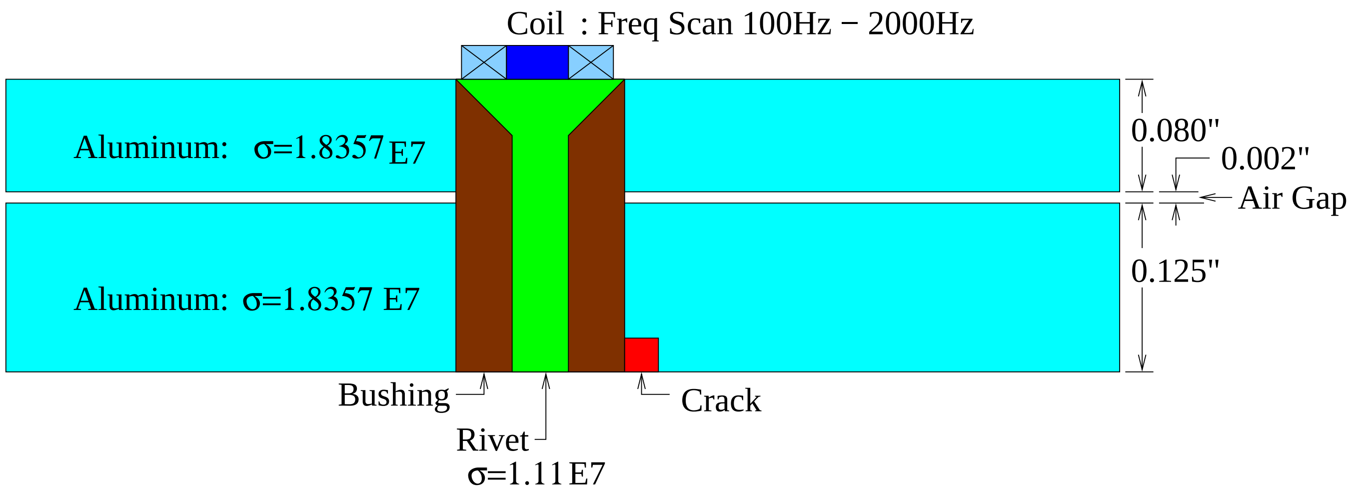
Table 5: Results of Inversion Without Noise

ORDER	Φ	σ/Sensitivity	LO/Sensitivity
1	0.2086	1.842(7)/0.2036(-2)	30.00/0.8210(-3)
2	0.1474	1.837(7)/0.1429(-2)	30.00/0.5290(-3)
3	0.1480	1.837(7)/0.1426(-2)	30.00/0.5324(-3)
4	0.1347	1.835(7)/0.1273(-2)	30.00/0.4782(-3)

Table 6: Results of Inversion With Noise

ORDER	Φ	σ/Sensitivity	LO/Sensitivity
1	0.1102(4)	2.000(7)/0.1116(2)	32.0/0.4332(1)
2	0.1629(4)	2.000(7)/0.1720(2)	32.3/0.6180(1)
3	0.8705(3)	1.214(7)/0.4062(1)	27.4/0.2954(1)
4	0.1246(4)	1.982(7)/0.1275(2)	28.0/0.4249(1)
AVG		1.799(7)	29.9

A MULTIFREQUENCY INVERSE MODEL TO DETERMINE CRACK HEIGHT



Procedure

- The coil is fixed over the rivet, and excited with 39 frequencies, equally spaced between 100Hz and 2000Hz.
- Use **VIC-3D©** to generate a five-point interpolation table for crack height: 20, 22.5, 25, 27.5 and 30 mils at these 39 frequencies.
- Use model-generated input ('measured') impedance data for HT = 25 mils at these 39 frequencies, with and without noise.
- One DOES NOT make a decision by observing the measured data.
- Apply NLSE to this system with interpolation orders of 1-4.

