Practical Methods to Simplify the Probability of Detection Process

Investigation of a Model-Assisted Approach for POD Evaluation

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ASIP 2006
San Antonio, TX
November 29, 2006

Acknowledgments

- Experimental Data Acquired by AFRL/UDRI (Hughes, Dukate, Martin)
- Air Force Office of Scientific Research
- Chuck Annis
- The R software environment for statistical computing and graphics was used for all statistical computation and statitical plots. R is an open source (free) software and is available for download at: www.r-project.org
- VIC-3D® was used for all eddy current simulations

Outline

- Motivation / Significance
- Background and Challenges
- Test Samples and Empirical Results
- Model-Assisted POD feasibility study
  - Full Model Assisted (FMA) protocol
  - Input Parameters
  - Signal and Noise Distributions
  - POD analysis
- Issues and Future Work

Wave of Requirements and Technologies

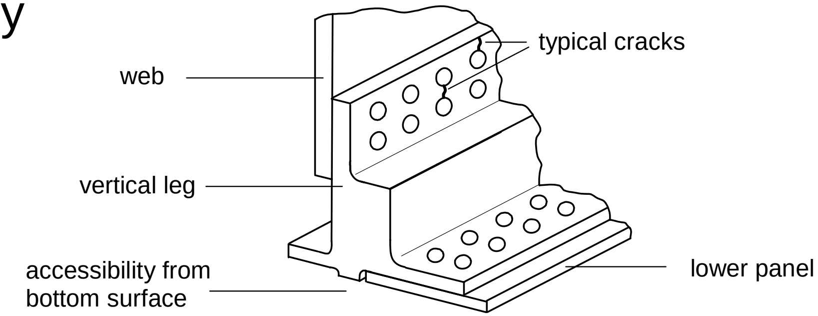
- Man-hours for NDT scheduled to increase dramatically
- Need to insert new technologies into the field, faster and cheaper
- Implementation of inspections without POD undermines NDE Reliability
- Damage tolerant risk analysis techniques demand Quantitative NDE

(Gallagher, Babish, and Malas, 2005)

Motivation

- Requirements for Performing Empirical (MIL HDBK 1823) POD Evaluation
  - High cost of parts (material) *(Wing carry through, Ti)*
  - High cost of flaw creation *(corner cracks, real load profiles)*
  - Labor to perform POD study
- Additional Opportunities using Model-Assisted Approaches
  - Streamline validation of new technologies for in-field application
  - Improve confidence in NDE techniques for complex inspections
    - Address wide variations in flaw characteristics and location
    - Address variations in part geometry

Ex: C-130 Beam Cap Holes



Definition of MAPOD

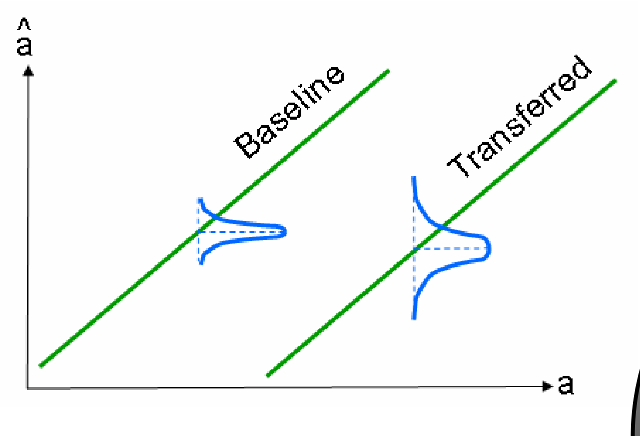
- Model-assisted Probability of Detection:
- Leverage existing information
- Transfer Function Approach (XFN)
  - Transfer from one set of conditions to another
  - Limited number of parameters change
- Full Model-assisted Approach (FMA)
  - Use physics-based models to determine capability of inspection process
  - Requires empirical data to validate models

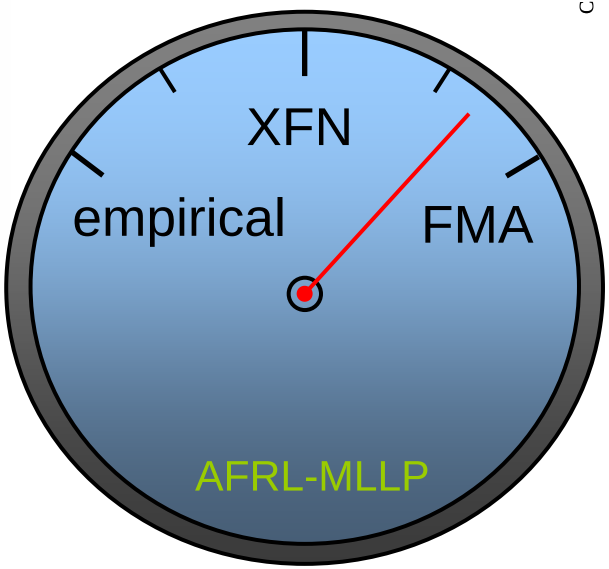
Previous Work

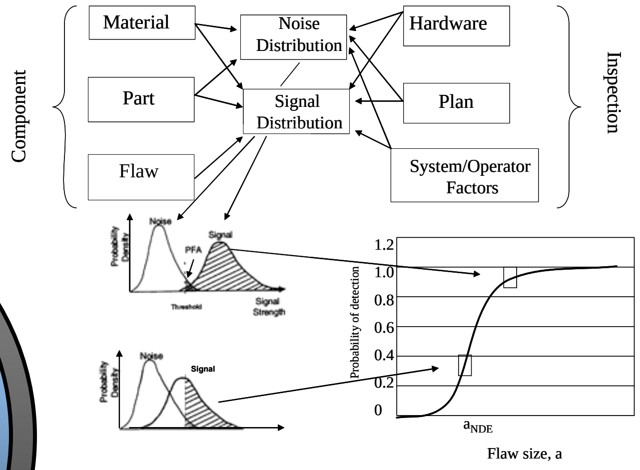
- Model-Assisted Probability of Detection (MAPOD) working group established (2003) www.cnde.iastate.edu/research/MAPOD/MAPODWG.htm
- AFRL/Computational Tools efforts described in multiple journal articles (Knopp and Aldrin, et. al.)
- J.N. Gray, T.A. Gray, N. Nakagawa, and R.B. Thompson, “Models for Predicting NDE Reliability”, ASM Metals Handbook, Vol 17 (1989)
- S.N. Rajesh, L. Udpa, and S.S. Udpa, “Numerical Model Based Approach for Estimating Probability of Detection in NDE Applications”, IEEE Transactions on Magnetics (1993)
- R.B. Thompson, “Using Physical Models of the Testing Process in the Determination of Probability of Detection”, Materials Evaluation (2001)
- Presentations of demonstrations presented at MAPOD working group
  - Kevin Smith (Pratt & Whitney)
- Repositories and protocols developed

