Recent Advances in Model-Assisted Probability of Detection

R. Bruce THOMPSON and L. J. BRASCHE,
Center for Nondestructive Evaluation
Iowa State University
D. FORSYTH,
Texas Research Institute/Austin
E. LINDGREN,
Air Force Research Laboratory
P. SWINDELL,
FAA William J. Hughes Technical Center
and W. WINFREE,
NASA Langley Research Center

Outline

- Motivation
- MAPOD WG Formed
- Strategies and Protocols
- Demonstrations
- Conclusions

Outline

- **Motivation**
  - **Primarily a U.S., Aerospace Perspective**
- MAPOD WG Formed
- Strategies and Protocols
- Demonstrations
- Conclusions

"Have Cracks, Will Travel":
Detection Reliability Elevated to a High Priority

- AFLC Depot/Field NDE Capability Evaluation Programs

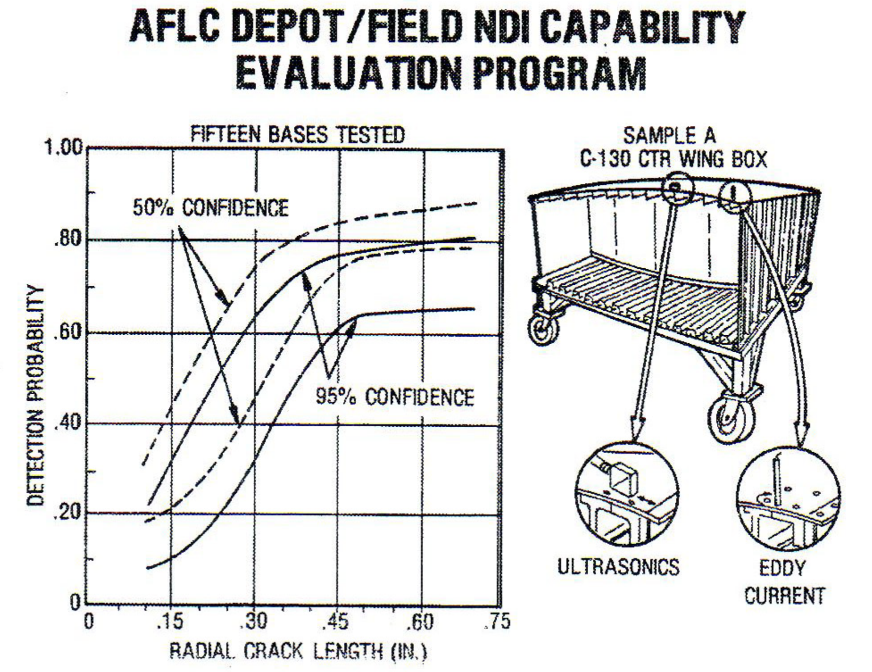
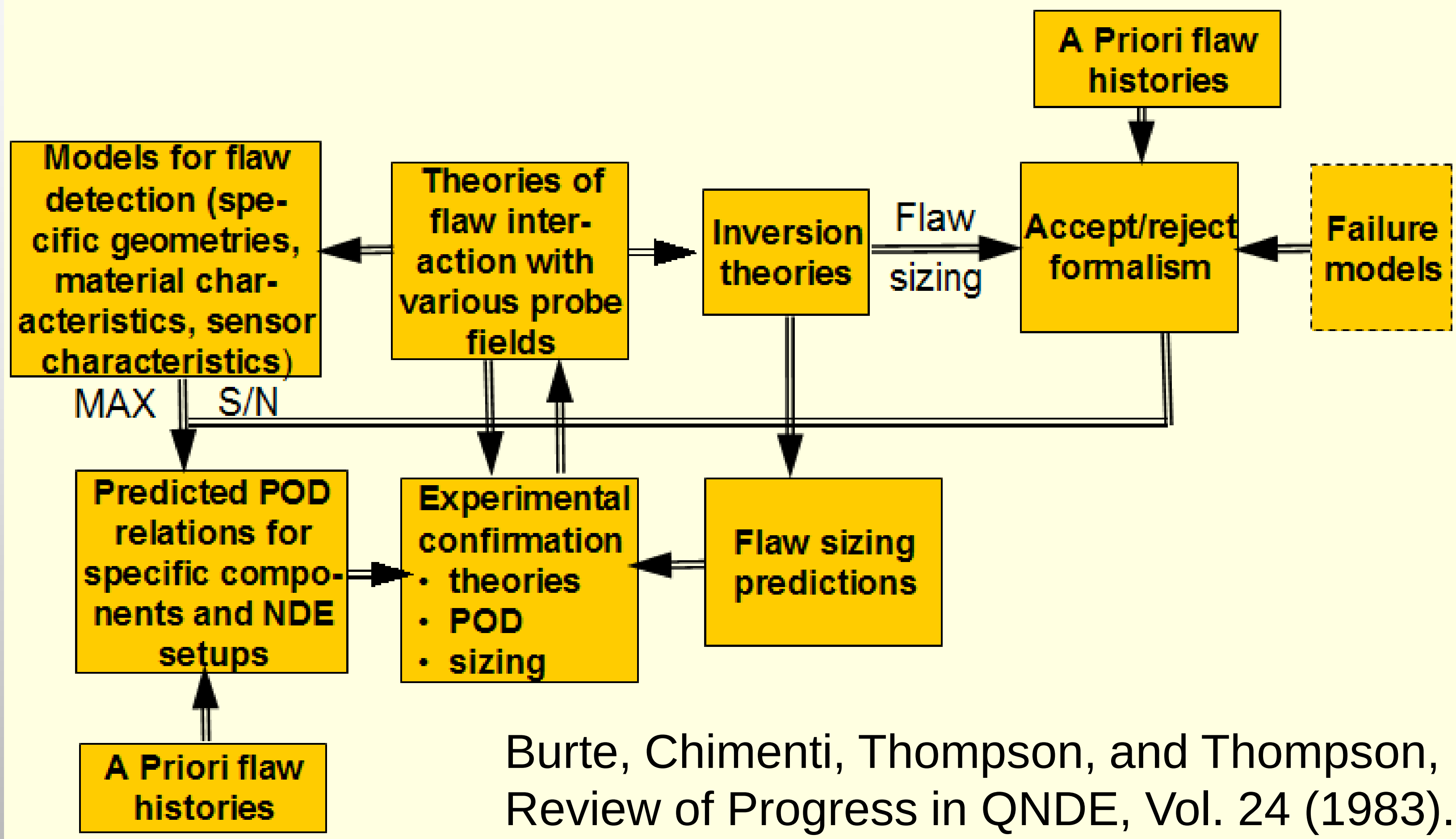


Figure 3.6. AFLC Depot/Field NDI Capability Evaluation Program.

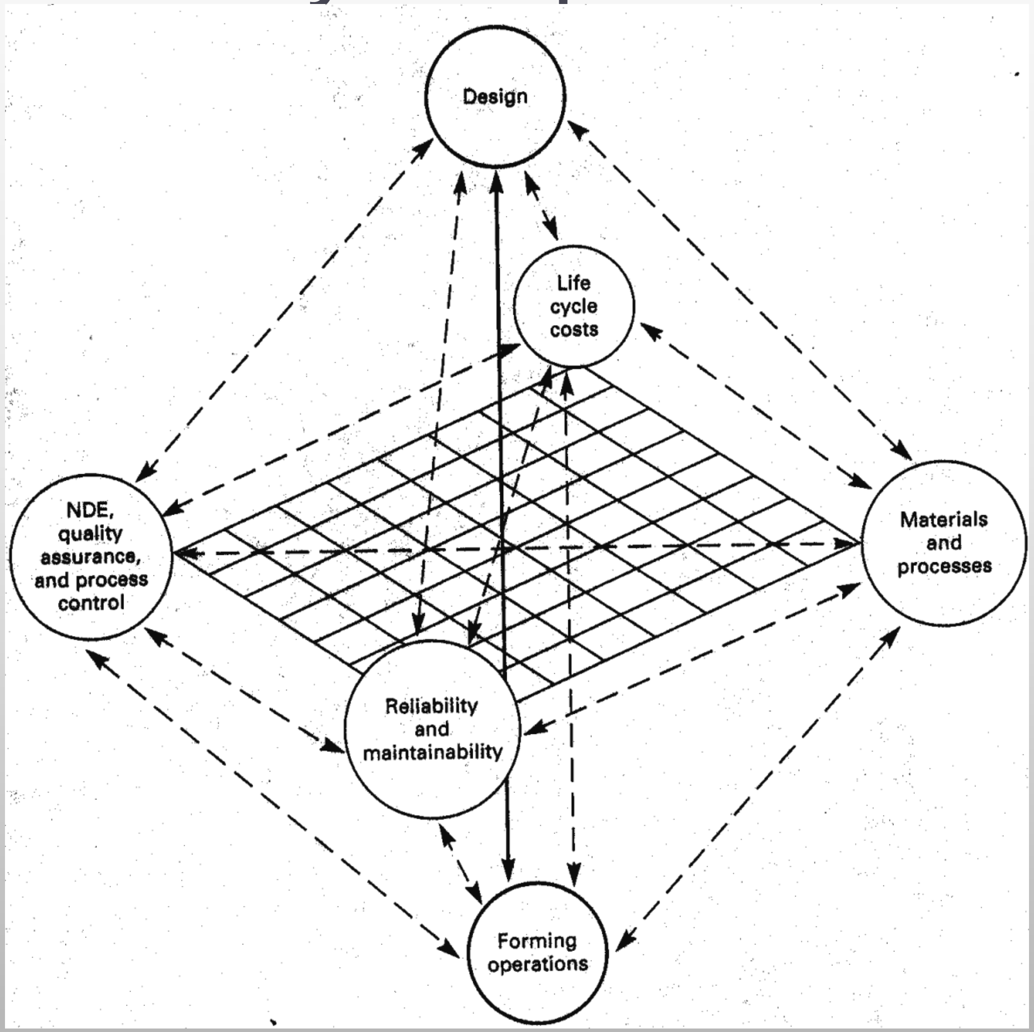
Lewis, W. H., Sproat, W. H., Dodd, B. D., and Hamilton, J. M., "Reliability of Nondestructive Evaluations," Lockheed Report SA-ALC/MME 76-6-38-1, 1978.

Research Response: First Steps Towards a Generic Engineering Approach to POD



Burte, Chimenti, Thompson, and Thompson, Review of Progress in QNDE, Vol. 24 (1983).

An Early Response



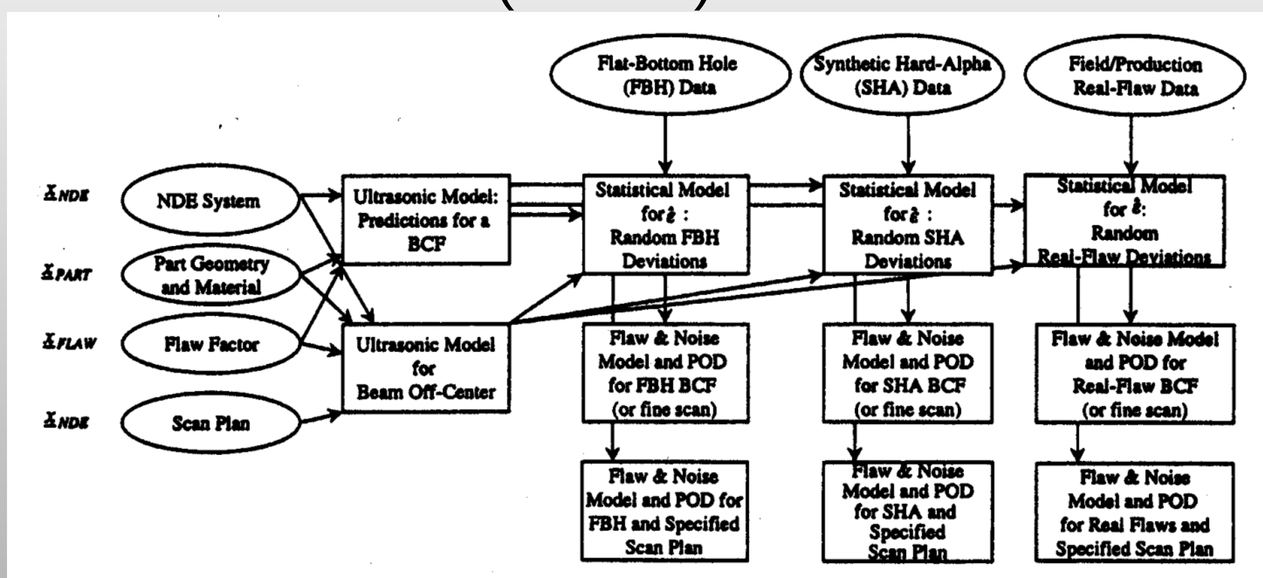
"Models for Predicting NDE Reliability," Gray, Gray, Nakagawa, and Thompson, Metals Handbook, Vol. 17, NDE and QC (1989).