RESULTS OF MULTIFREQUENCY INVERSE PROBLEM TO DETERMINE CRACK HEIGHT

Table 7: Results of Inversion Without Noise

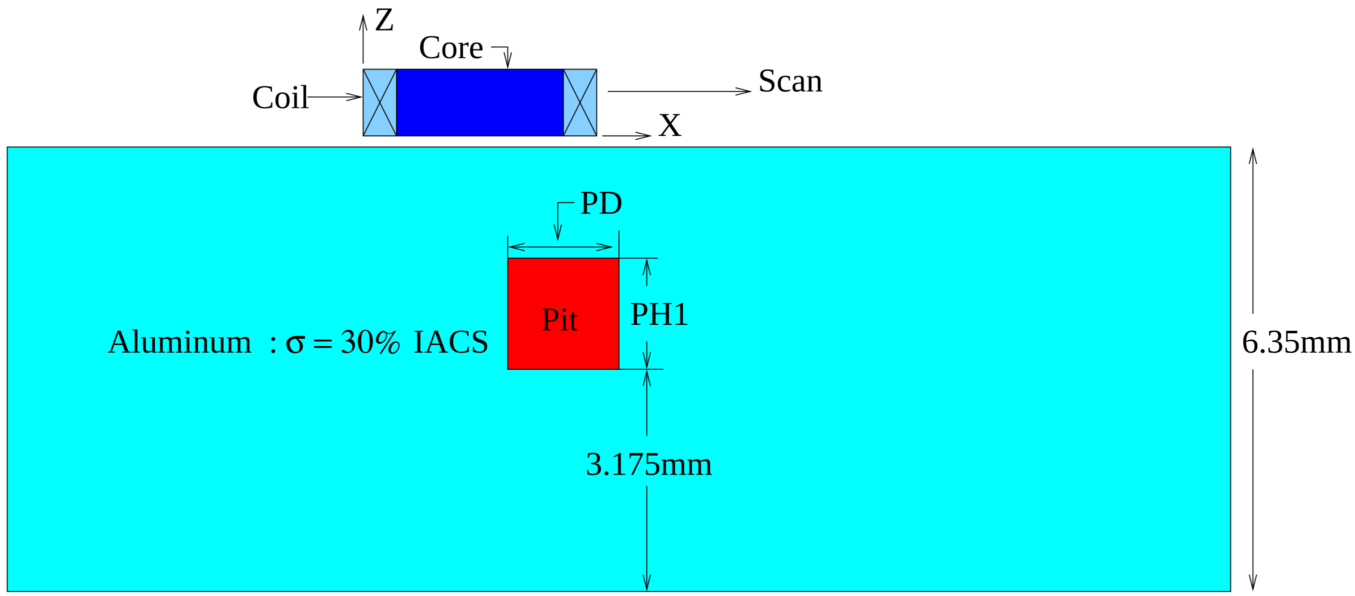
ORDER	Φ	HT/Sensitivity
1	0.8269(-9)	25.00/0.5747(-3)
2	0.8248(-9)	25.00/0.4788(-3)
3	0.8235(-9)	25.00/0.4867(-3)
4	0.8242(-9)	25.00/0.4826(-3)

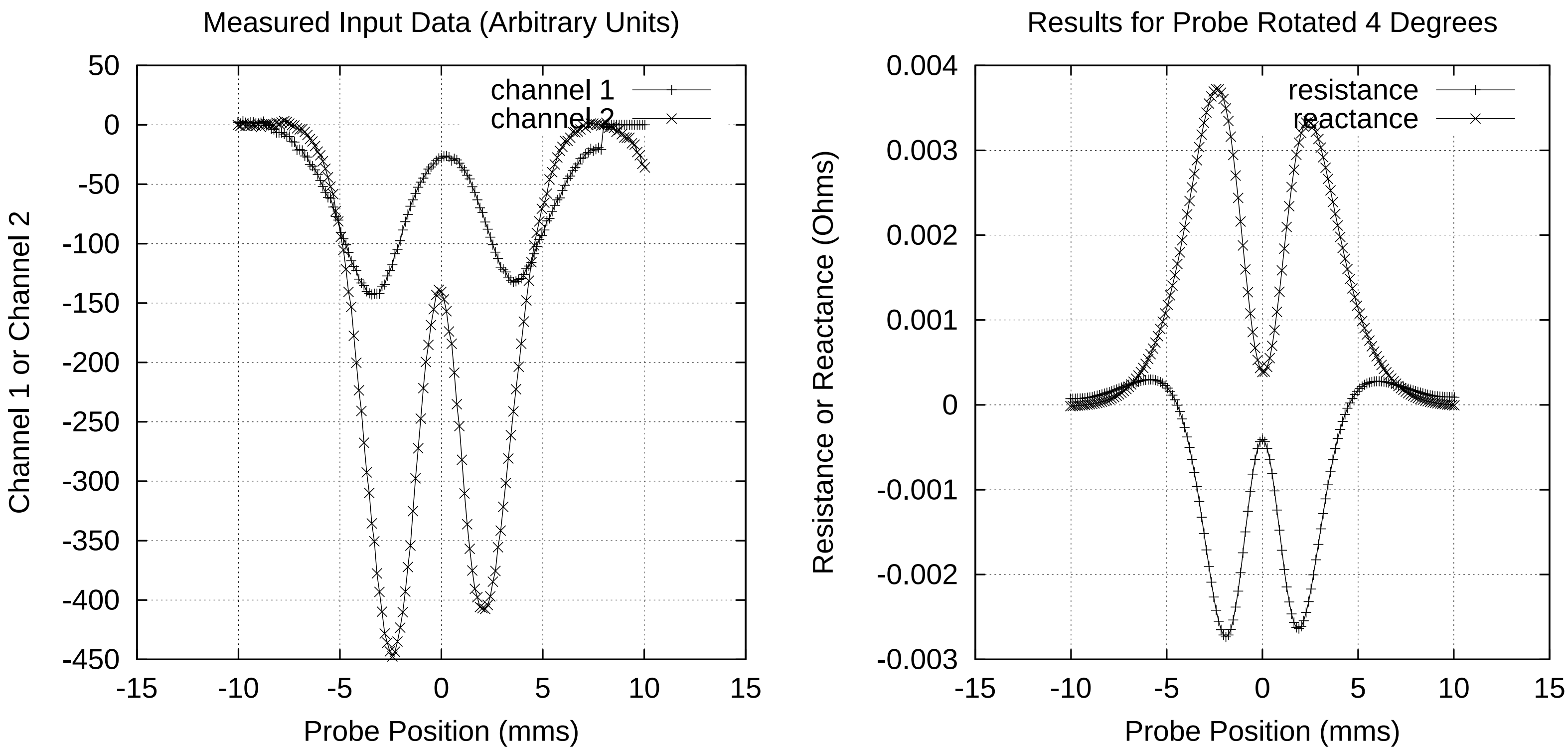
Table 8: Results of Inversion With Noise