Hybrid MAPOD Approach

- **MAPOD Demonstration with Empirical Comparison**
- **Explore continuum from XFN (empirical) to FMA**



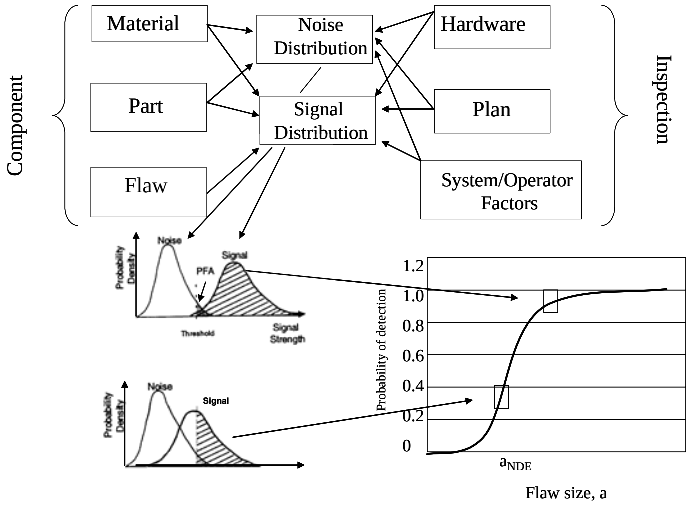




XFN

FMA

FMA Protocol (Thompson)



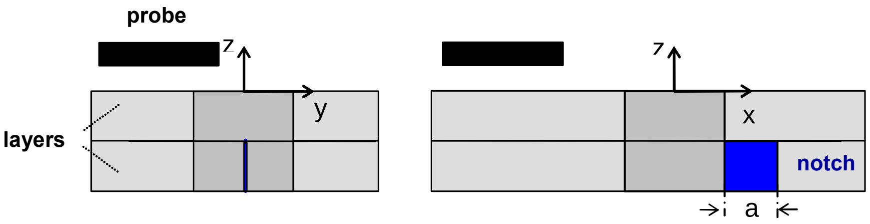
1. Identify the scope of the POD study
2. Identify factors that control signal and noise
3. Evaluate quality of physics-based models
4. Acquire / develop / validate simulation tools
5. Acquire input parameters / parameter distributions
6. Conduct flaw signal distribution simulations and noise signal distribution simulations
7. Acquire remaining information on factors empirically
8. Acquire marginal information on independent factors (average and variance of stochastic variable)
9. Acquire covariance information on dependent factors
10. Combine 6, 8 and 9 into full signal and noise distributions
11. Compute POD / POFC, ROC

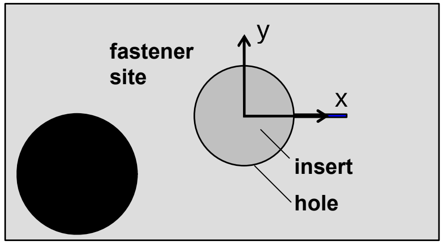
Protocol available on MAPOD Website

Representative Structure

- Wing Splice Fatigue Crack Specimens:
  - Two layer specimens are 14" long and 2" wide,
  - 0.156" thick top layer, 0.100" thick bottom layer
  - 7075-T6 aluminum material
  - exterior coat: 0.004"-0.006" (0.10 – 0.15 mm)
  - faying surface: sealed with polysulfide and chromate corrosion inhibitor
  - 22 samples with 10 fastener sites each
  - 90% fasteners were titanium, 10% fasteners were steel
  - Fatigue cracks position at 6 and 12 o’clock positions (forward and aft directions)
  - Crack location in 2nd layer at near (faying) surface
  - Crack length ranged from 0.027" – 0.169"
  - Estimated length of 0.10" when changes from corner to through wall crack

Fasteners, Probes, Scanning

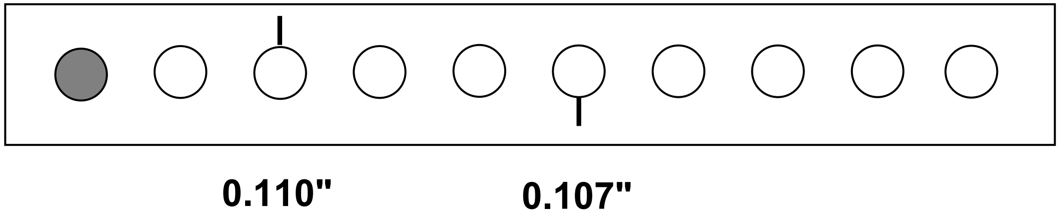




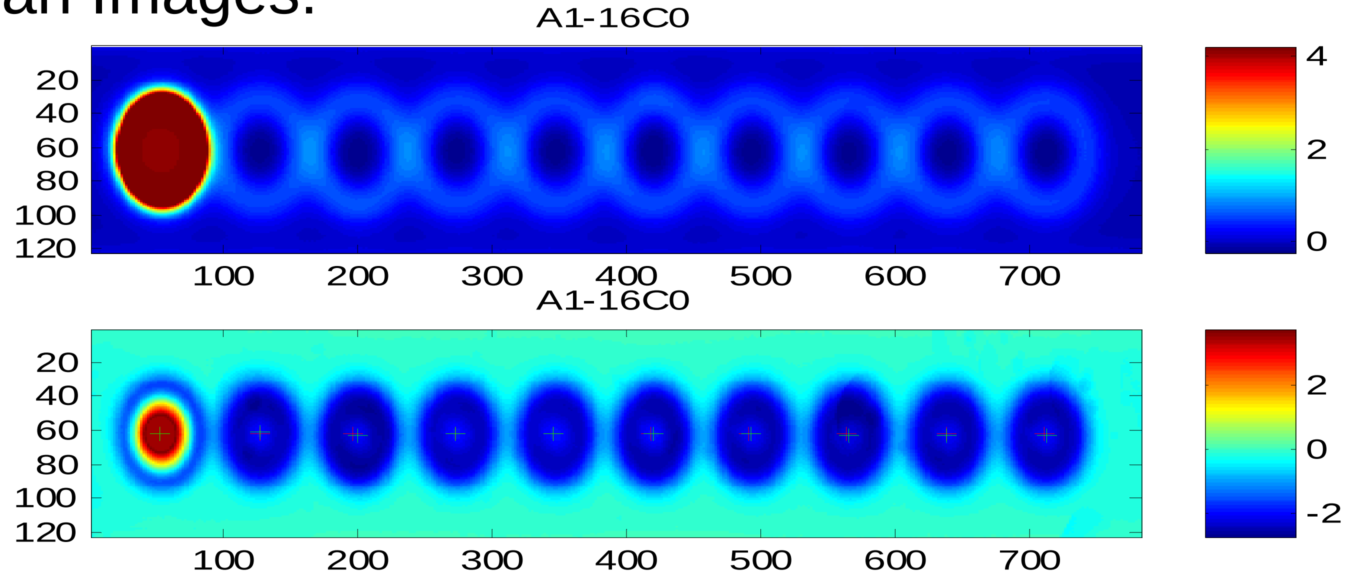
- Fastener Site:
  - countersunk fastener
  - diameter: 0.250" (6.35 mm)
  - 100 degree (cone) flush head
  - material: steel and titanium
  - distance between holes: ~0.73" (18.5 mm)
- Probe:
  - reflection probe
  - frequency of 600 Hz
  - initial estimate of coil – inner diameter: 3 mm
  - initial estimate of coil – outer diameter: 6 mm
  - cup core – outer diameter: 15 mm (outer casing about 5/8”)
- Scan Plan:
  - scan step size: 0.01" (0.25 mm)