Interest Heightens and Broadens in the 1990's

- Simulators more mature
- Interest in POD grows
- At FAA, the Sioux City crash was a big driver

One Element of Response

- A methodology for the assessment of the capability inspection systems for detection of subsurface flaws in aircraft turbine engine components
  - Burkel, Chiou, Keyes, ***Meeker***, Rose, Sturges, ***Thompson***, and Tucker with important input **from *Annis*, *Brasche*,** Gilmore, Margetan, ***Schaeffer*****,** and ***Smith***
- DOT/FAA/AR-01/96 (9/2002)



AF Interest Renewed by Practical Requirements

- Bow wave of new requirements

- Man-hours for NDE scheduled to increase dramatically!
- Need to insert new technologies into the field, faster and cheaper!
- Implementation of inspections without POD undermines NDE and reliability!
- Damage tolerant risk analysis techniques demand Quantitative NDE! (Gallagher, Babish, and Malas, 2005)

- In conflict with large time/cost of empirical determination of POD
- Probability of Detection for NDE, NTIAC-TR-00-01 (8/2001)
  - After Malas and Knopp

NASA Drivers for a Computational Simulation Assisted Estimate of POD

- Reduce validation cost
- Reduce time required for validation
- Validation of in-space inspections
- Rapid comparison of different methodologies for particular application – pretesting down select of methods
- Optimization of techniques for particular requirements
- Identification of critical inspection parameters
- Assessment of automated flaw detection methodologies
- Optimization of data reduction techniques
- Sanity check on technique claims

Winfree

NASA Desired Products – Simulation Based POD Estimate

- Establish validated procedures for simulation based estimation of POD (Handbook)
  - Generalized flaw
  - Complex structure
- Validated simulations for widely applied techniques
- User friendly packages for POD estimation

Winfree

Outline

- Motivation
- **MAPOD WG Formed**
  - **Emphasis on Model-Assisted, not Model-Based**
- Strategies and Protocols
- Demonstrations
- Conclusions

Model-Assisted POD Working Group

Precursors

- Strawman Plan for a Consortium on Computational Nondestructive Evaluation (NDE) for Modeling POD (POD), NTIAC, 9/03
- A Planning Meeting for the Formation of a Consortium on Computational NDE for Modeling POD was organized by NTIAC on 11/18-19/03.
- Outcome: Formation of a POD Working Group to establish next steps and serve as the basis for longer-term activities.

Model-Assisted POD Working Group

Objective

- To promote the increased understanding, development and implementation of model-assisted POD methodologies

Model-Assisted POD Working Group Prospectus Summary

Approach

Meet periodically and conduct the following activities:

- Discuss **strategies** for model-assisted POD determination
- Discuss **requirements** for models to be used in POD studies
- Identify **gaps** that need to be addressed between state of the art physics-based models and real world problems
- Provide input regarding examples of specific problems that would **demonstrate** the utility of model-assisted POD activities
- **Communicate** the results of model-assisted POD demonstrations

Model-Assisted POD Working Group Prospectus Summary

Metric

The Model-Assisted POD Working Group will be considered a success if, during its duration, activities under a variety of programs lead to

- Draft **protocols** for model-assisted POD
- Draft **requirements** for model qualification for use in POD determination
- Model-assisted POD **demonstrations**

MAPOD WG

Model-Assisted POD Working Group

Center for Nondestructive Evaluation

Home

About Us

Contact Us

Meeting Minutes

Reference Documents

Meeting Minutes

MEETING MINUTES

- Austin, TX - November, 2003
- Albuquerque, NM - September 23-24, 2004
- Palm Springs, CA - February 4, 2005
- Orlando, FL - June 9-10, 2005
- Orlando, FL - September 22-23, 2005
- Atlanta, GA - March 9-10, 2006
- Fort Worth, TX - October 19, 2006
- Houston, TX - October 26-27, 2006
- Palm Springs, CA - April 20, 2007
- Las Vegas, NV - November 16, 2007

MAPOD WG (cont)

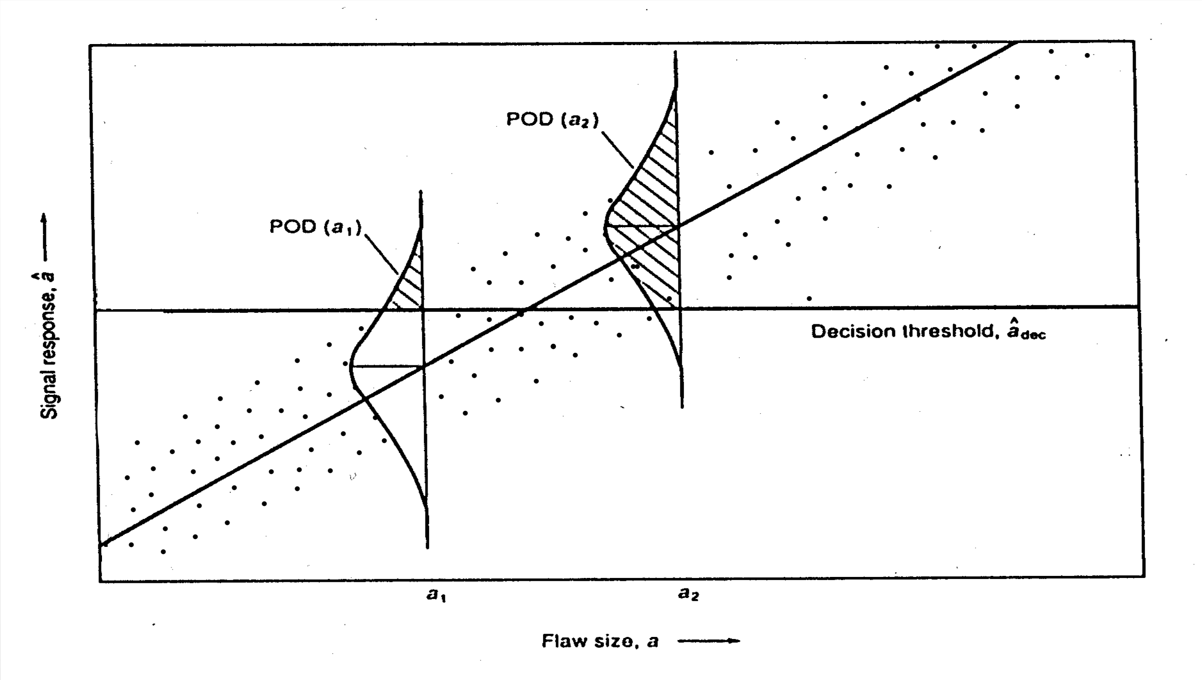
- Minutes of meeting in Charleston, SC, November 14, 2008 in draft form
- Next meeting in Columbus, OH, October 23, 2009 (Sequel to ASNT Annual Fall Meeting)
- Full information at:

  www.cnde.iastate.edu/MAPOD/

Outline

- Motivation
- MAPOD WG Formed
- **Strategies and Protocols**
  - **Coupling empirical and physical understandng**
- Demonstrations
- Conclusions

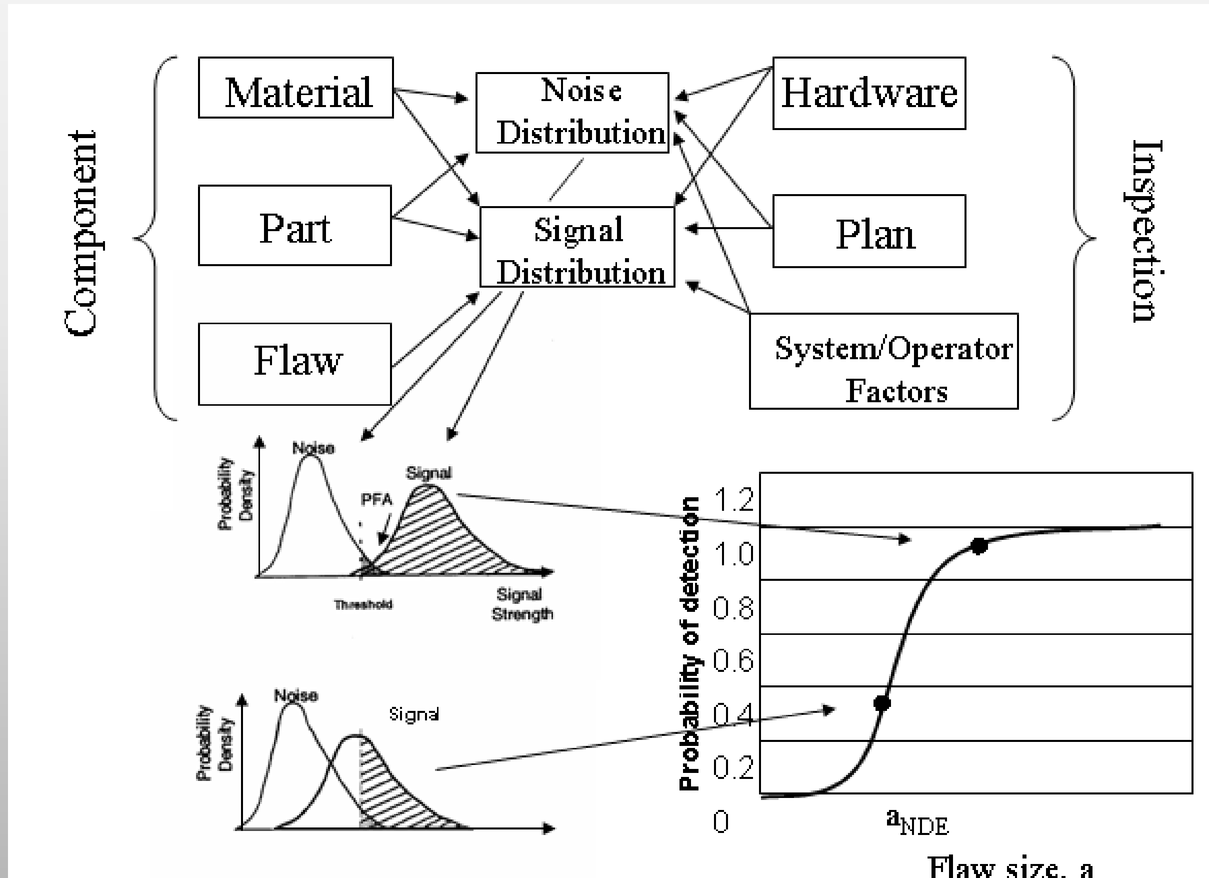
Pictorial Representation of Empirical POD Determination (a-hat versus a)



- Obtain and plot data of log (flaw response) versus log (flaw size), known as a a-hat versus a
- Perform a linear regression
- When distribution about regression line is normal, POD determined by:
  - Mean
  - Standard deviation
  - Threshold

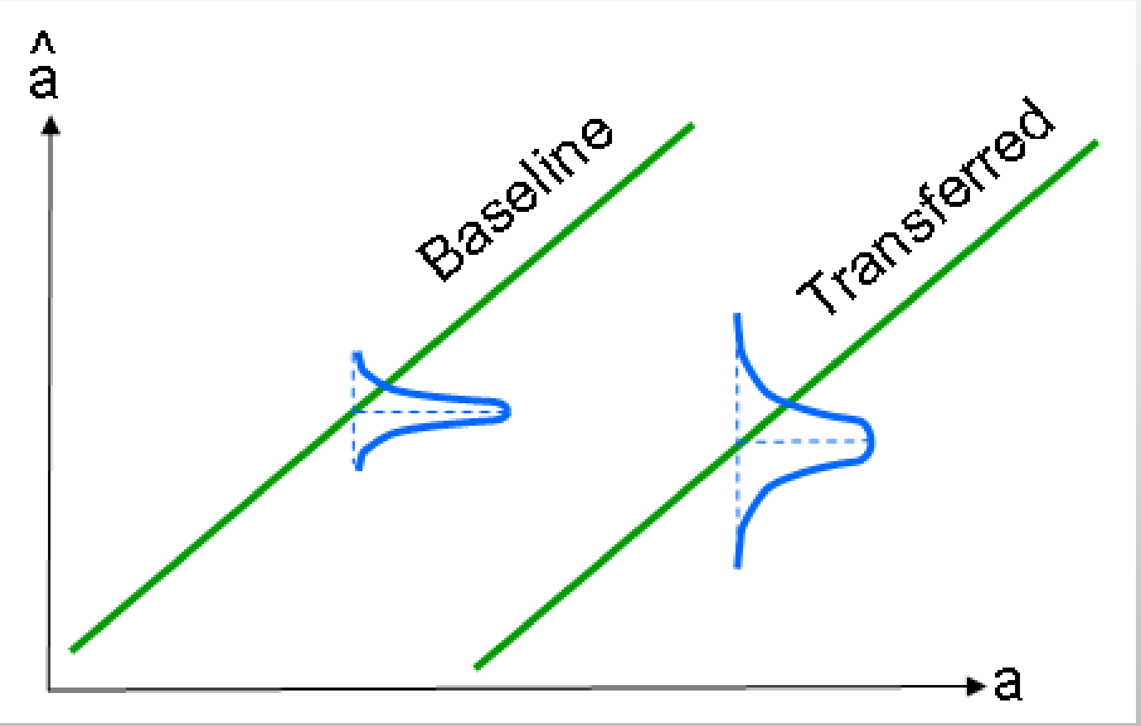
Two Approaches Identified

- Full Model-Assisted Approach (FMA)