ORDER	Φ	HT/Sensitivity
1	0.5901(-4)	28.16/0.2448(2)
2	0.4752(-4)	24.69/0.2419(2)
3	0.4297(-4)	24.84/0.2332(2)
4	0.5374(-4)	20.00/0.2695(2)
AVG		24.42

'Noisy' results are not good when only 10 frequencies are used between 100Hz and 1000Hz.

A RELATED INVERSE PROBLEM: QUANTIFYING CORROSION TOPOLOGY IN AIRCRAFT STRUCTURES

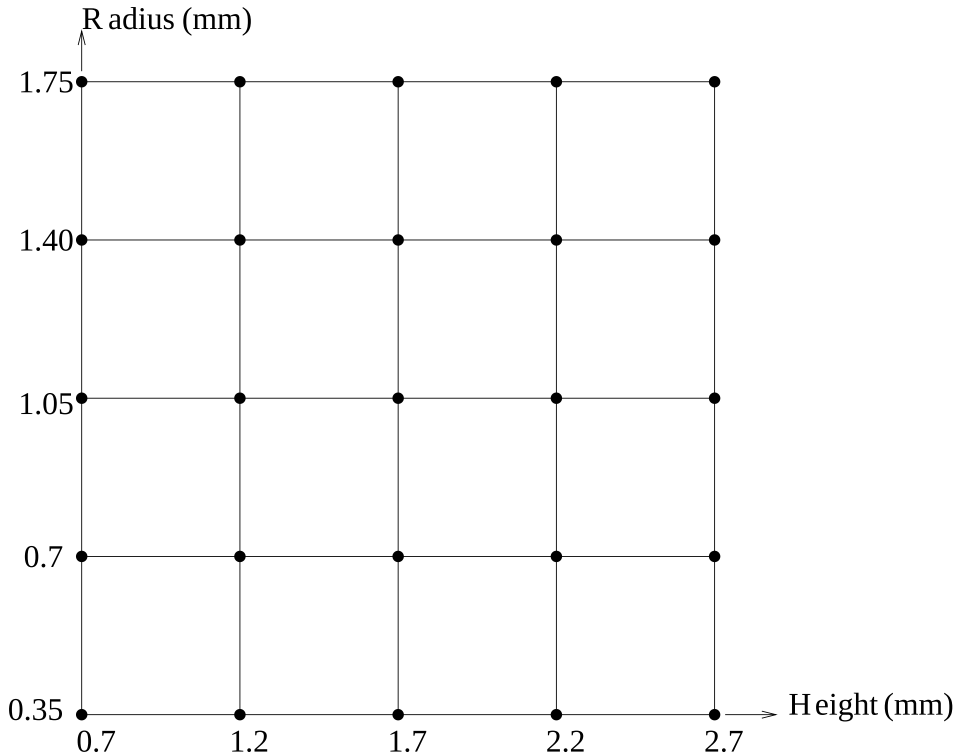




The measured input data taken on the SAIC Ultra-Image instrument (left).

'$\beta-$normalized' input data when the probe-model is tilted 4 degrees about the $Y-$axis, which is normal to the plane of the figure (right).