Experimental Data

- Acquired by AFRL/UDRI using Automated surface scanning eddy current

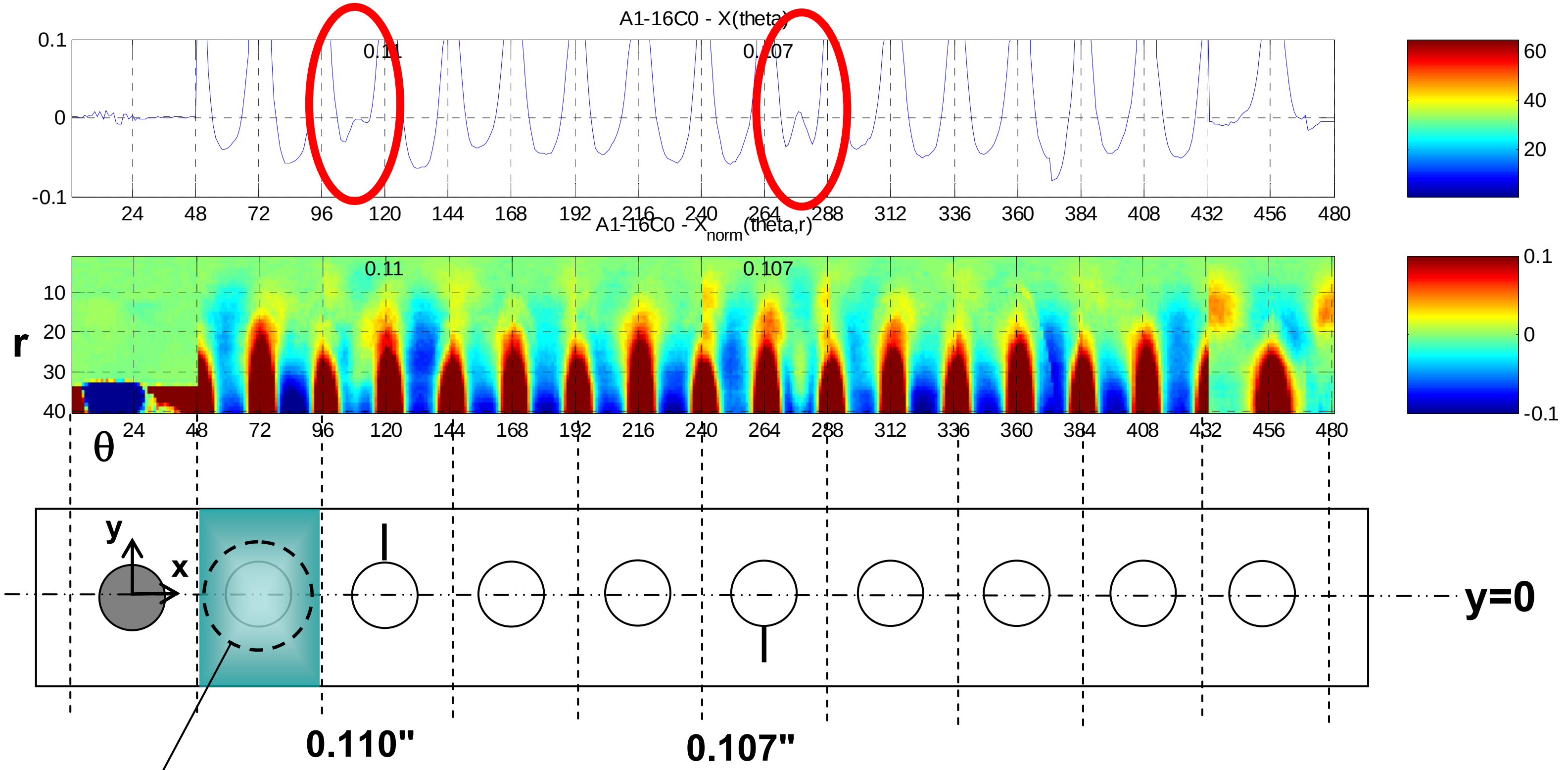


- C-scan Images:



Bonus: Analysis of Experimental Data

- Circumferential feature plots
  - *top: single line plot around hole*
  - **bottom: transformed polar image (r,θ → x,y):**



circumferential line plot about estimated center of hole

Aldrin & Knopp, “Crack Characterization Method with Invariance to Noise Features for Eddy Current Inspection of Fastener Sites” (submitted to Journal of Nondestructive Evaluation October 2005)

FMA Protocol (Thompson)

1. Identify the scope of the POD study

- Demonstration of FMA MAPOD using wing splice as basis
- Compare with empirical evaluation