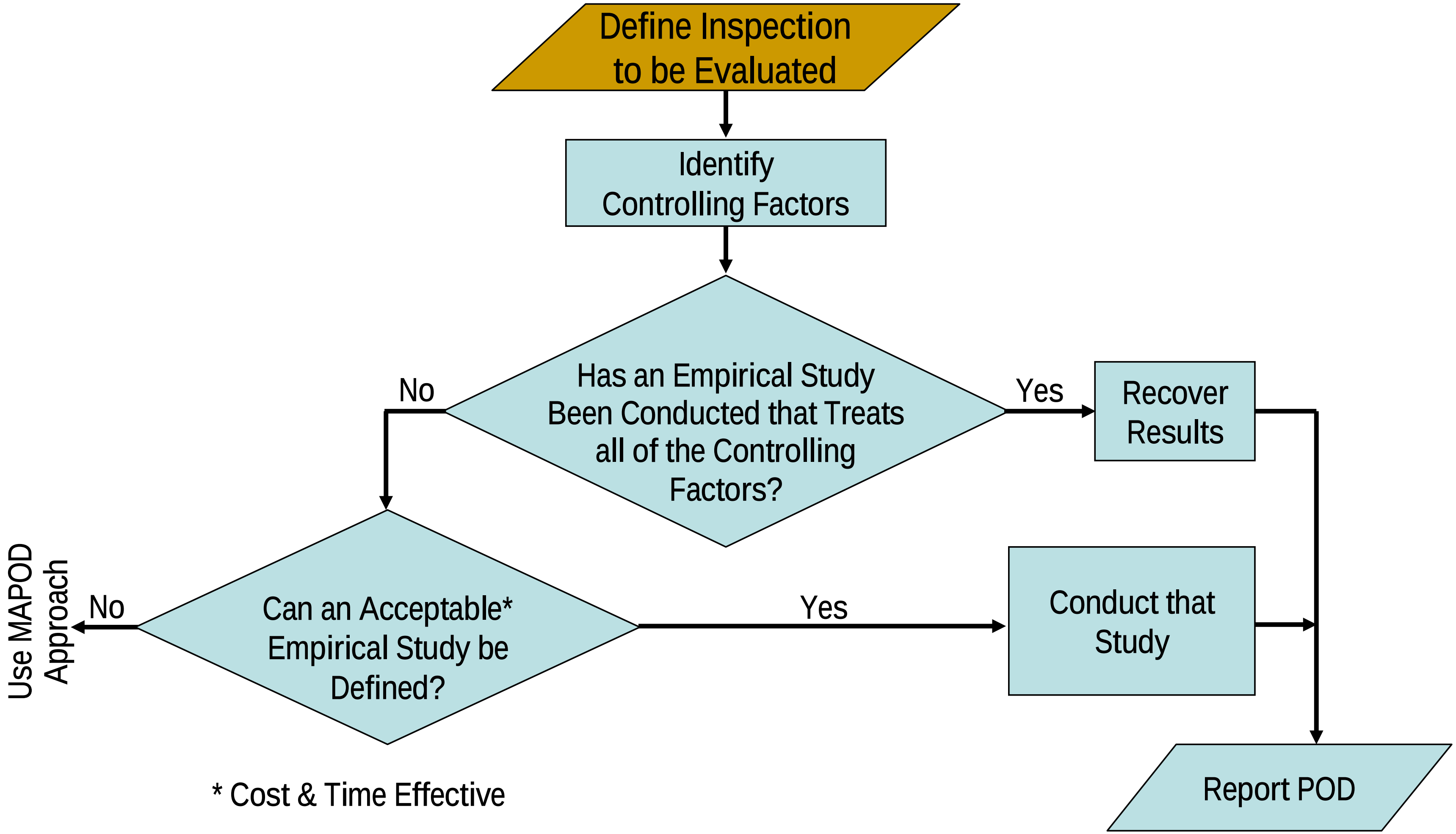


Two Approaches Identified

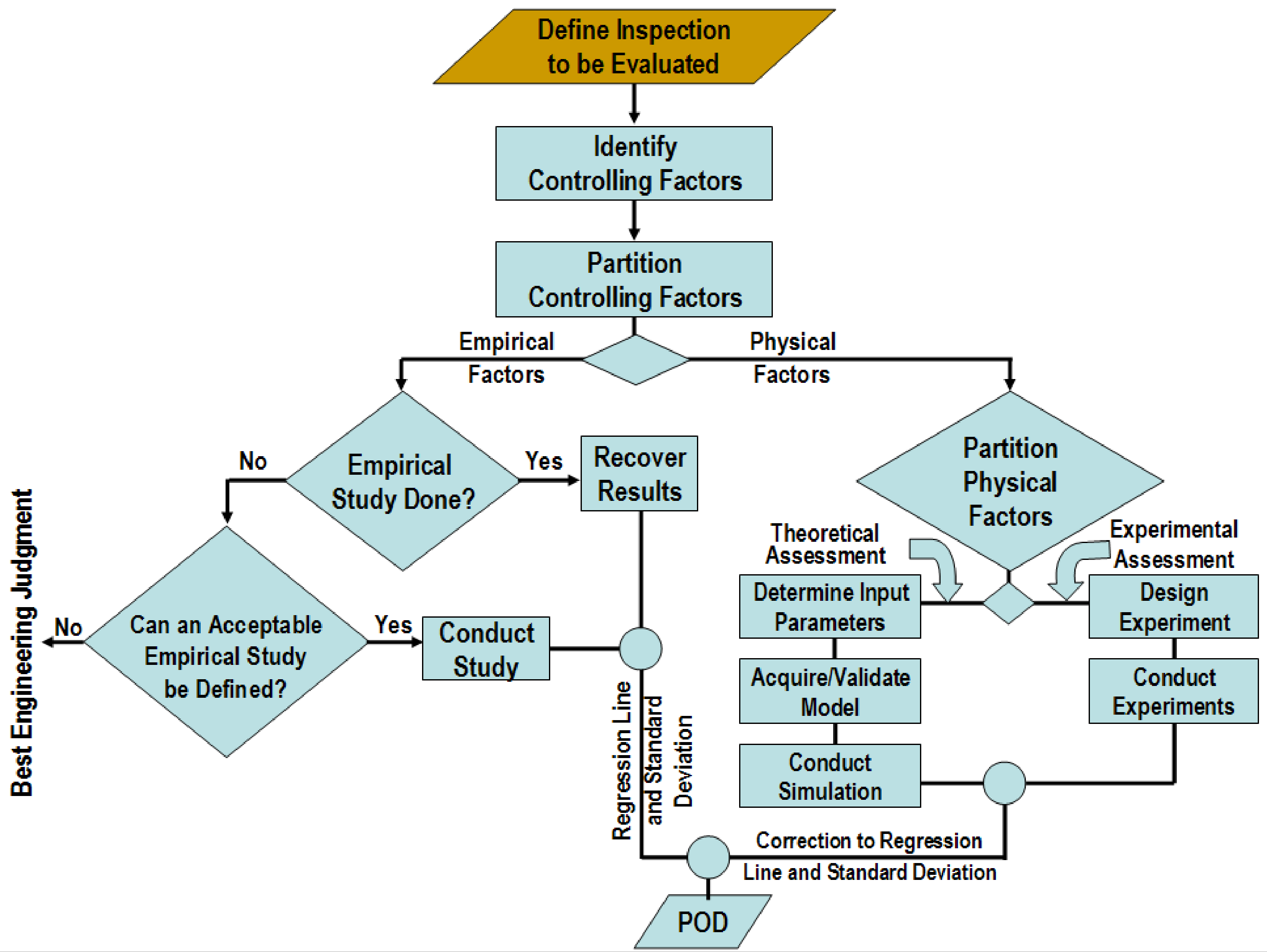
- Transfer Function Approach (XFN)



Fully Empirical Determination of POD



Model-Assisted Determination of POD (MAPOD)



Protocol for Model-Assisted Determination of POD

- Define the intended use of the POD Study
- Identify the controlling factors whose influence is to be assessed in the POD study
- Identify a subset of those factors (empirical factors) whose influence is to be assessed empirically
- Prepare sample sets and empirical test protocol
- Conduct the empirical test
- Analyze the results to obtain the best estimate of the regression line (and the standard deviation of the data about that line) relating flaw response to flaw size
- Determine whether controlled laboratory experiments or physics-based models are to be used in the assessment of the influence of the remaining factors (physical factors)
- Conduct that assessment using the appropriate sub-protocol
- Analyze the results to obtain best estimates of the modifications of the regression line and the standard deviation of the data about this line as influenced by the physical factors.
- Make an estimate of POD based on the results of steps 6 and 9, combined with a specification of the threshold.

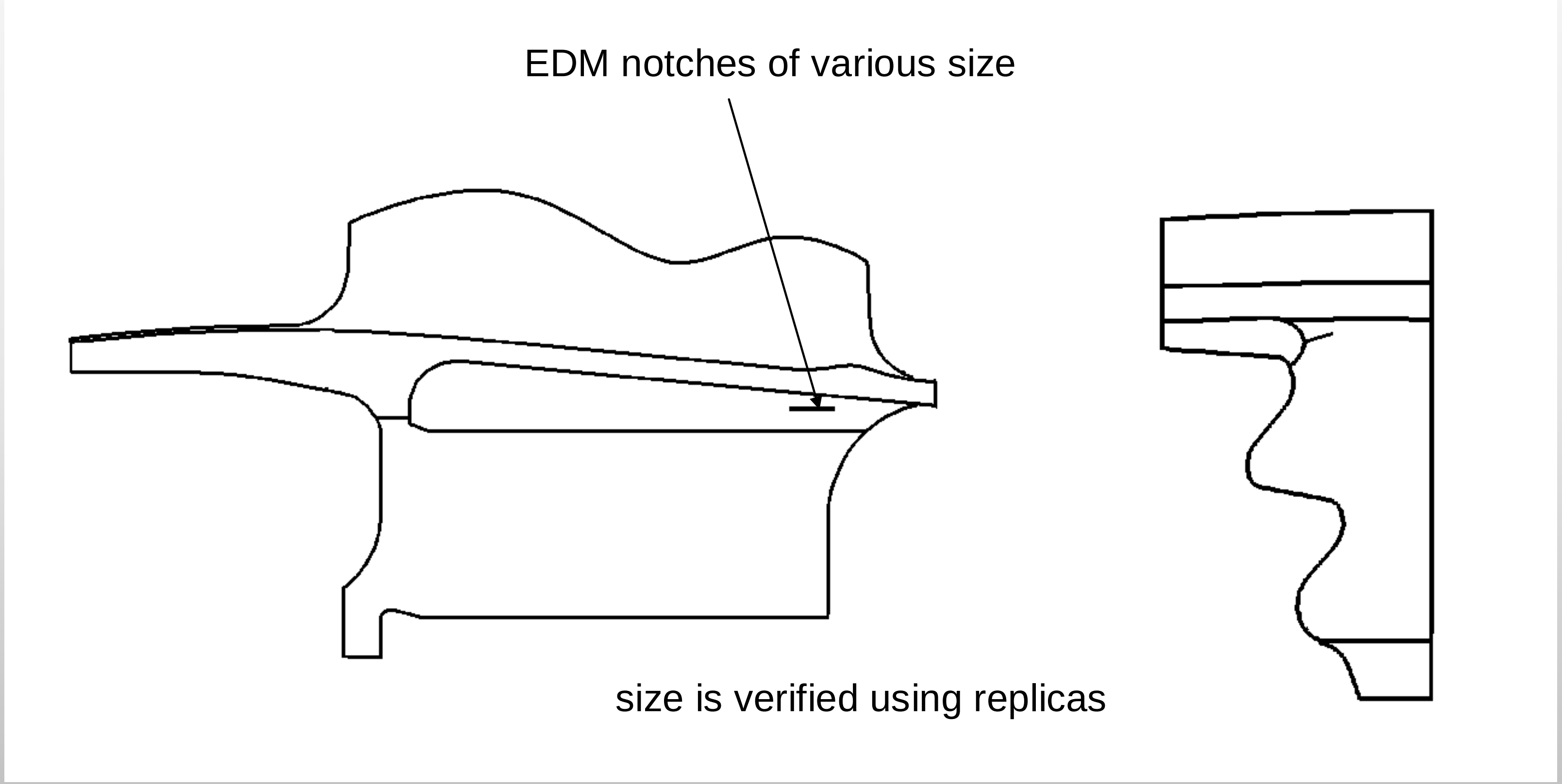
Outline

- Motivation
- MAPOD WG Formed
- Strategies and Protocols
- **Demonstrations**
- Conclusions

Example #1

- Eddy current detection of fatigue cracks in complex engine geometries
  - Unanticipated field durability problem
  - Pratt & Whitney (Smith)
  - Empirical factors from measurements on EDM notches in real geometries
  - Laboratory experiments define the physical effect of the relative response of cracks and notches