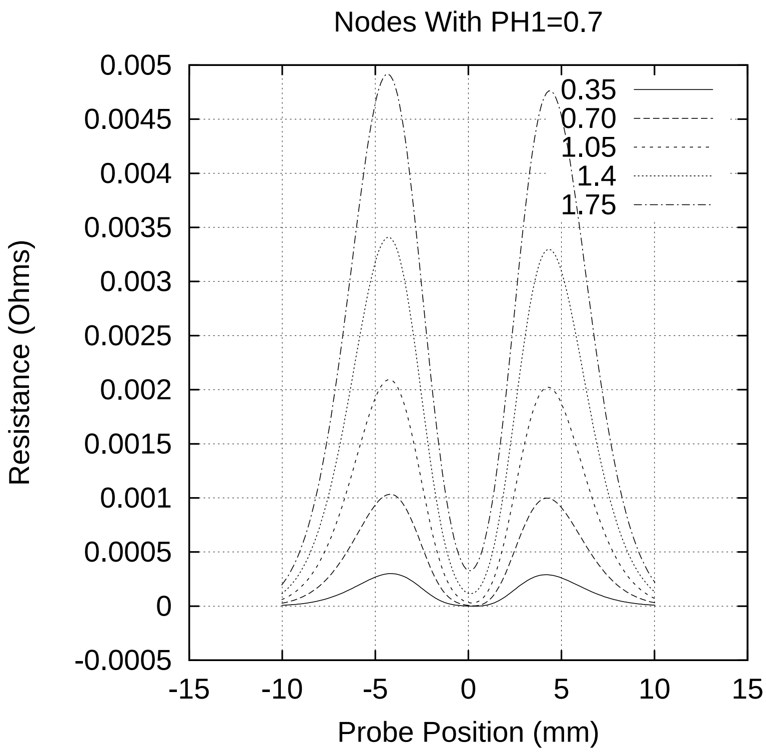
Use the same $\beta-$scale factor for all other measured data, thereby transforming the Ultra-Image instrument into an impedance analyzer.

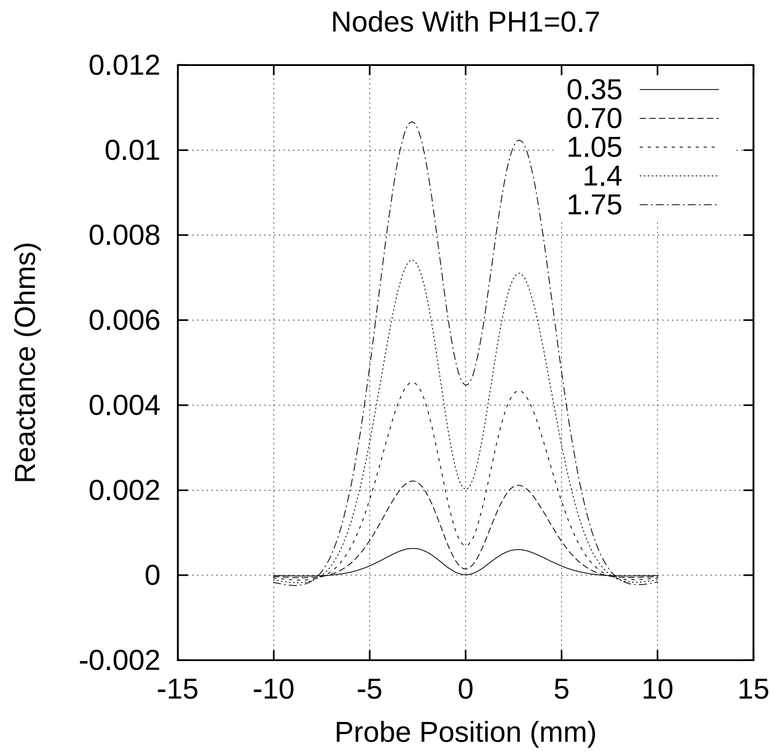


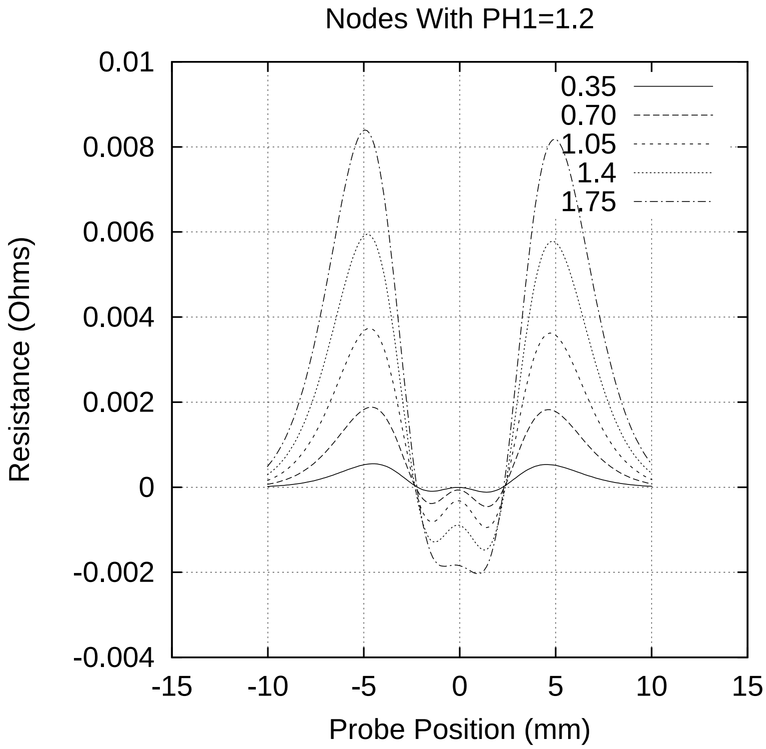
An interpolating grid that is suitable for polynomial-spline interpolation up to order 4 in Radius and Height of a flaw.