2. Identify factors that control signal and noise

A. NDE technique:

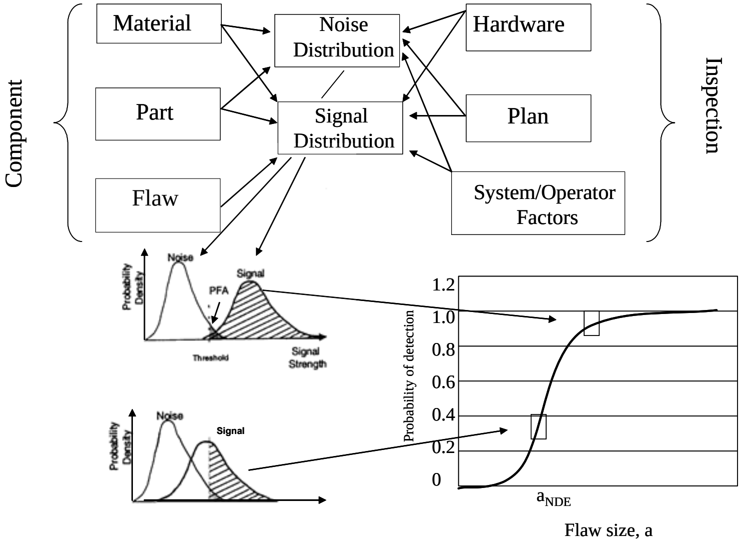
1. Probe characteristic response (asymmetry)
2. Probe lift-off
3. Scan resolution
4. Measurement noise (variability)
5. Classification algorithm design

B. Part geometry, material and condition:

1. Outer layer surface condition (paint)
2. Layer thickness
3. Fastener type
4. Fastener / hole geometry (asymmetric gap / fit)
5. Proximity of adjacent fasteners and edges

C. Flaw characteristics:

1. Flaw dimension and aspect ratio
2. Flaw orientation (around fastener site)
3. Flaw condition (partial closure, residual stress)

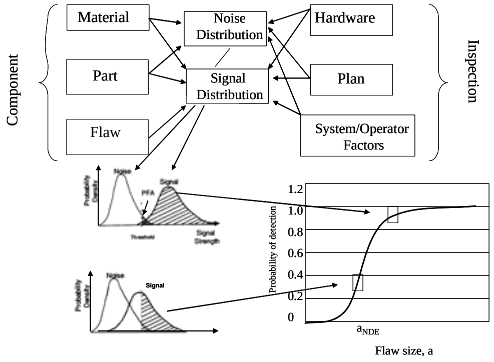


Demonstration of FMA Protocol

3. Evaluate quality of physics-based models
4. Acquire / develop / validate simulation tools
5. Acquire input parameters / parameter distributions

A.	NDE technique:	Models
1.	**Probe characteristic response (asymmetry)**	**unknown - determine empirically**
2.	**Probe lift-off**	**variable – can address using classifier**
3.	**Scan resolution**	**known**
4.	**Measurement noise (variability)**	**unknown - determine empirically**
5.	**Classification algorithm design**	**known**
B.	Part geometry, material and condition:	
1.	**Outer layer surface condition (paint)**	**unknown - determine empirically**
2.	**Layer thickness**	**known**
3.	**Fastener type**	**known**
4.	**Fastener / hole geometry (asymmetric gap / fit)**	**variable – can address using classifier**
5.	**Proximity of adjacent fasteners and edges**	**known**
C.	Flaw characteristics:	
1.	**Flaw dimension and aspect ratio**	**unknown – apply expert opinion**
2.	**Flaw orientation (around fastener site)**	**unknown – apply expert opinion**
3.	**Flaw condition (partial closure, residual stress)**	**unknown – not addressed in this study**

Demonstration of FMA Protocol



6. Conduct flaw signal distribution simulations and noise signal distribution simulations
7. *Acquire remaining information on factors empirically*
8. Acquire marginal information on independent factors (average and variance of stochastic variable)
9. Acquire covariance information on dependent factors
10. Combine 6, 8 and 9 into full signal and noise distributions

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Plan to Address FMA Protocol Steps 6-10 in Demonstration:

A. Use Calibration Procedure to Characterize Probe **(probe response)**

B. Perform Simulated Studies **(flaw dimension and aspect ratio, probe liftoff)** **[transfer function approach: scan resolution, layer thickness, fastener type]**

C. Perform Empirical Evaluation **(measurement noise, surface conditions)**

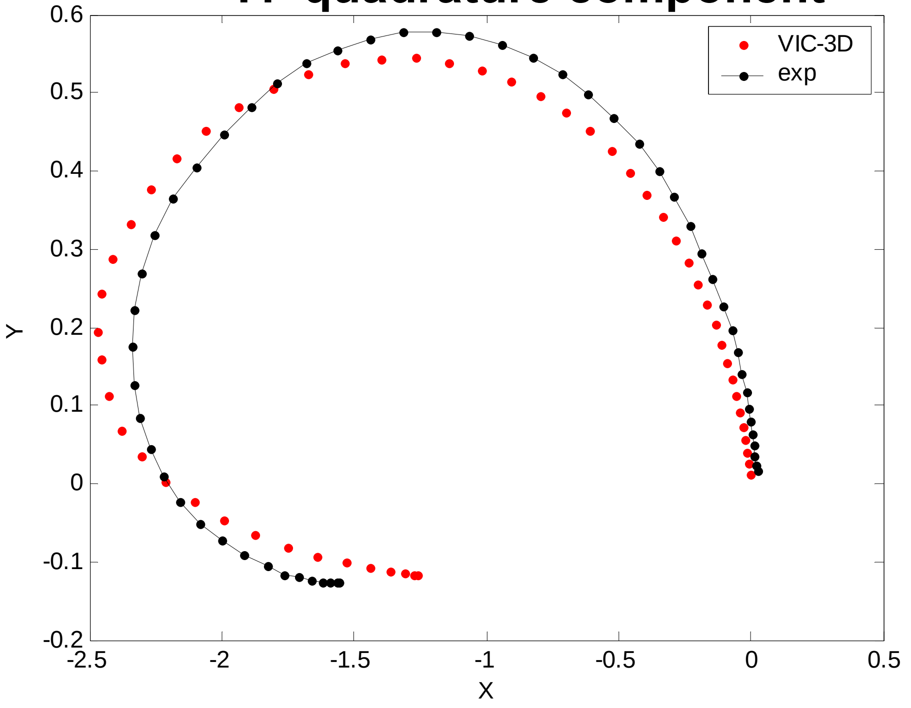
D. Address Factor Variation with Algorithm Design **(liftoff, geo. asymmetry)**

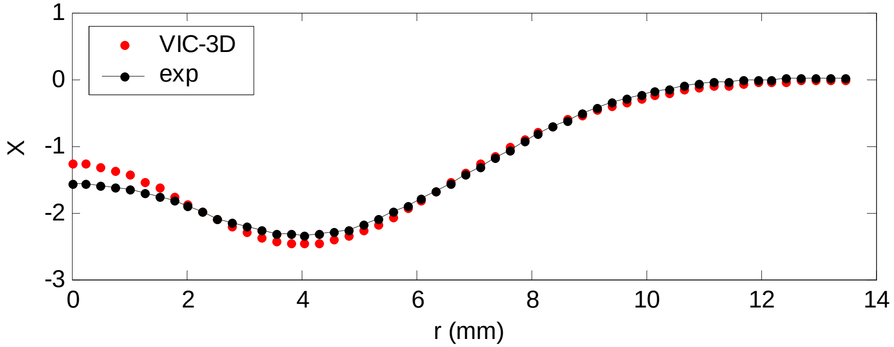
E. Use Expert Opinion and Some Empirical Data to Estimate Variation Due to Unknown Factors **(flaw aspect ratio, partial closure, residual stress)**