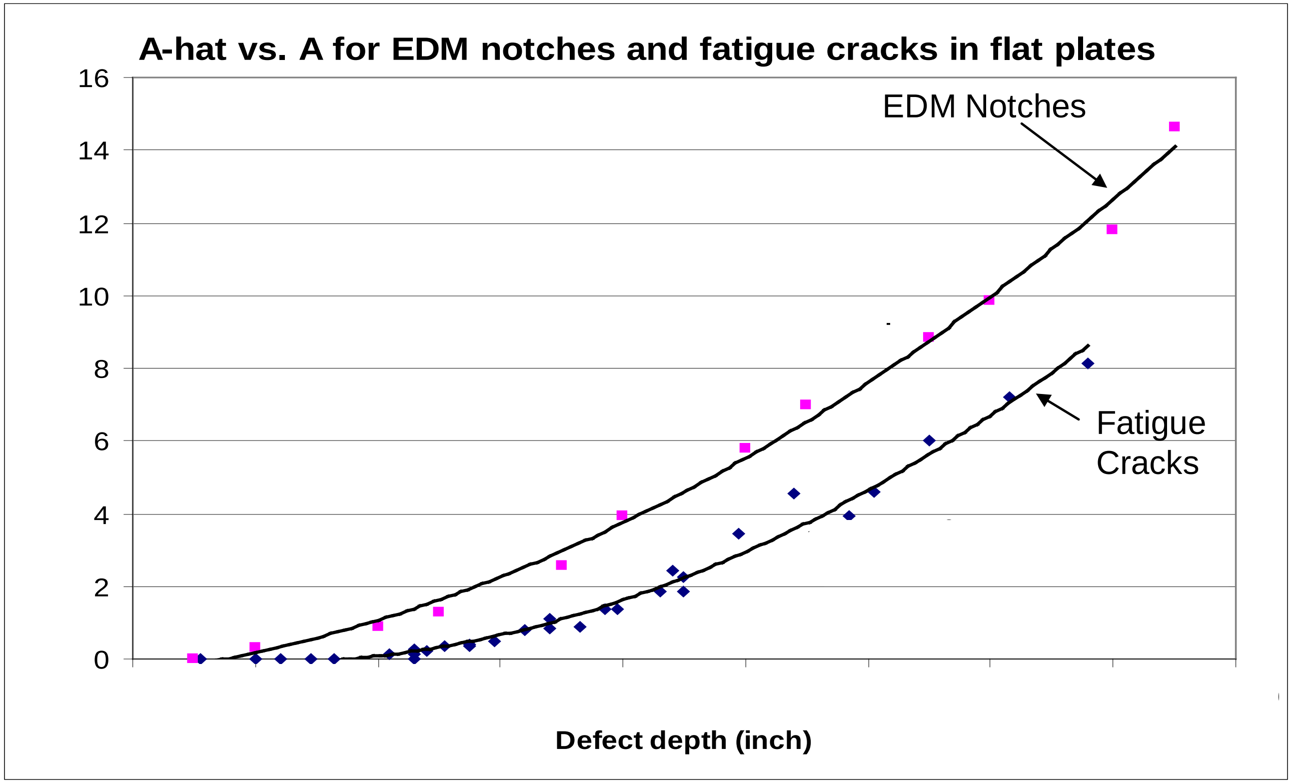
Geometry of Interest



Sample to empirically assess the effects of component geometry

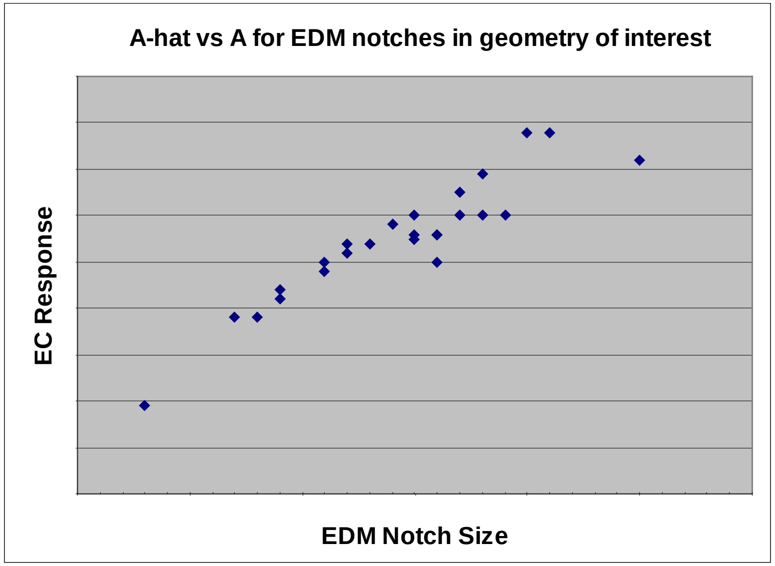
Relative Responses of Fatigue Cracks and EDM Notches

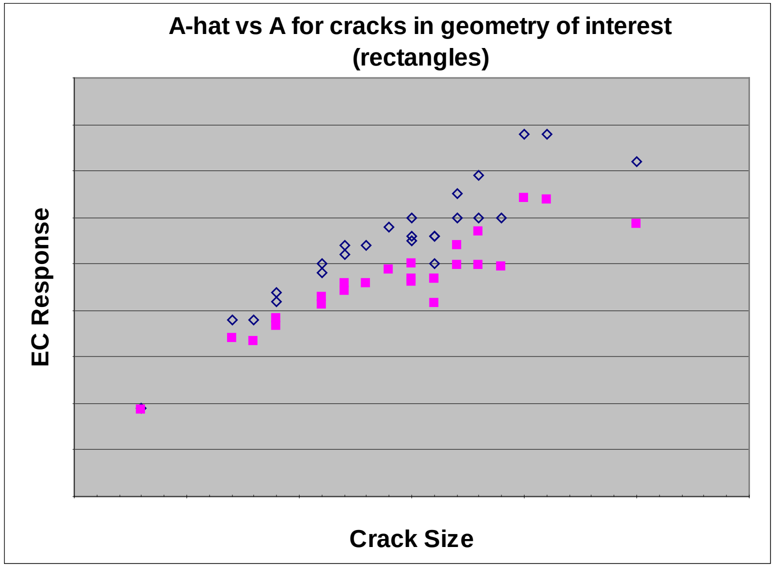
Establish relationship between cracks and EDM notches for flat plate using well-controlled lab studies



Predicted Variability Data for Cracks in the Geometry of Interest

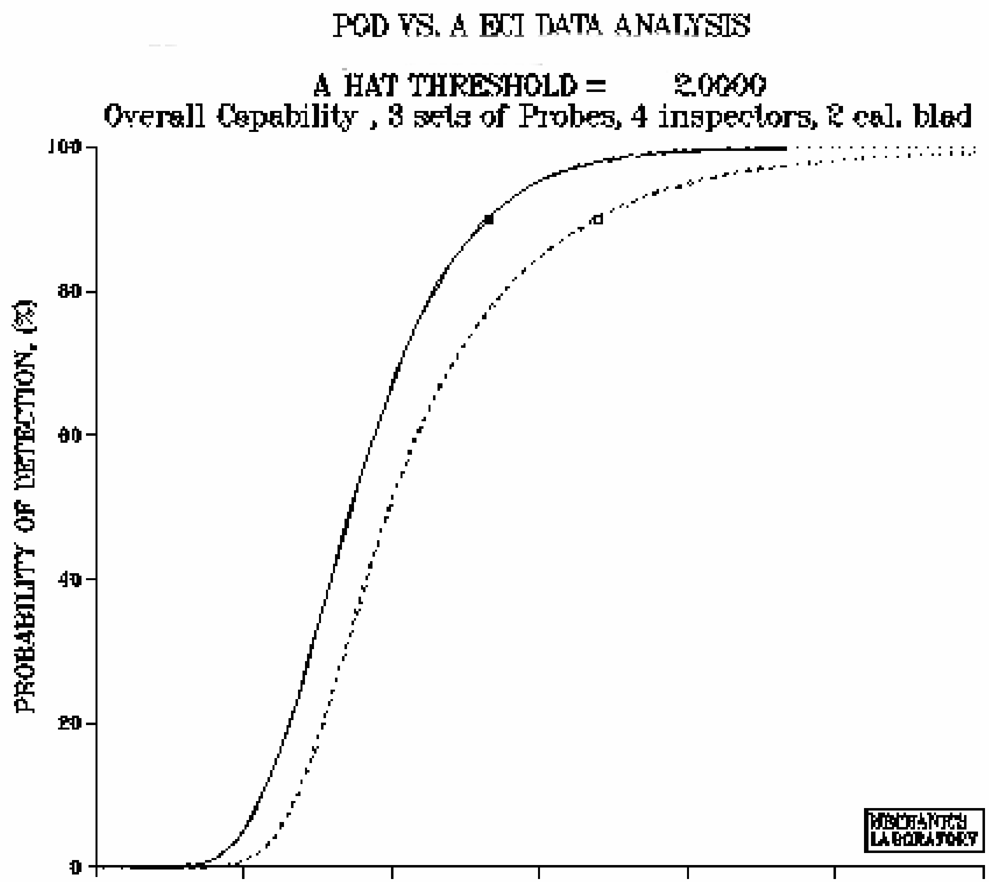
Utilize relationship from flat plates and variability data from notches to generate variability data for cracks in geometry of interest



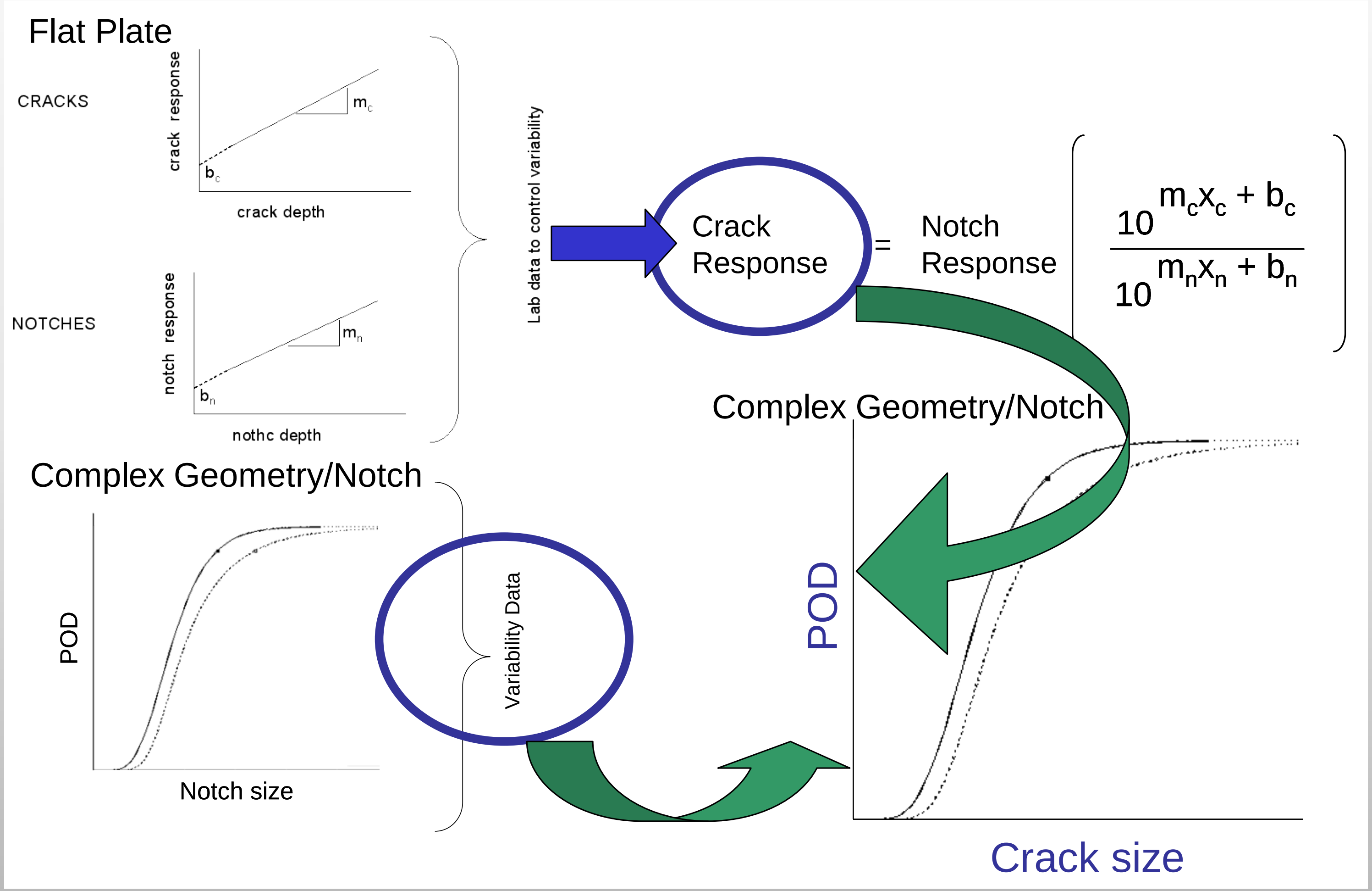


Final POD Curve for Crack in Engine Geometry

Generate POD vs. crack size curves for the geometry of interest



Summary of the Model-Assisted POD Process for Eddy Current Detection of Fatigue Cracks in Complex Engine Geometries



Sub-Protocol for Use of Controlled Laboratory Measurements to Determine Influence of Model-Assessed Factors

- Design an experiment to isolate the effect of one or more factors (e.g. the responses of fatigue cracks as compared to EDM notches)
- Construct or acquire necessary samples
- Perform controlled laboratory measurements on the samples
- Analyze the data to determine changes in the regression line (and the standard deviation of the data about that line) relating flaw response to flaw size associated with the selected factors
- Document the results