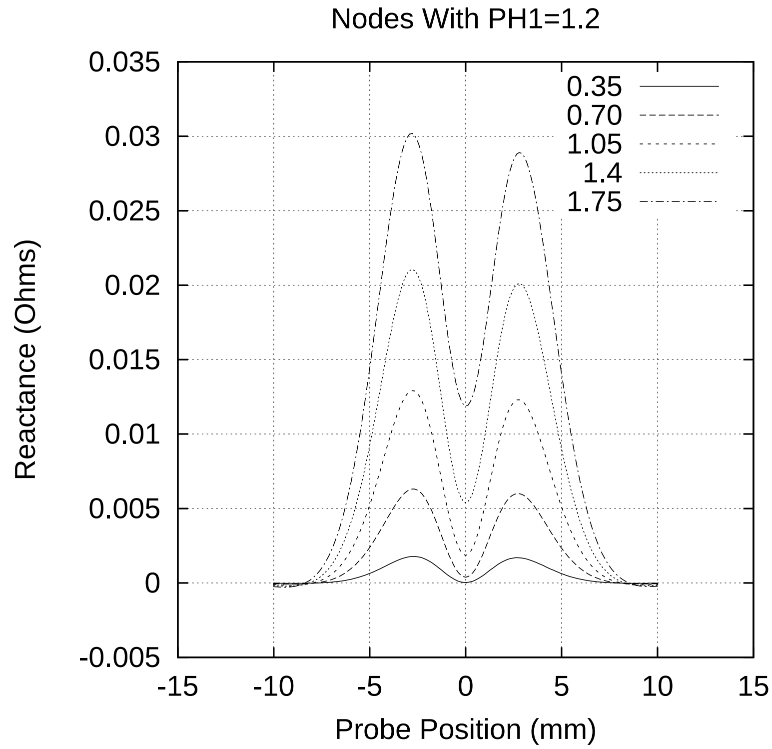
The 'blending functions' associated with these nodes are computed using **VIC-3D©**. There is no need for hardware standards.

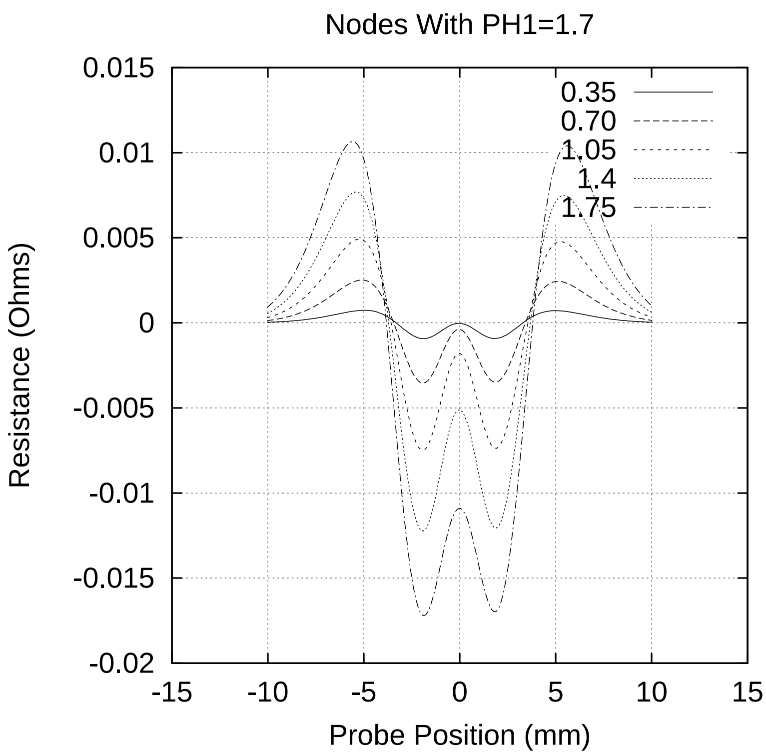
Blending Functions For Interpolating Grid