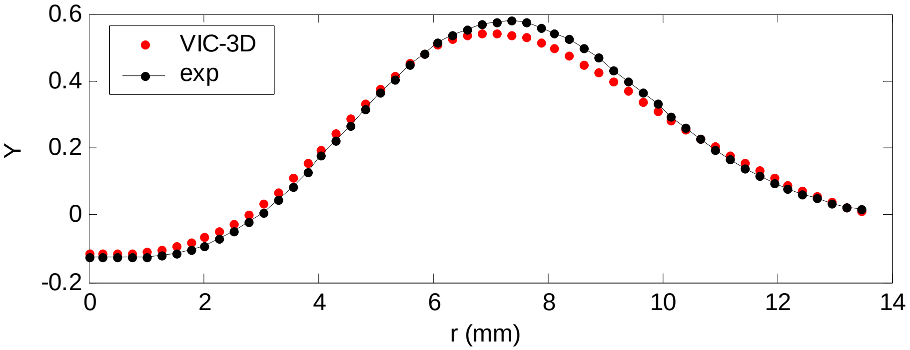
Probe Characterization

A. Use Calibration Procedure to Characterize Probe **(probe response)**

- **Model fit with experimental data**
- **Based on fit of response for titanium fastener site**
  - **X: in-phase component**
  - **Y: quadrature component**





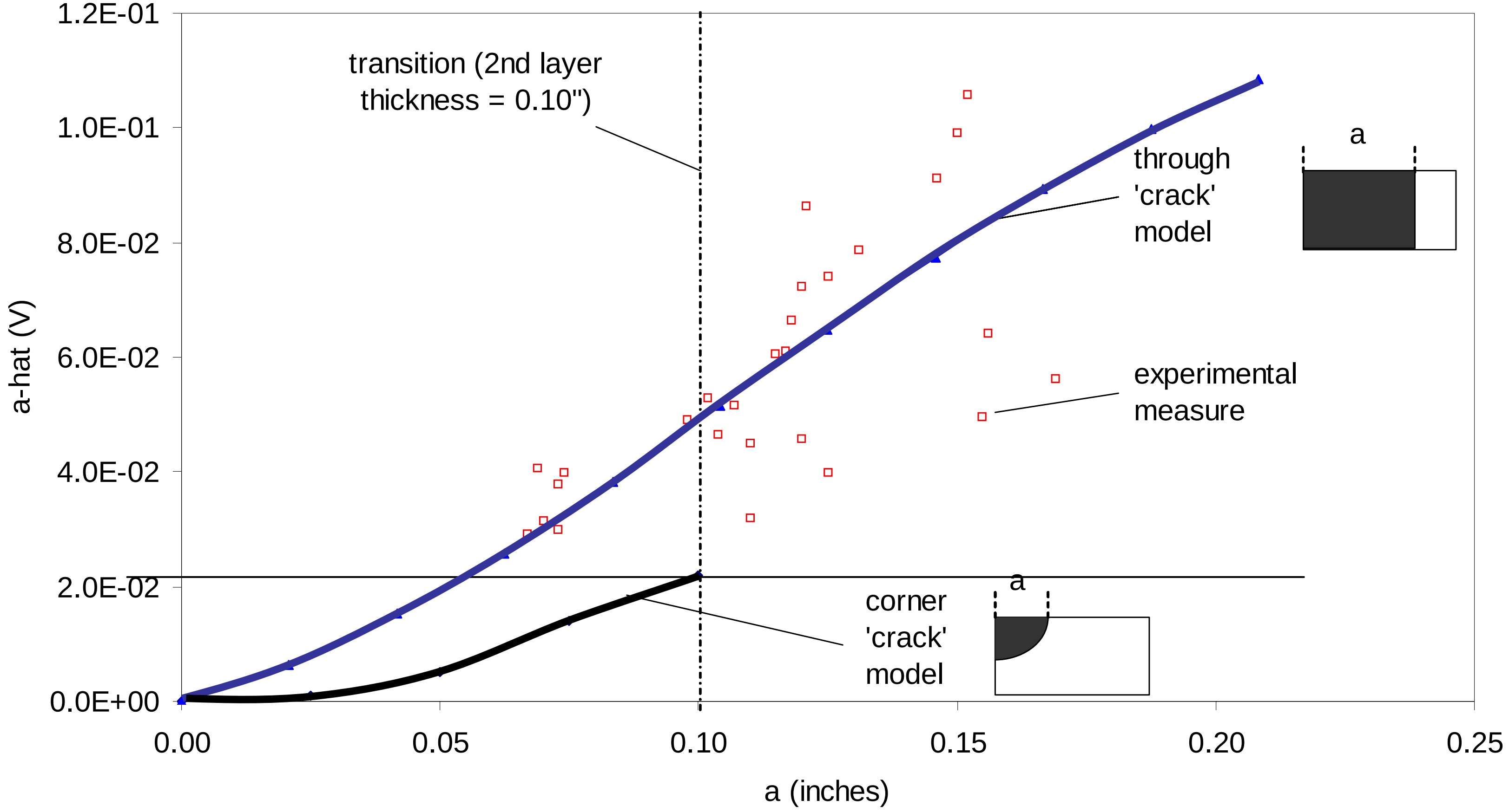


Knopp, Aldrin, and Misra “Considerations in the Validation and Application of Models for Eddy Current Inspection of Cracks around Fastener Holes”
Accepted for Publication – Journal for Nondestructive Evaluation, Vol 25 Issue 3

Parametric Studies of Signal Response using Models

B. Perform Simulated Studies **(flaw dimension and aspect ratio, probe liftoff, scan plan, layer thickness, fastener type)**