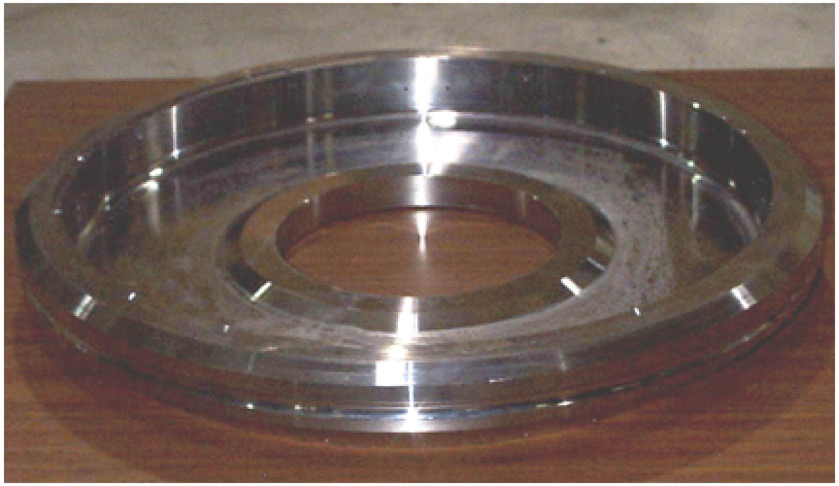
Example #2

- Ultrasonic detection of flat-bottom holes in different engine alloys
  - Desire to take alloy/grain size into account in POD determination
  - Pratt & Whitney (Smith) and Iowa State University (Brasche, Thompson, Meeker, Gray)
  - Empirical factors (test system variability) determined by measurements on low noise alloy
  - Physics-based models used to extend to noisier alloys

Sample Used in Empirical Assessment of Test System Variability

Steps to UT POD Methodology Validation

- Design, fabricate and characterize sample
- Generate and analyze system/operator data
- Calculate empirical POD curve
- Calculate model-based POD using validated signal and noise models
- Compare empirical POD to model-based POD



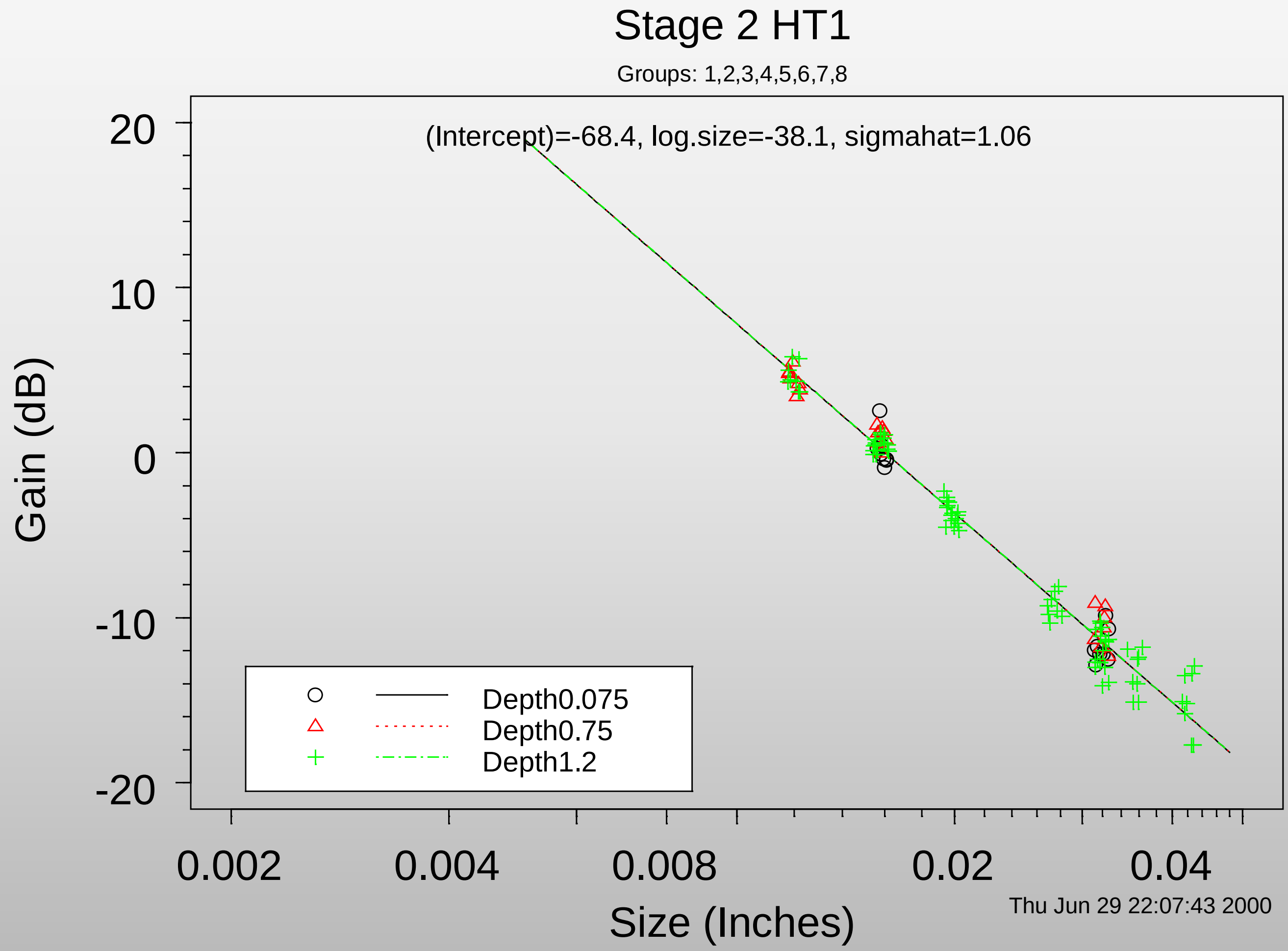
Experimental Design for Determination of Test System Variability

UT POD Methodology Validation

- Tests 1 through 8 use indexing of 0.02”
- Two systems:
  - XR pulser is in Tank B
  - HR pulser is in Tank A
- Four transducers:
  - Transducer 1 = KB 002m99
  - Transducer 2 = TLC p90903
  - Transducer 3 = UTX 1 (0004073)
  - Transducer 4 = UTX 6 (0004074)
- Four inspectors

TEST	OPERATOR	TRANSDUCER	TANK
1	A	1	A
2	B	2	A
3	C	3	B
4	D	4	B
5	A	4	B
6	B	3	B
7	C	2	A
8	D	1	A
9th data set is a repeat of one of the test to produce C-scans with 0.005” increments			

Experimental Results of Ultrasonic Response for a Range of Depths



Comparison of Fully Empirical and Model-Assisted POD Curves

Comparison of curves (denoted by HT in legend) for three depths as determined following MIL-HDBK-1823 procedures with model-assisted curves (denoted by pp in legend) for four transducers at the same three depths for ultrasonic detection of FBH's in engine components.

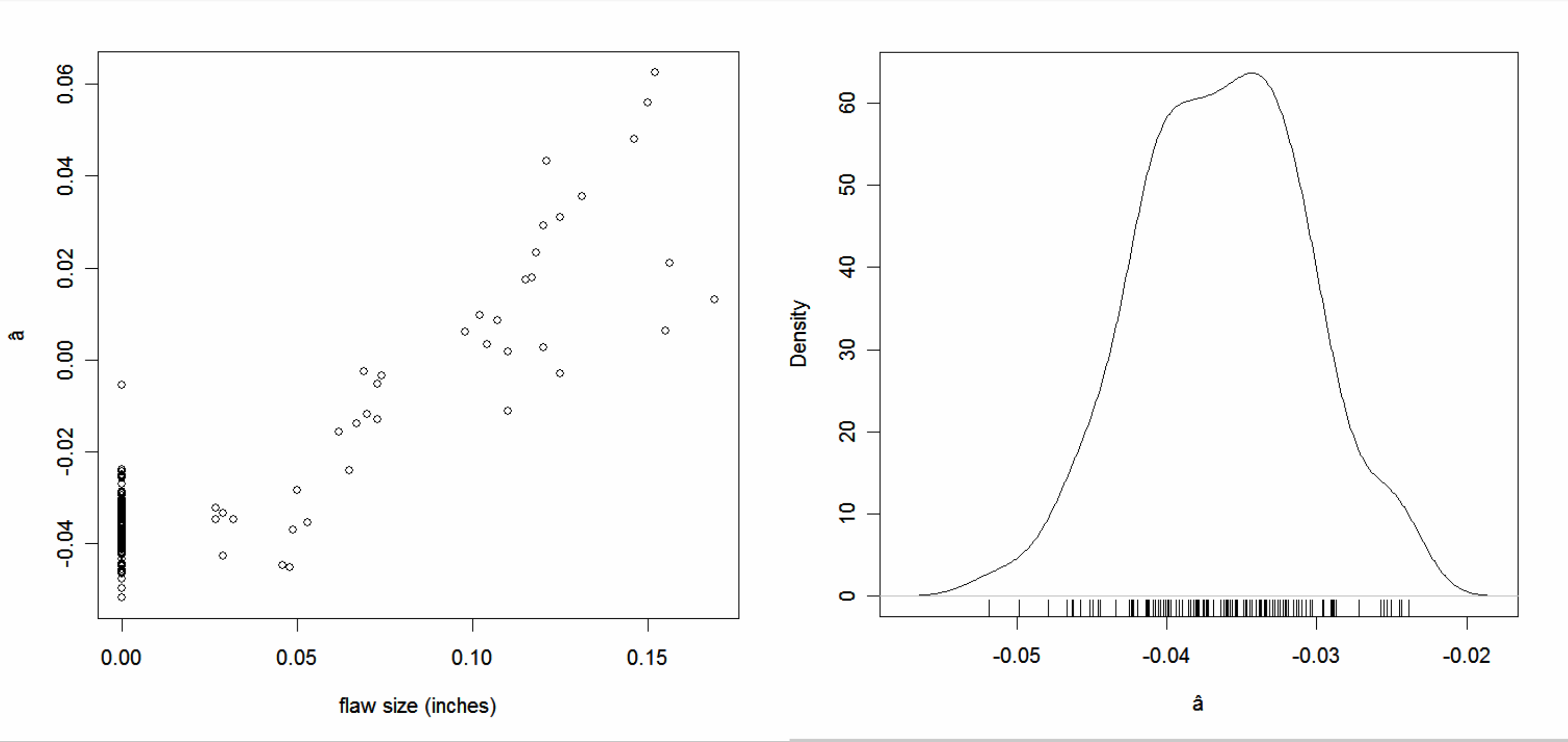
Sub-Protocol for Use of Physics-Based Models to Determine Influence of Model-Assessed Factors

- Identify factors that control signal and noise
- Select best available physics-based theoretical models that are applicable for the conditions of interest
- Acquire input parameters and parameter distributions
- Acquire, develop, and validate simulation tools
- Calculate flaw signal distribution simulations and noise signal distribution simulations
- Analyze the data to determine changes in the regression line (and the standard deviation of the data about that line) relating flaw response to flaw size associated with the selected factors
- Document the results

Example #3

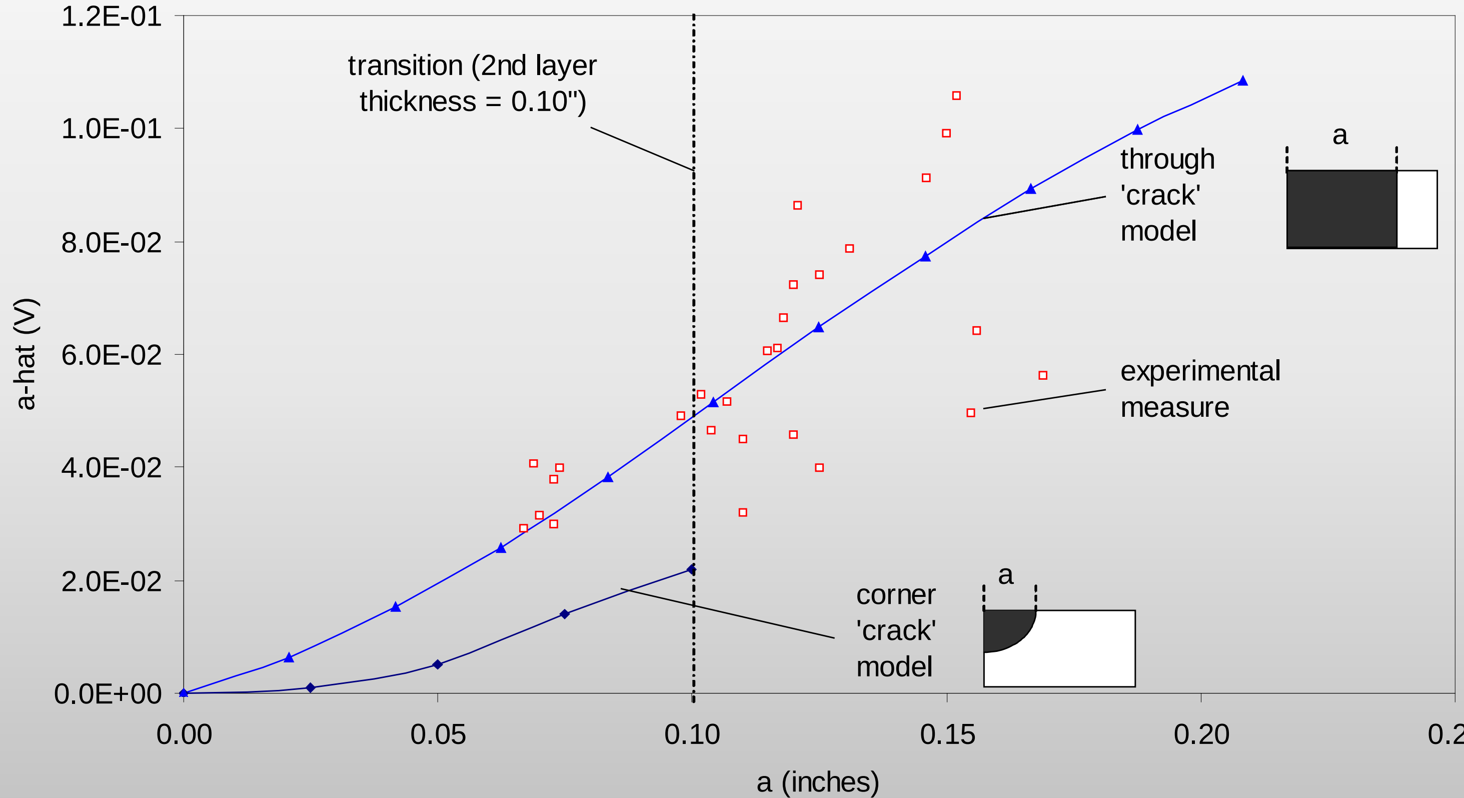
- Capability of eddy current techniques to detect fatigue cracks in wing lab joints
  - Desire to evaluate capability of proposed, advanced techniques
  - AFRL (Knopp, Aldrin) and Statistical Engineering (Annis)
  - Empirical factors determined by response of unflawed holes
  - Physics-based models extend to cracked holes