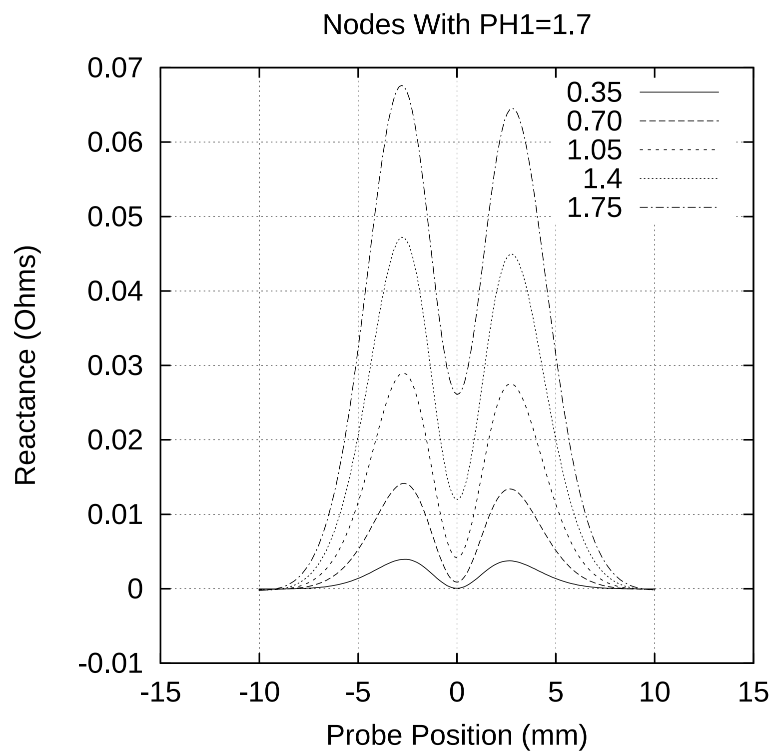


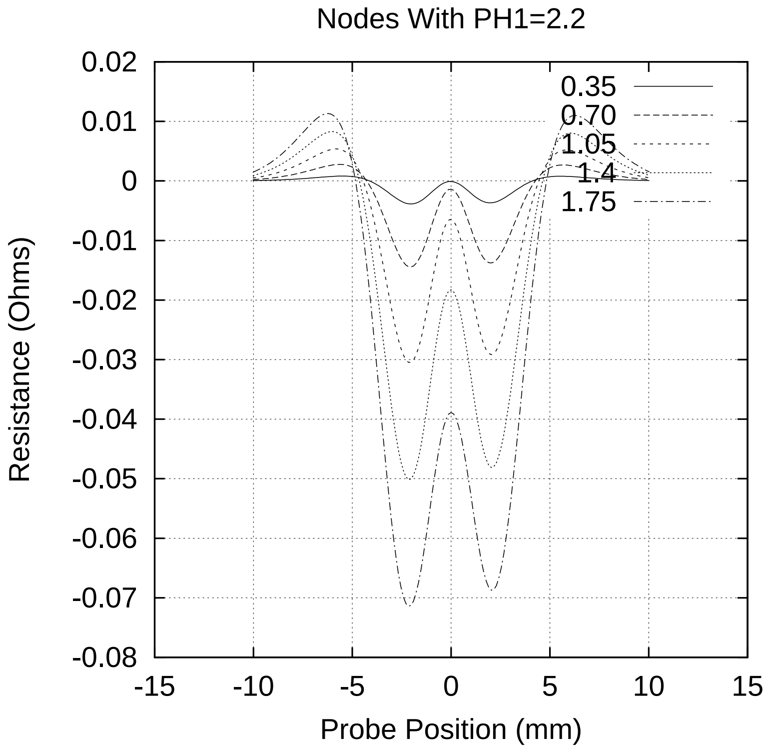


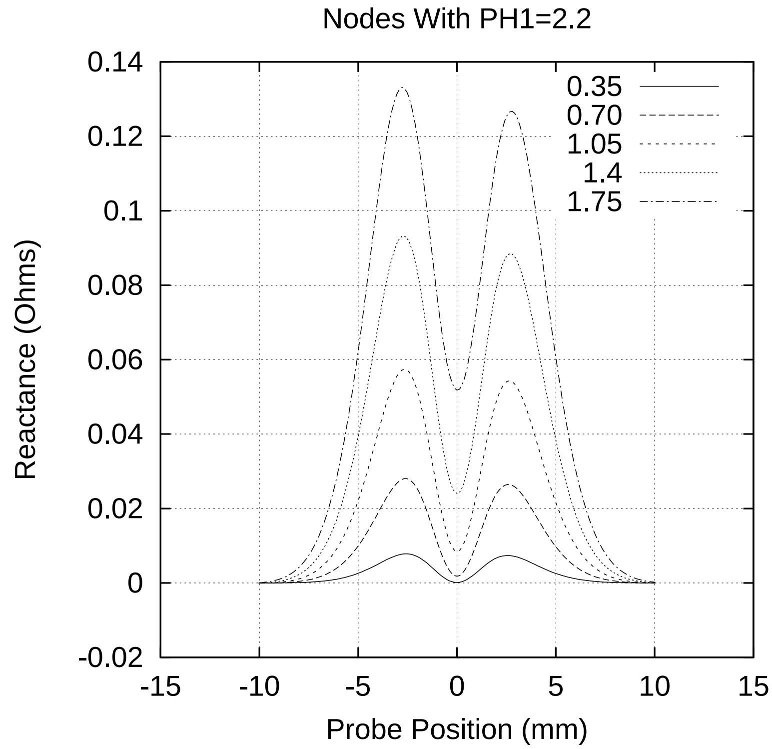

Nodes With PH1=1.2
Resistance (Ohms)
Probe Position (mm)
0.35
0.70
1.05
1.4
1.75

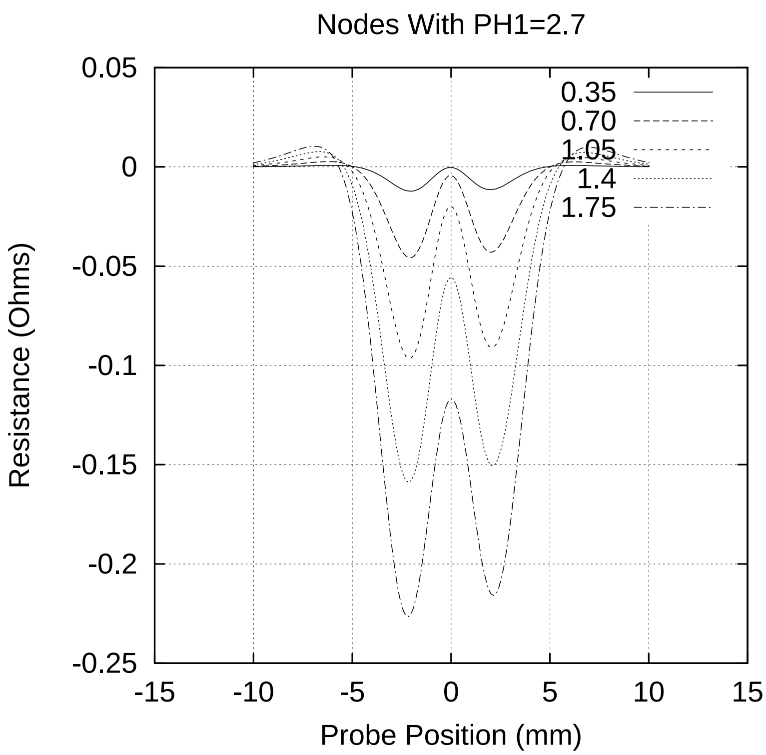

Nodes With PH1=1.2
Reactance (Ohms)
Probe Position (mm)
0.35
0.70
1.05
1.4
1.75

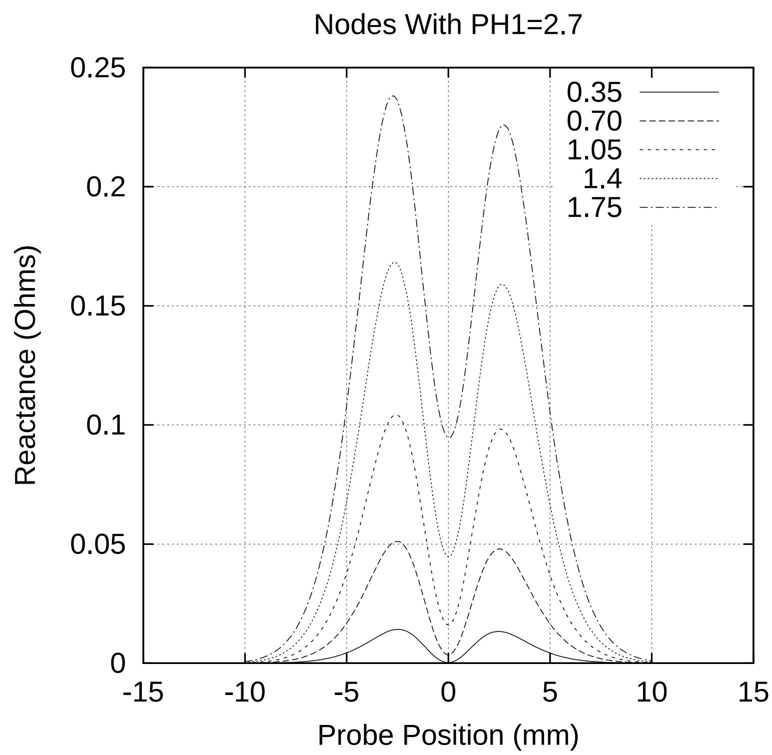

Nodes With PH1=1.7
Resistance (Ohms)
Probe Position (mm)
0.35
0.70
1.05
1.4
1.75


Nodes With PH1=1.7
Reactance (Ohms)
Probe Position (mm)
0.35
0.70
1.05
1.4
1.75


Nodes With PH1=2.2
Resistance (Ohms)
Probe Position (mm)
0.35
0.70
1.05
1.4
1.75


Nodes With PH1=2.2
Reactance (Ohms)
Probe Position (mm)
0.35
0.70
1.05
1.4
1.75


Nodes With PH1=2.7
Resistance (Ohms)
Probe Position (mm)
0.35
0.70
1.05
1.4
1.75


Nodes With PH1=2.7
Reactance (Ohms)
Probe Position (mm)
0.35
0.70
1.05
1.4
1.75

RESULTS AT 2200 HZ

Polynomial Order	Φ	R	Σ_R	H	Σ_H
1	0.0278	1.651	0.02259	2.317	0.01275
2	0.0199	1.6283	0.01530	2.3554	0.00984
3	0.0191	1.6289	0.01469	2.3554	0.009546
4	0.01323	1.620	0.010	2.3747	0.00702