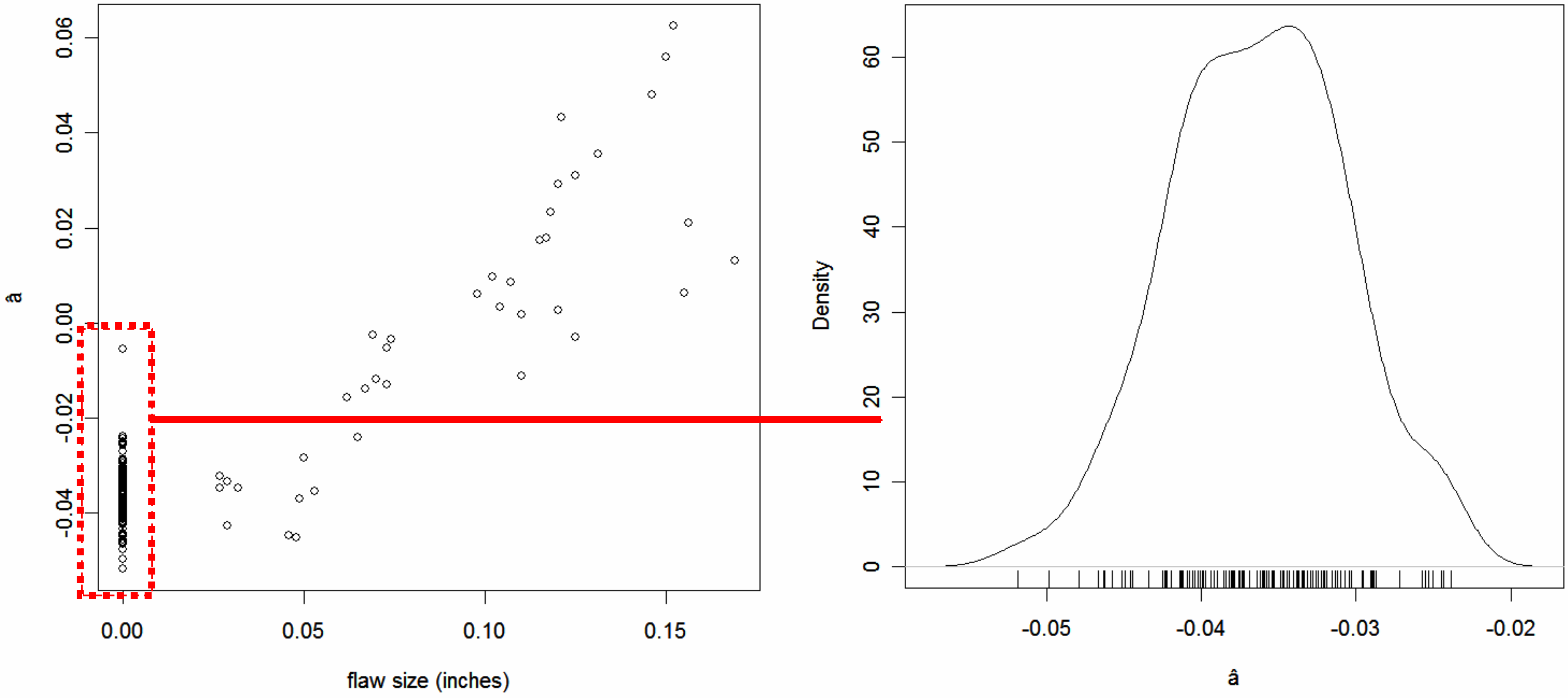
- Compare Simulated and Experimental Results



Empirical Noise Evaluation

C. Measurement of noise and surface conditions on regions without cracks

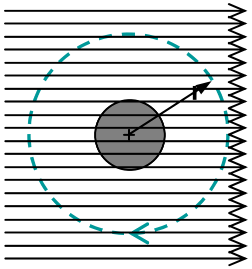
- Evaluation of Noise Distribution

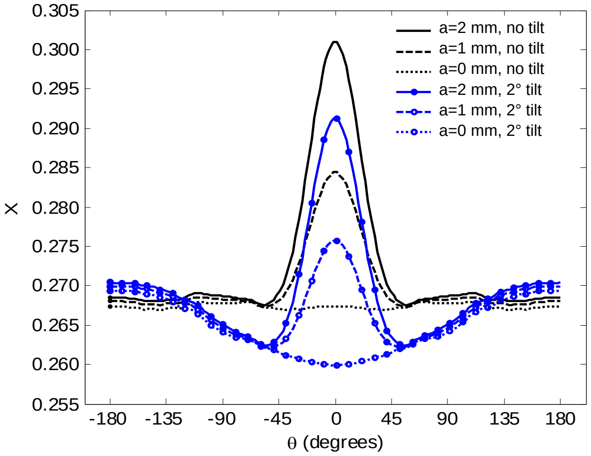


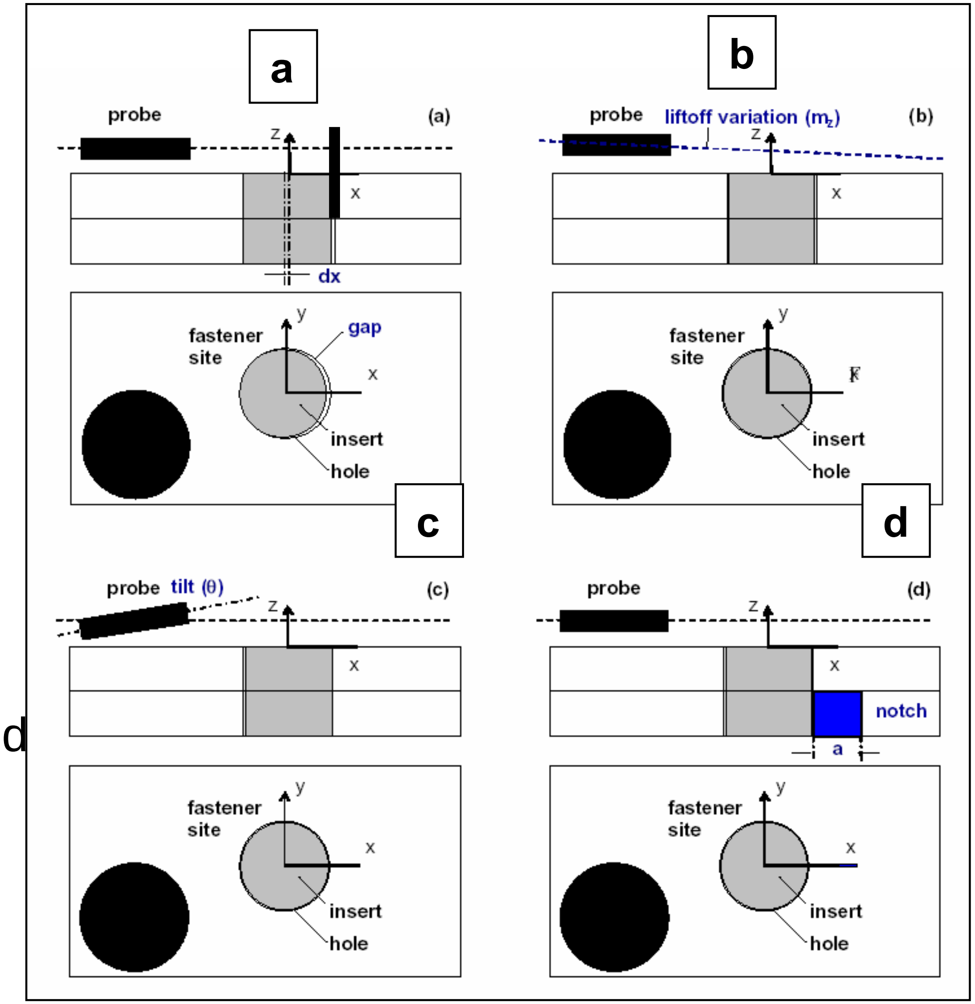
Include Typical In-Field Measurement Variables