Unflawed Hole Response



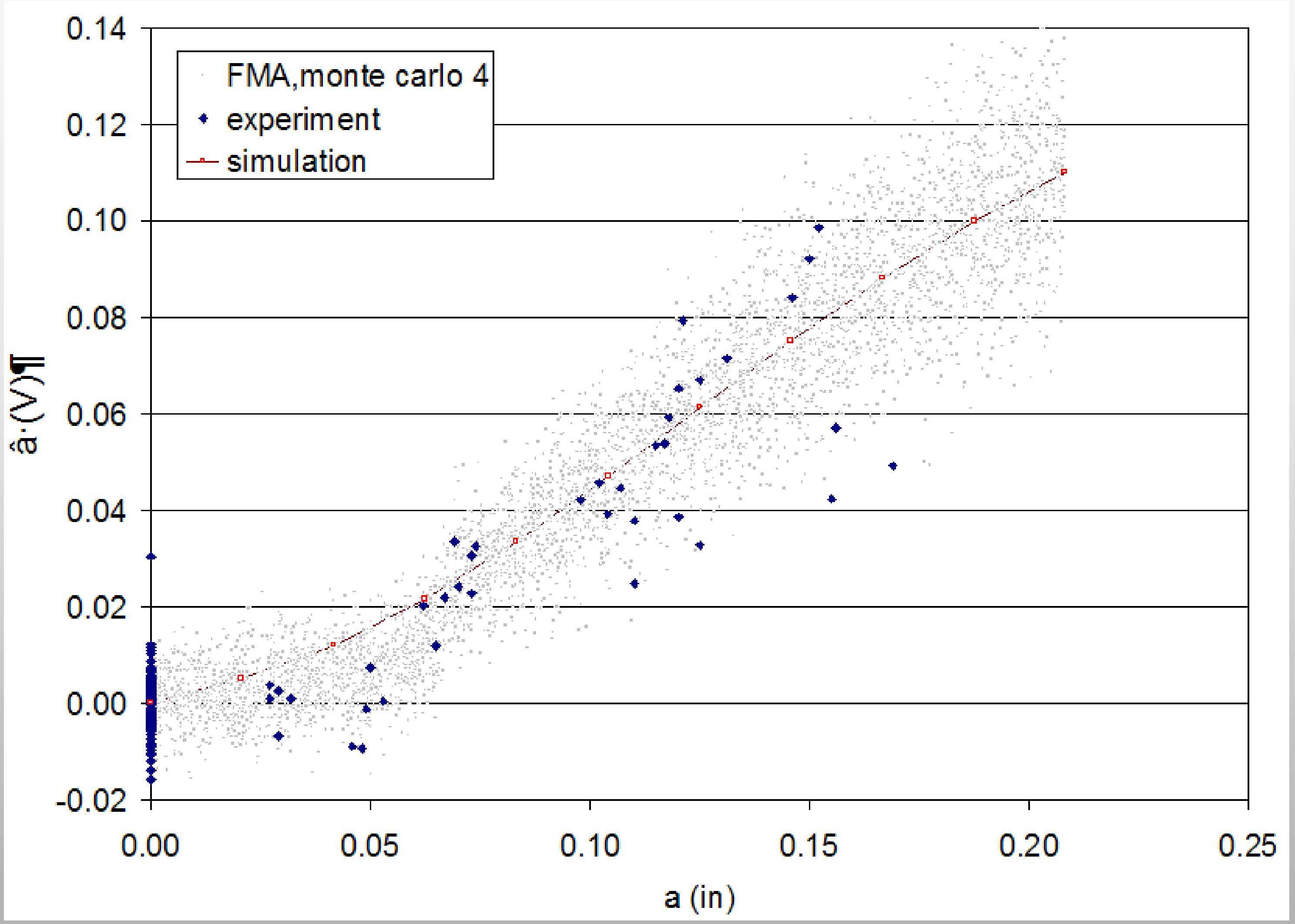
(a) Experimental data including unflawed responses and (b) probability density function for unflawed responses showing that the noise follows a basic Gaussian distribution.

Validation of Model

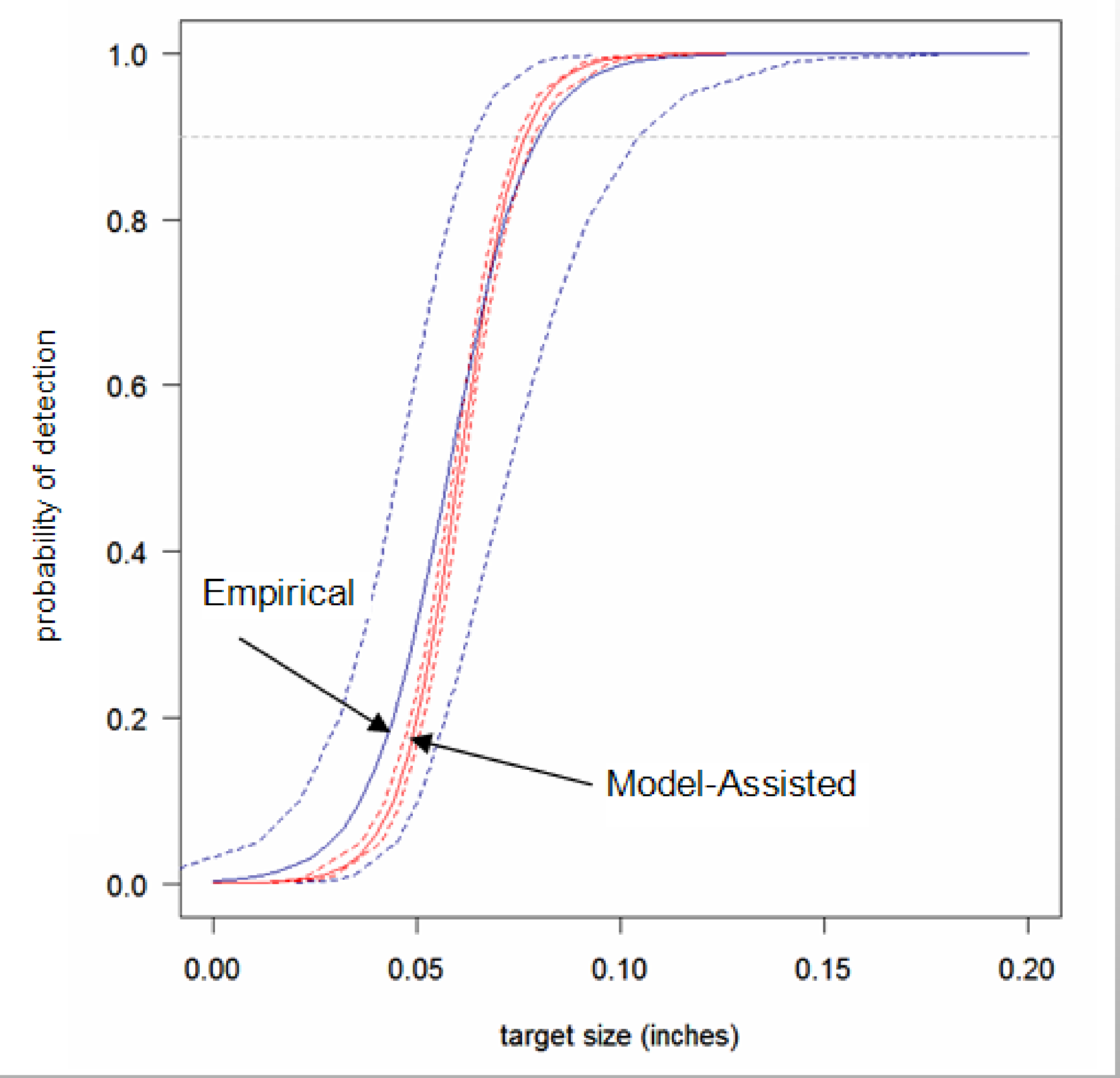


Simulated data for both through 'crack' and corner 'crack' responses with experimental data.

Comparison of Experimental Data and Monte Carlo Simulation Results



POD Results for Empirical and MAPOD Evaluations



Additional Programs in Progress

Airframe problems

- Harding & Hugo, DSTO (Australia) – UT
- Smith & Georgiou, Qinetic (UK) – UT
- Butcher & Mandache (Canadian Forces) – EC
- Nakagawa (CNDE) – EC with Cessna

Engine Problems

- Nakagawa (CNDE) – EC with Pratt & Whitney

Recent Snapshot of Australian and Canadian Work

- Transfer Function Approach (a-hat versus a)

$$\log(r) = \beta_0 + \beta_1 \log(a) + \varepsilon$$

$$\varepsilon \xrightarrow{d} N(0, \delta)$$

- DSTO: Lab experiment
  - Cayt Harding Ph.D. dissertation
- Canadian Forces: Physics-based model

Transfer Function Modelling UTResponse for Cracks in Wings

Assume ultrasonic response for defect of size *a* follows:

$$\log(r) = \beta_0 + \beta_1 \log(a) + \varepsilon$$

$$\varepsilon \xrightarrow{d} N(0, \delta)$$

Transfer function for predicted response from cracks in wings:

$$\beta_{0,CW} = \beta_{0,CS} + \beta_{0,EW} - \beta_{0,ES}$$

$$\beta_{1,CW} = \beta_{1,CS} + \beta_{1,EW} - \beta_{1,ES}$$

$$\delta_{CW}{}^2 = \delta_{CS}{}^2 + \delta_{EW}{}^2 - \delta_{ES}{}^2$$

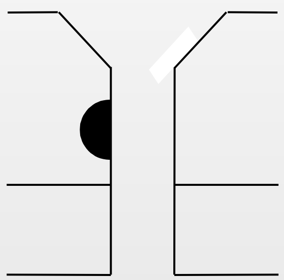
ES – EDM in specimens

EW – EDM in wings

CS – cracks in specimens

CW – cracks in wings

Modelled POD for Mid-bore Cracks



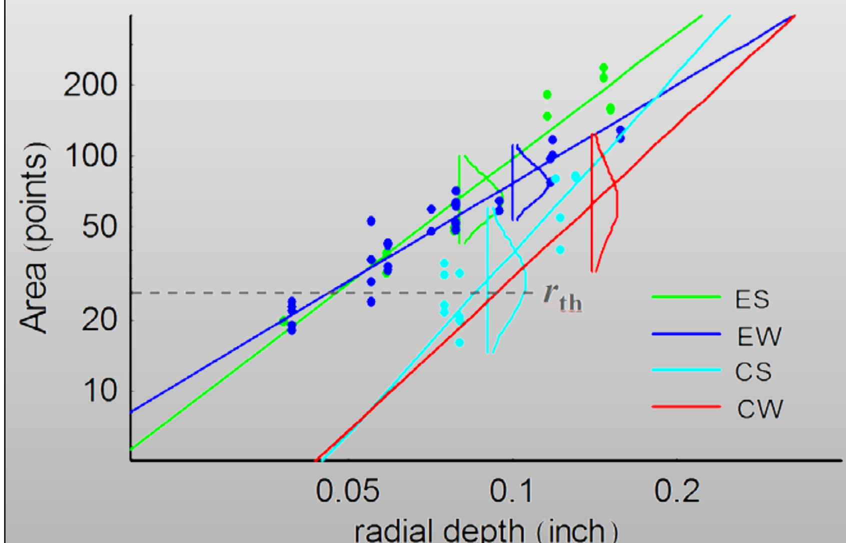
Mid-bore
crack

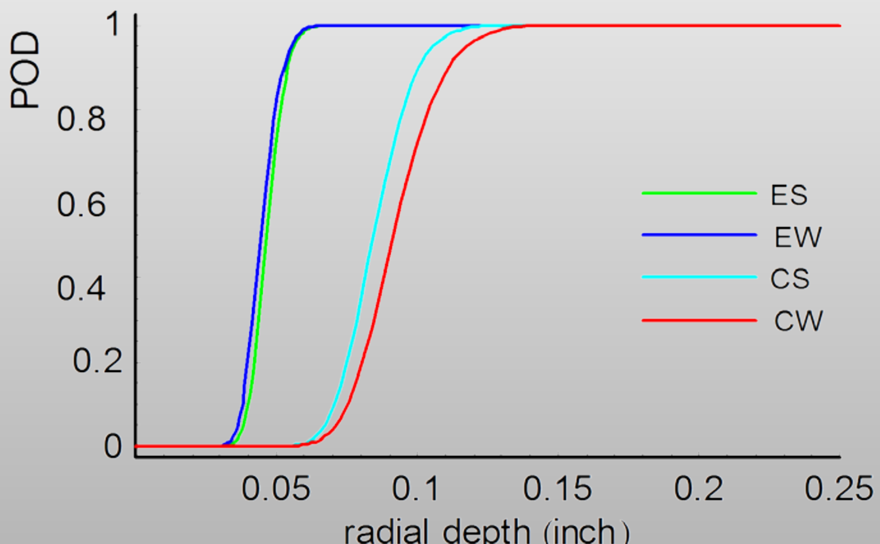
ES – EDM notches in specimens

EW – EDM notches in wings

CS – cracks in specimens

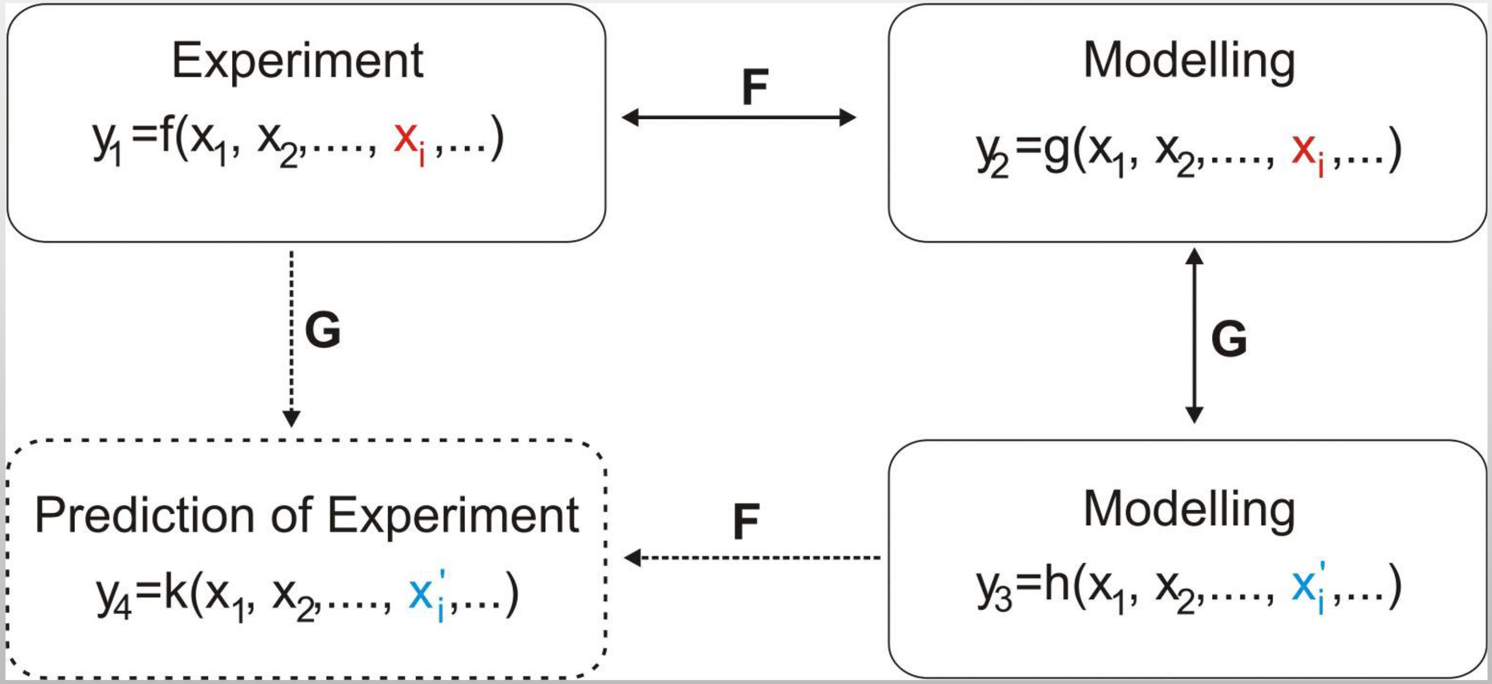
CW – cracks in wings (predicted)





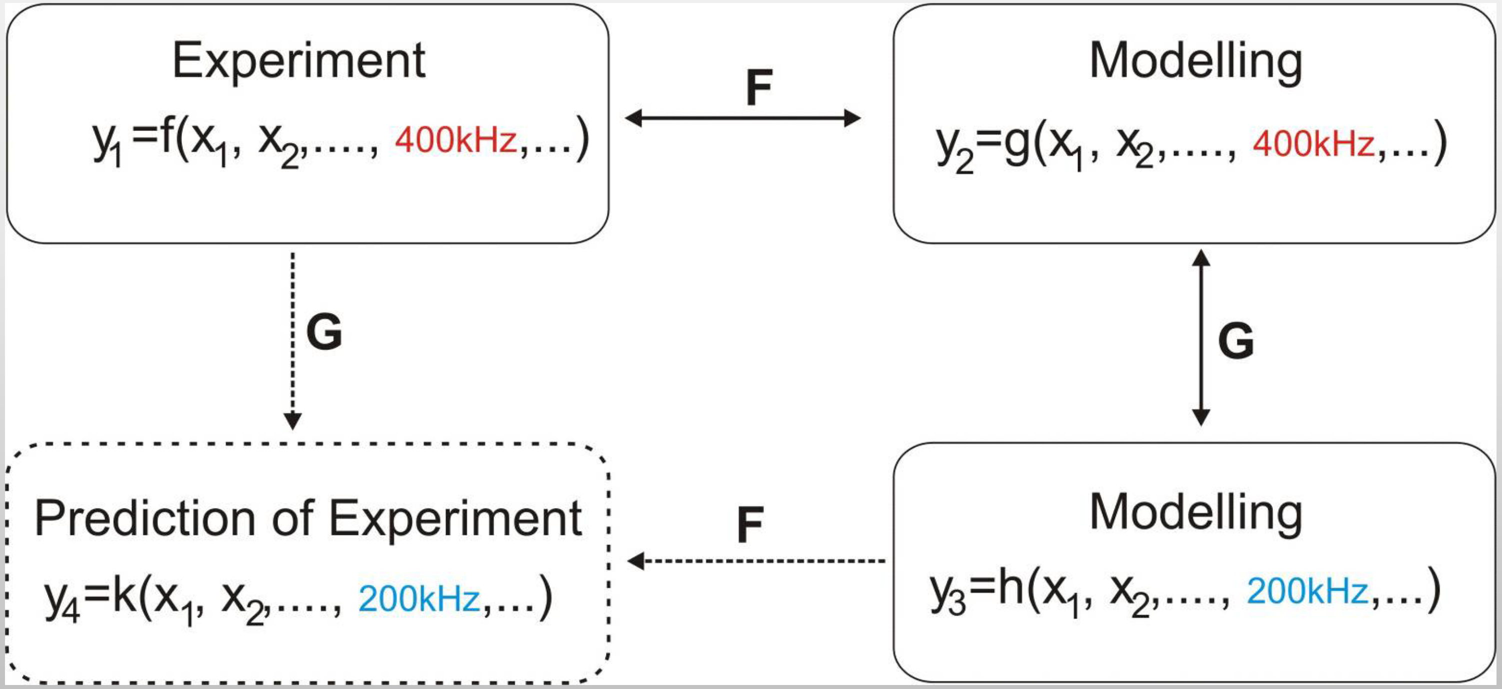
Numerical-based approach

- General principles of using numerical-based approach for estimating POD

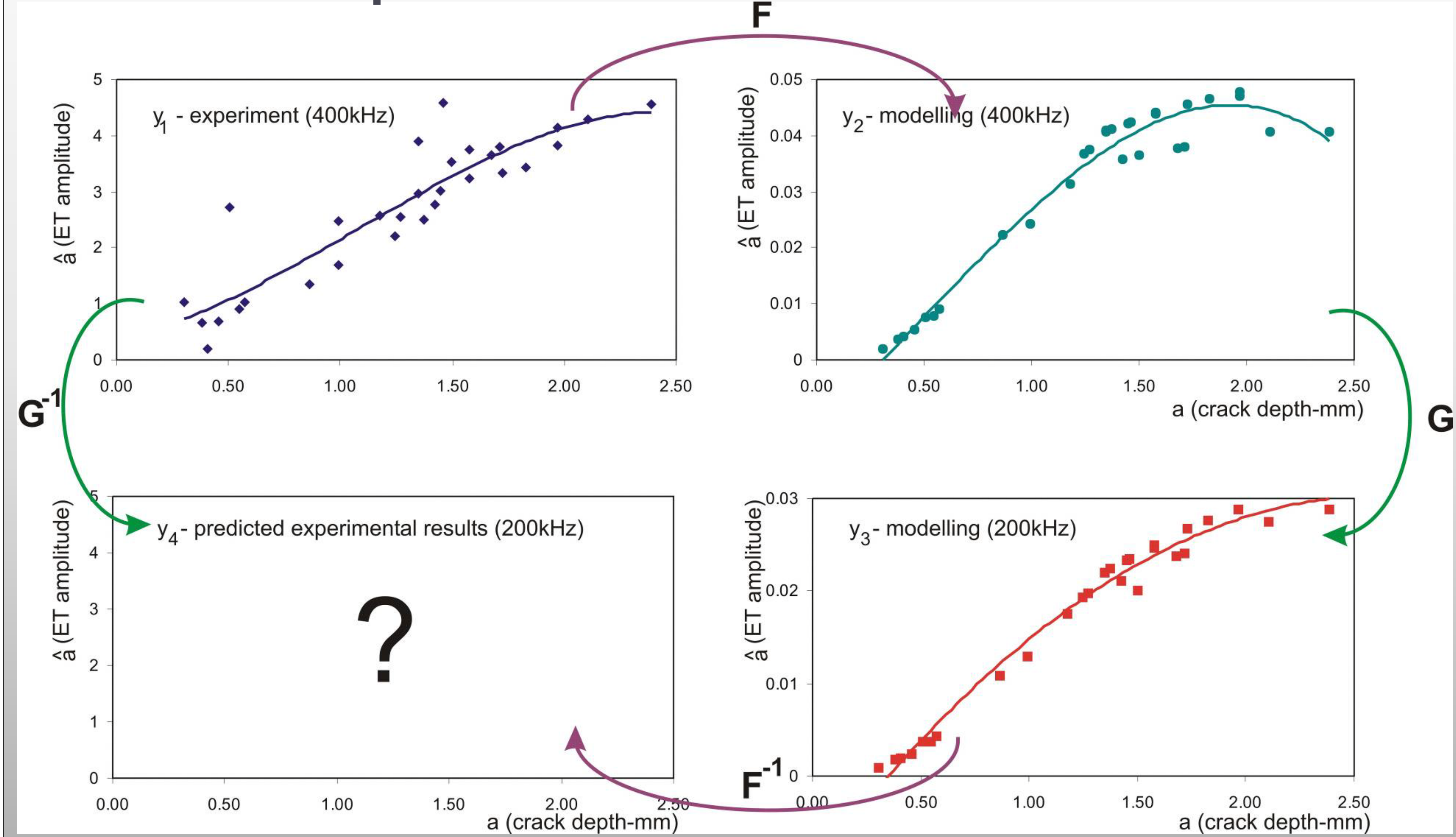


Example

- Consider only a change in the driving frequency:

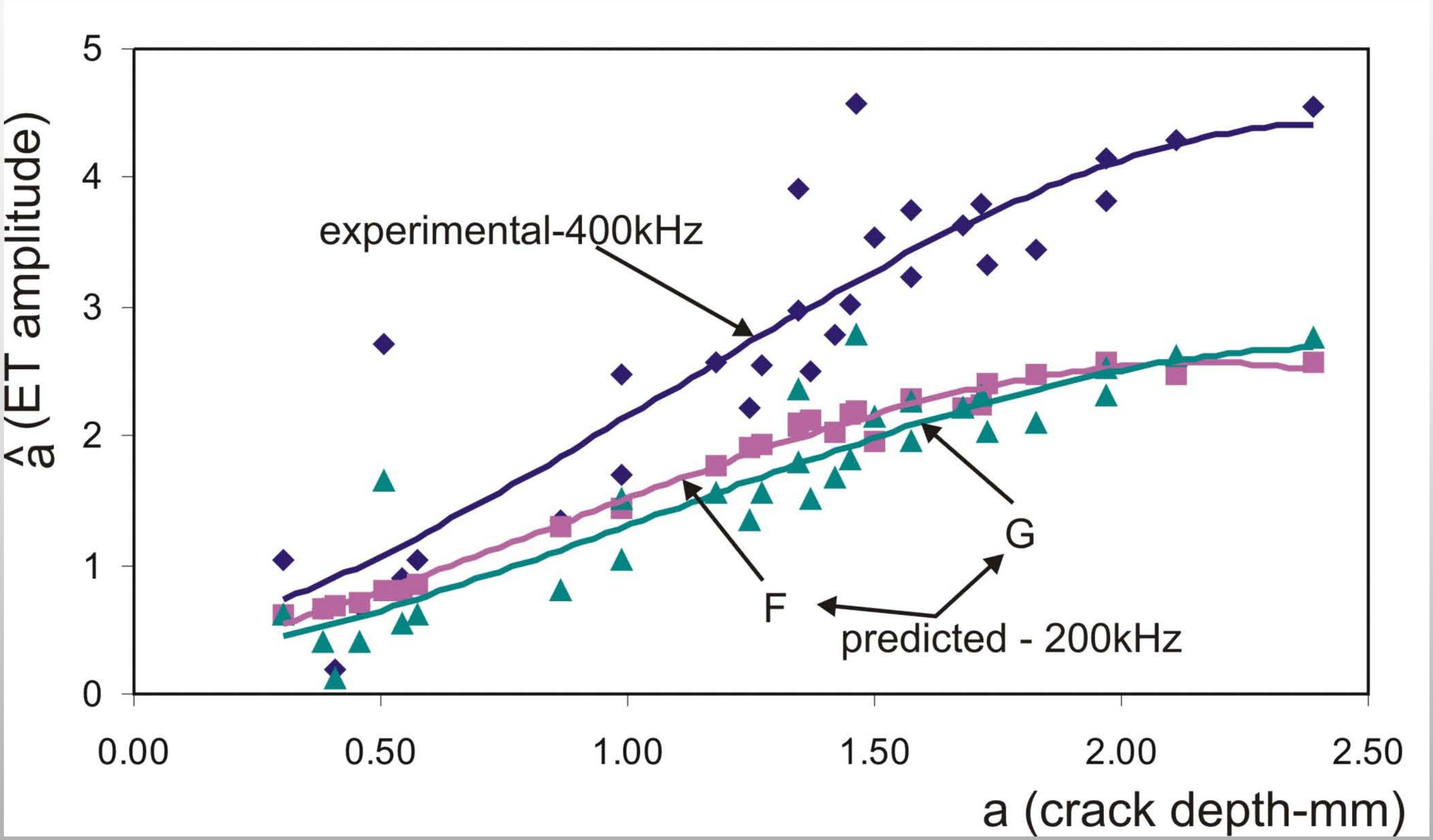


Example



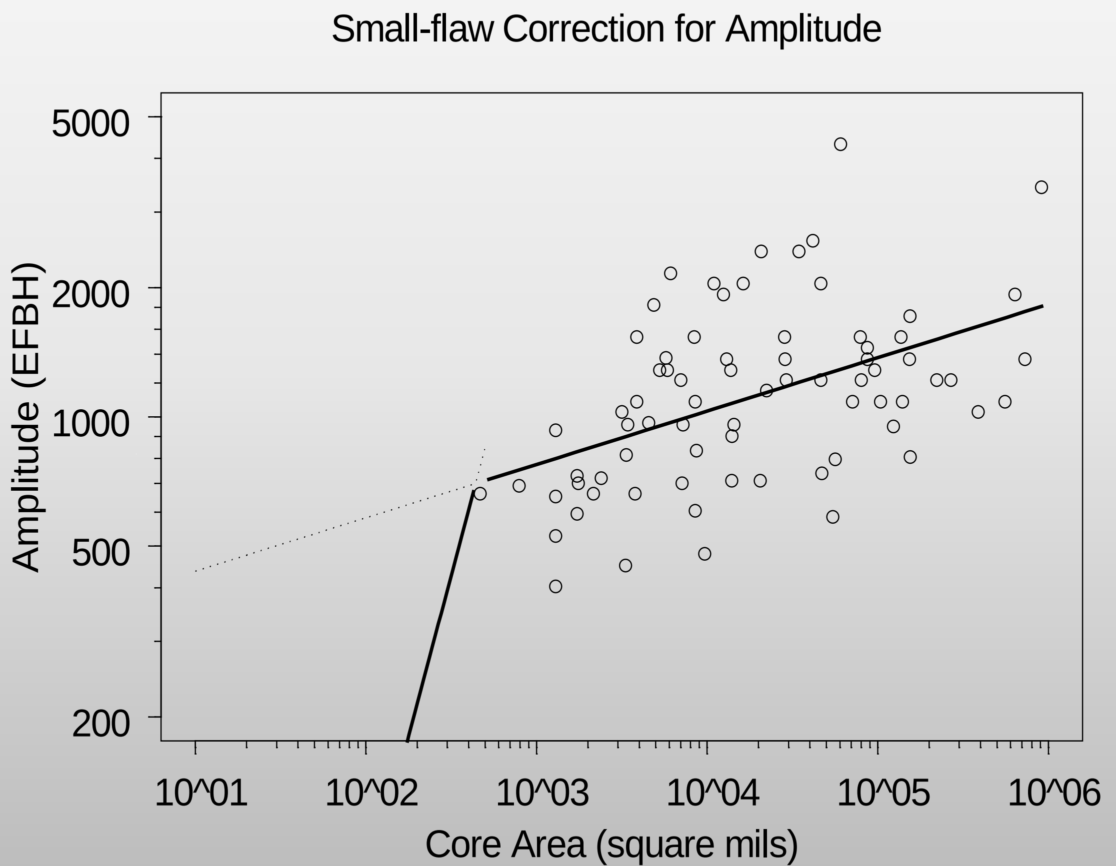
Mandache

Example

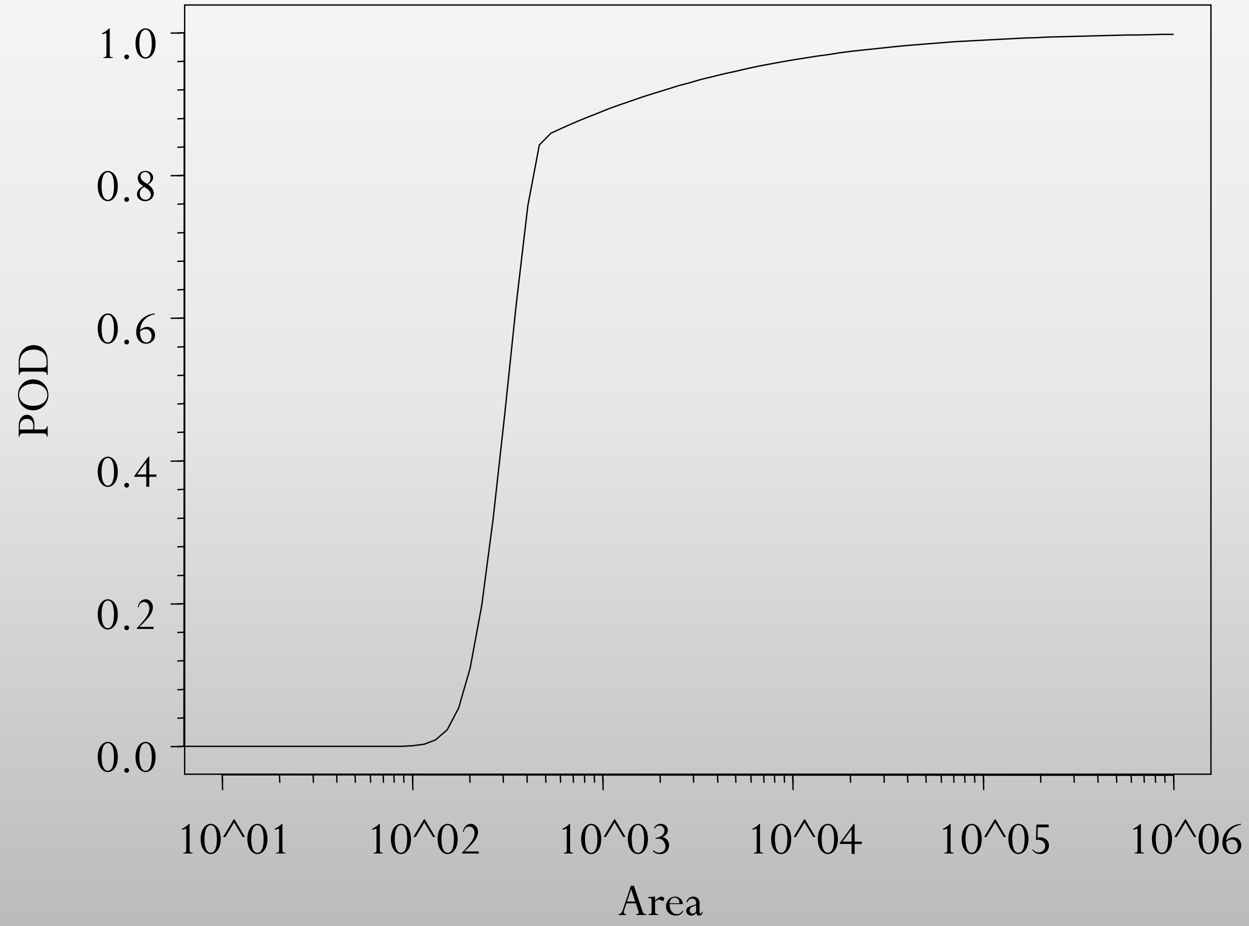


Mandache

Bounding Extrapolations



A Resulting POD Curve



Outline

- Motivation
- MAPOD WG Formed
- Strategies and Protocols
- Demonstrations
- **Conclusions**

Summary

- The **time and cost** of the empirical POD tests required in structural integrity programs is becoming an increasing burden
- The MAPOD approach mitigates this by incorporating **knowledge of physical effects** to reduce the empirical experiments required
- The use of both **controlled laboratory experiments and validated, physics-based theoretical models** has been reported
- A **unified protocol** has been developed

Future Directions of MAPOD Working Group

- Documentation of **benefits via case studies**
- Development of **formal protocols** for engineering practice
  - Appendix on MAPOD in draft update of MIL HDBK 1823 a first step.
- A number of **technical issues**
  - How do we think of accuracy?

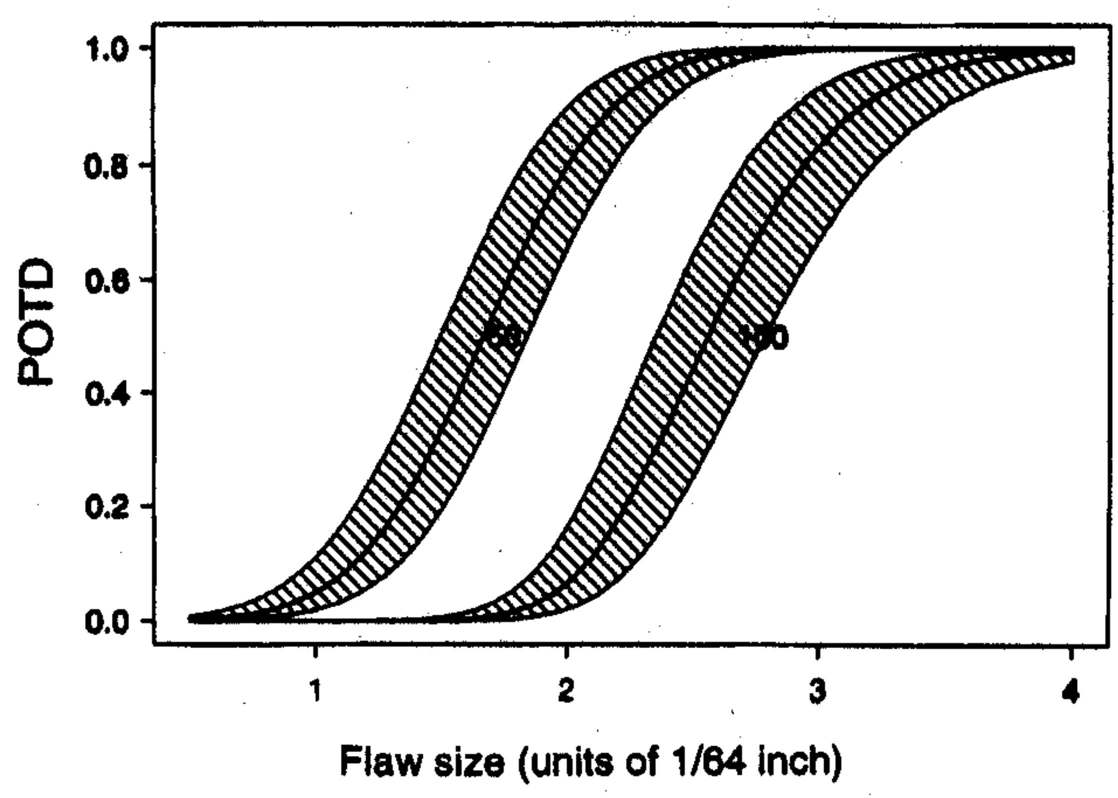
How Accurate are Predictions?

- Statistical confidence intervals characterize this for empirical studies
- What is the analogous concept when using models
- Future studies required
- Some initial thoughts follow

Uncertainty Bounds

- When using a model, can generate large number of data points
- Therefore, statistical uncertainty, as traditionally measured by confidence bounds, can be driven to zero
- However, uncertainty in model predictions will affect predictions of POD
- As an example, in the FAA ETC program, the ultrasonic simulation models were taken to be accurate to 3 dB, believed to be on the order of the reproducibility of typical ultrasonic experiments

Example of Uncertainty Bounds



Further Information

MAPOD Working Group web site

http://www.cnde.iastate.edu/MAPOD/