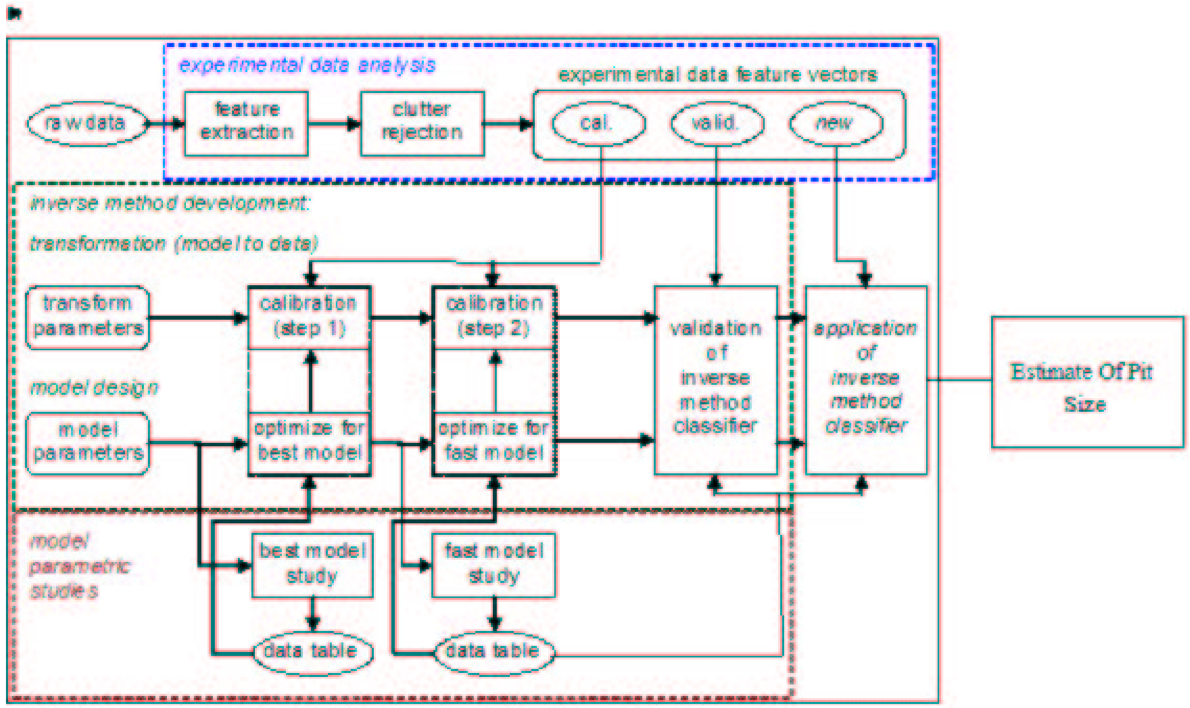
Table 9: Results of higher-order spline interpolator. Σ_V denotes the sensitivity of the solution to the variable, V.

The fourth-order result of Table 9 has an error in radius of about 2% and in height of about 0.27%.

MODEL-BASED INVERSION

- introduces 'Probability of Inversion'
  - how many parameters are to be inverted?
  - how large is the interpolation table for each parameter?
- does not use a variety of reference calibration blocks, with a variety of edm notches, for a variety of probe orientations
- is objective–no 'operator/inspector calls' based on *a priori* raw data
- gives an *a posteriori* estimate of sensitivity of each parameter
- gives an *a posteriori* estimate of harmful noise level
- gives a **constructive** reconstruction algorithm
- is based on a system of support algorithms, such as clutter removal, noise reduction, 'fast' models, etc.
- is robust, efficient, mathematically rigorous, and reliable.

IMPROVE INVERSE METHOD PROCESS



Process Diagram

- Experimental data analysis
  1. clutter rejection
- Model parametric studies
- Experiment/model data transformation
- Model design optimization
  2. equivalent/fast models
- Design/validate inverse method
  3. novel inversion schemes

SUMMARY AND CONCLUSIONS

- Commercial electronic instrumentation (impedance analyzers) exist that have the dynamic range to measure the rivet + bushing + flaw system
- Modeling is essential to establishing test and evaluation procedures
- Model-based inversion is an essential part of test and evaluation procedures
- Volume-Integral Methods are well-suited to eddy-current modeling