D. Address Factor Variation with Algorithm Design **(liftoff, geo. asymmetry)**

Use noise invariant features in circumferential direction (using 2D interpolation algorithm)





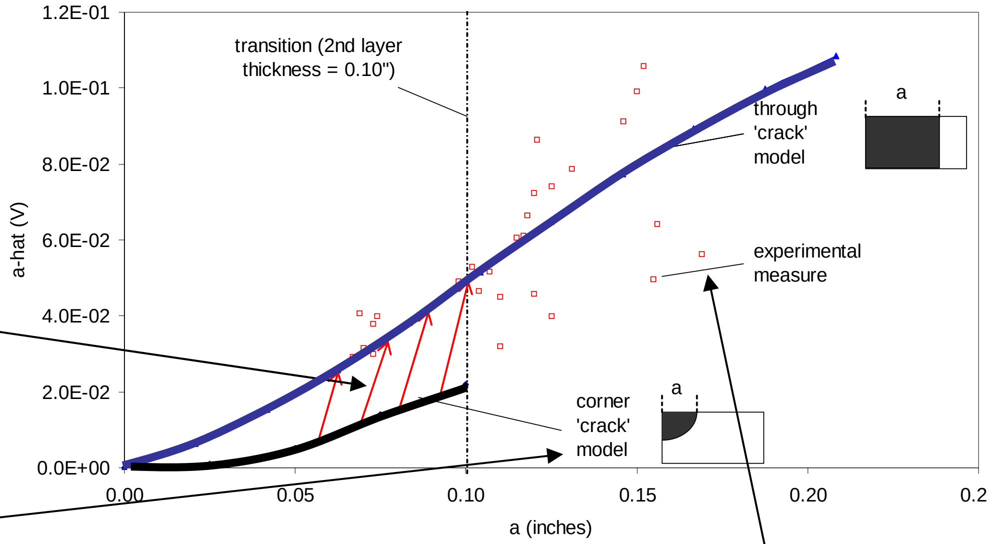


- ‘Localized Gaussian’ response associated with crack
- Can be distinguished from ‘sinusoidal’ response associated with all three ‘non-flaw’ conditions

Aldrin and Knopp “Crack Characterization method with Invariance to Noise Features for Eddy Current Inspection of Fastener Sites”
Submitted for Publication – Journal for Nondestructive Evaluation, Sept 2005

Opportunities for Improvement: Estimate of Unknowns

Use Expert Opinion and Some Empirical Data to Estimate Variation Due to Unknown Factors



Opportunities for Improvement:

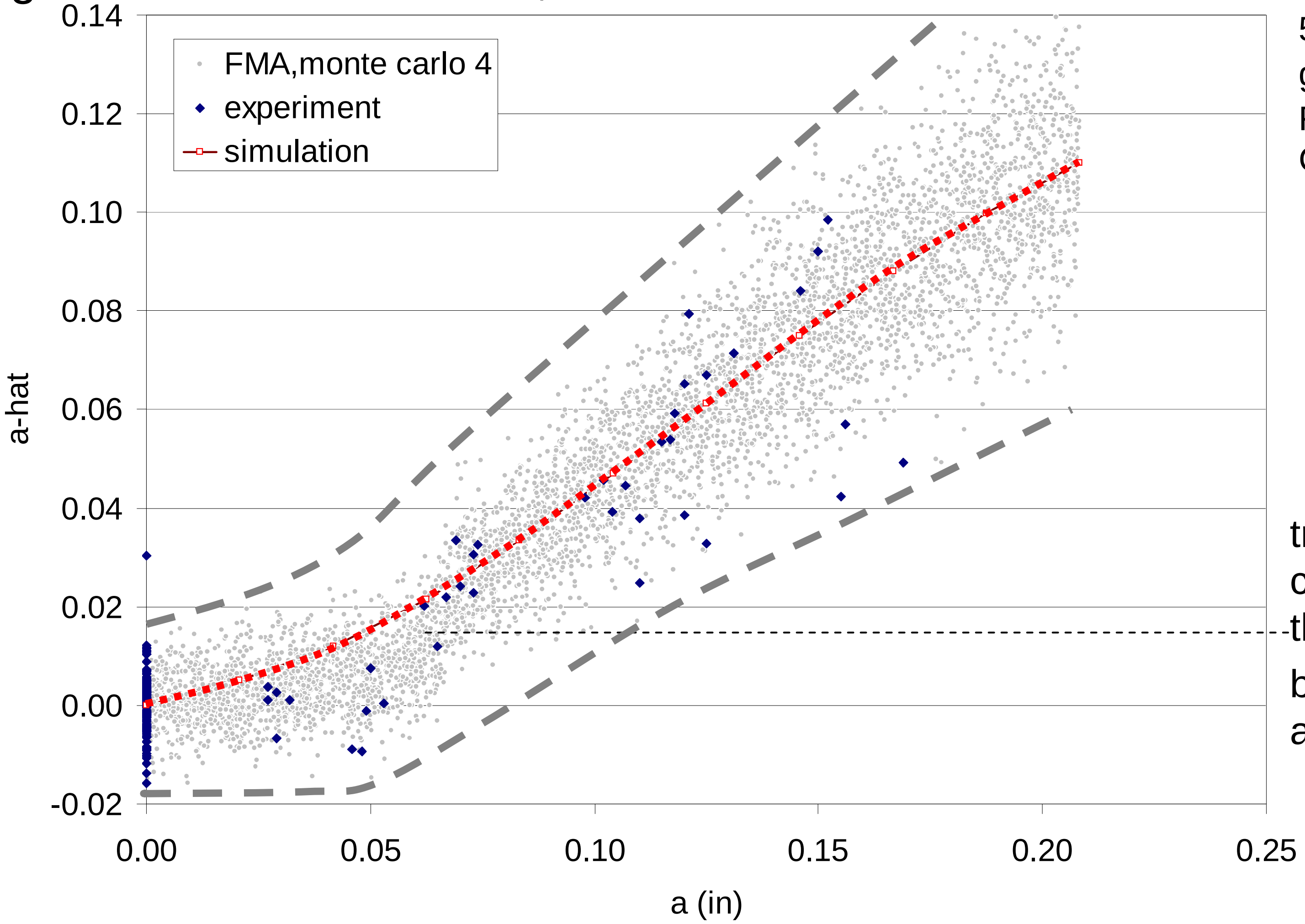
1. Corner Crack Model –
   Where is the transition from corner to through cracks?
2. Aspect Ratio Variation
   What is expected range for aspect ratio of corner cracks?
3. Equivalent Crack Size Factor
   What is the equivalent size distribution for partially closed cracks?
   Does the distribution (variance) vary linearly with crack size OR
   Is there a fixed flaw size correction factor?
   What is the shape of the response distribution? (Gaussian, Weibull)

More basic research needed to address unknowns (e.g. crack morphology)

Demonstration of FMA Protocol

10. Combine full signal and noise distributions

Through + corner notch model, variation function of flaw size



5000 data points generated for FMA Monte Carlo simulation

transition from corner notch to through notch between 0.060" and 0.070".

POD Analysis Methods

- Hit/Miss analysis
  - Probability of detection related to flaw size
  - Different cracks of the same size have different responses
  - Factors other than size influence detection capability
  - Non-constant variance being addressed for a vs. â

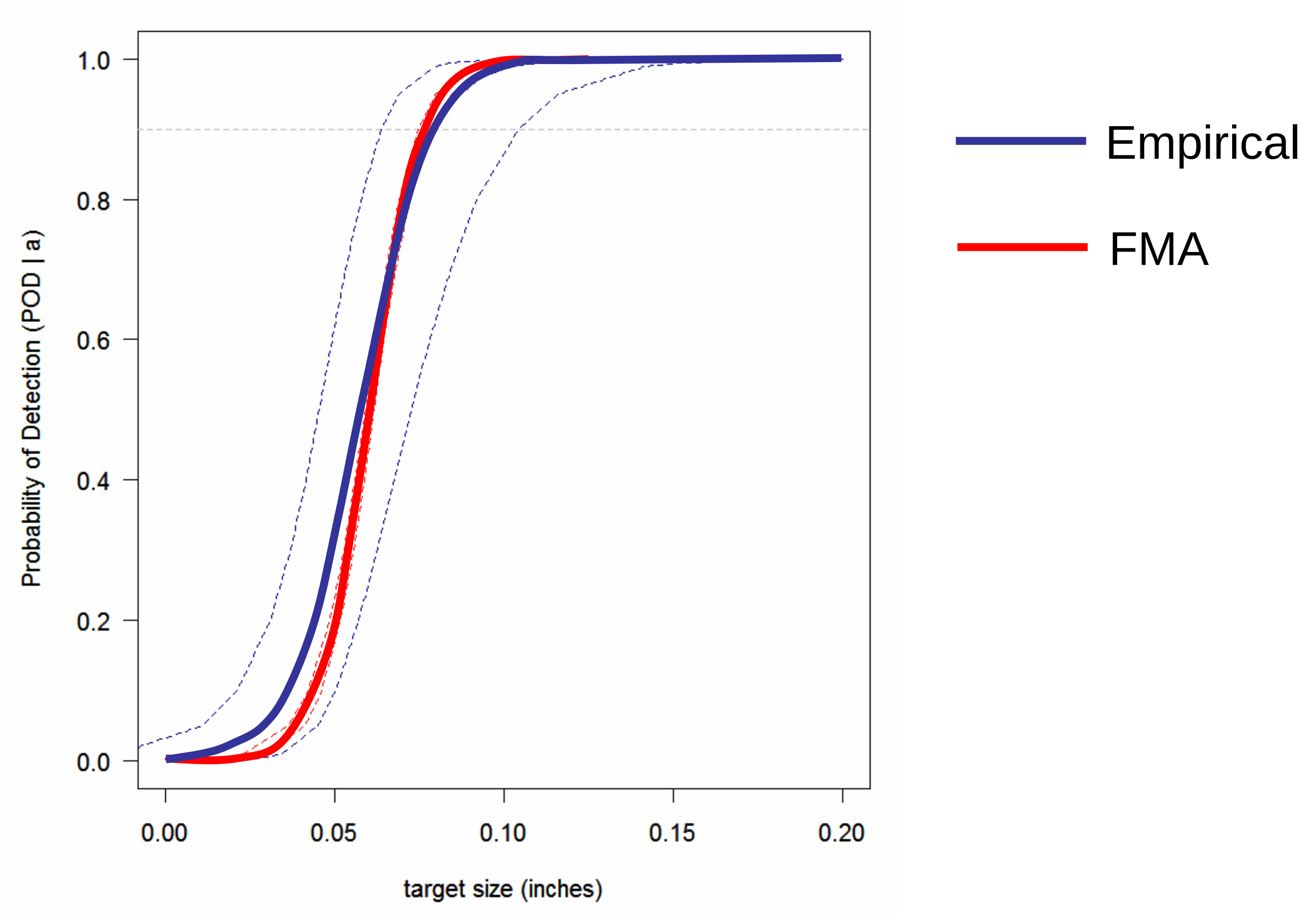
- Confidence Bounds Estimation (1823 Update)
  - Wald Method is anti-conservative.
  - Likelihood Ratio is a more accurate alternative to Wald method.

Successful Result Demonstrates Feasibility

11. Compute POD / POFC

- Calculate POD for threshold set to probability of false call of 0.50%

Experimental Comparison with Full Model-Assisted



Conclusions

- **Good match with experimental POD and Hybrid FMA**
- **Only required *unflawed samples* for Hybrid FMA demonstration**
  - **calibration of probe**
  - **noise evaluation**
- ***Improved modeling* and *knowledge of flaw conditions* (aspect ratio, partial closure) will improve results**
- **Can now demonstrate transfer function approach for:**
  - **varying fastener diameter**
  - **varying thickness of multiple layers**
  - **varying crack location (around fastener)**
  - **varying scan plans (resolution)**
  - **varying probe designs**
  - **new classifiers**

Issues and Future Work

- Confidence bounds for model-generated data needs research
- Cracks in between fastener hole sites (address with models)
- Crack Morphology
- Multiple cracks around fastener hole
- Uncertainty Analysis for XFN and FMA Methods
- Non-constant variance for a-hat measure
  - with respect to increasing flaw size,
  - likely due to crack contact conditions
    (i.e. not present for small / no flaw cases)