# Best Practices for Evaluating the Capability of Nondestructive Evaluation (NDE) and Structural Health Monitoring (SHM) Techniques for Damage Characterization

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Review of Progress in QNDE,
Minneapolis, MN – July 27, 2015

# Overview of Talk

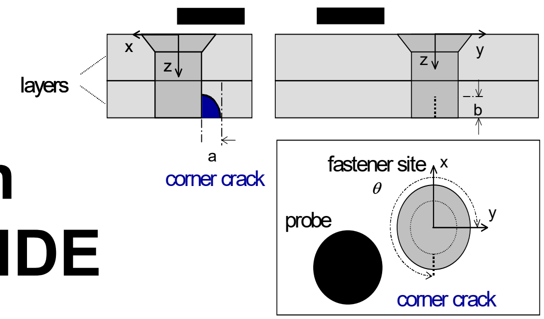
- Process for evaluating NDE ‘sizing’ capability
- Emphasize *understanding assumptions* in evaluation

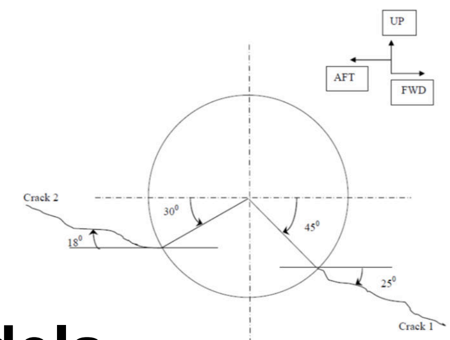
- Challenges with SHM Capability Evaluation
- Best Practices from Demonstration Study
- Opportunities for Models in Evaluation (MAPOD)

# Drivers for Damage Characterization in Aircraft Structures

**Opportunities for Accurate Characterization Techniques:**

- Need for *small crack size 'binning'*
  - Better guide *maintenance actions*
- Fatigue crack parametric characterization (sizing, localization) using eddy current NDE
  - Significant opportunity for support of *condition-based maintenance (CBM)*
- Complete crack characterization evaluation (*multiple cracks* at single site)
  - Provide better data for life prediction models
  - Supports *digital twin* concept




**Validation Procedures are Needed to Ensure Accurate Characterization and Localization Techniques**

# Quality Metrics for Damage Localization / Characterization

## Review of Evaluation Methods (Metrics) for Characterization:

- **1) Statistics Community:**
  - **A) Measurement System Analysis (MSA), ANOVA Gauge R&R (Repeatability and Reproducibility)**
    - ASTM E2782 - Standard Guide for Measurement Systems Analysis
    - NIST: Guide to the Expression of Uncertainty in Measurement

$$y = f(x_1, x_2, \ldots, x_n)$$

$$\sigma_y \approx \sqrt{\sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\sigma_{x_i}\right)^2}$$

where: $y$: measurement
$f$: measurement model
$x$: uncertainty components ($n$)

    - Brown, J., ASNT Fall Conference, 2011
  - **Issues:**
    - **Conventional analysis approaches (ANOVA) don't naturally address complex models with multiple parameters**
    - **Uncertainty propagation often assume 'independent parameters'; They typically do not address joint probability (covariance)**
    - **Need to address aleatory and epistemic uncertainty in evaluation**
    - **These approaches are solely dependent upon raw data.**

# 1. Capability Evaluation and Metrics for Damage Localization / Characterization

## Review of Evaluation Methods (Metrics) for Characterization:

- 1) 'Statistics' Community:
  - 95% Limit Against Undersizing: $H_{95} = Average(H_i) - 1.64 * RMS(H_i)$

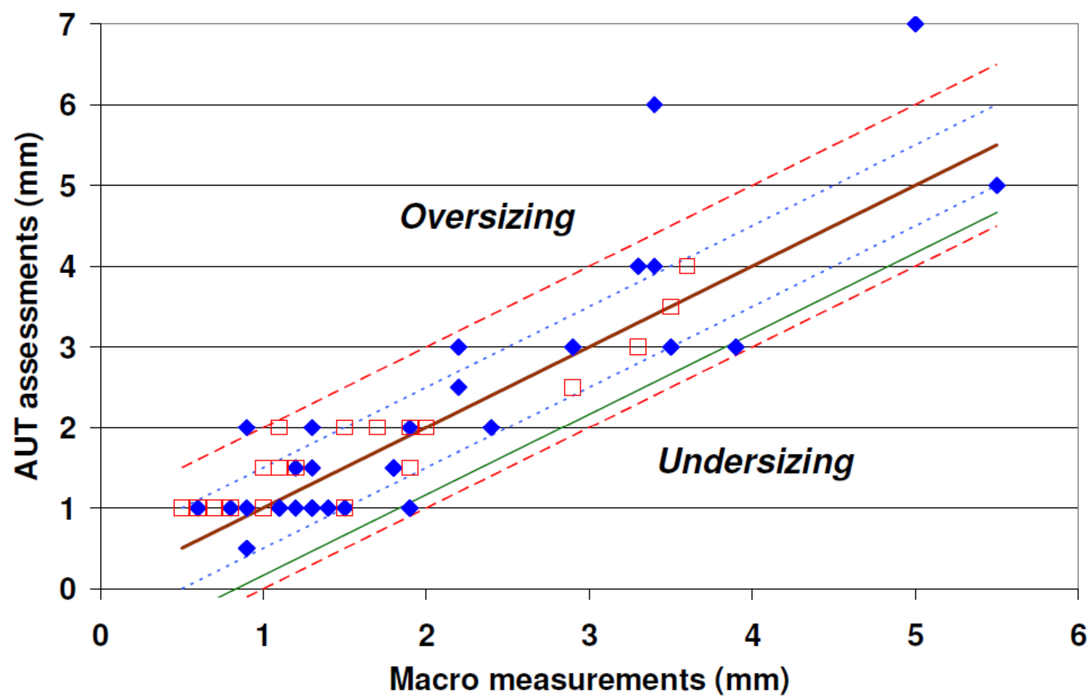



Figure 5: Comparison between AUT assessments and DT measurements

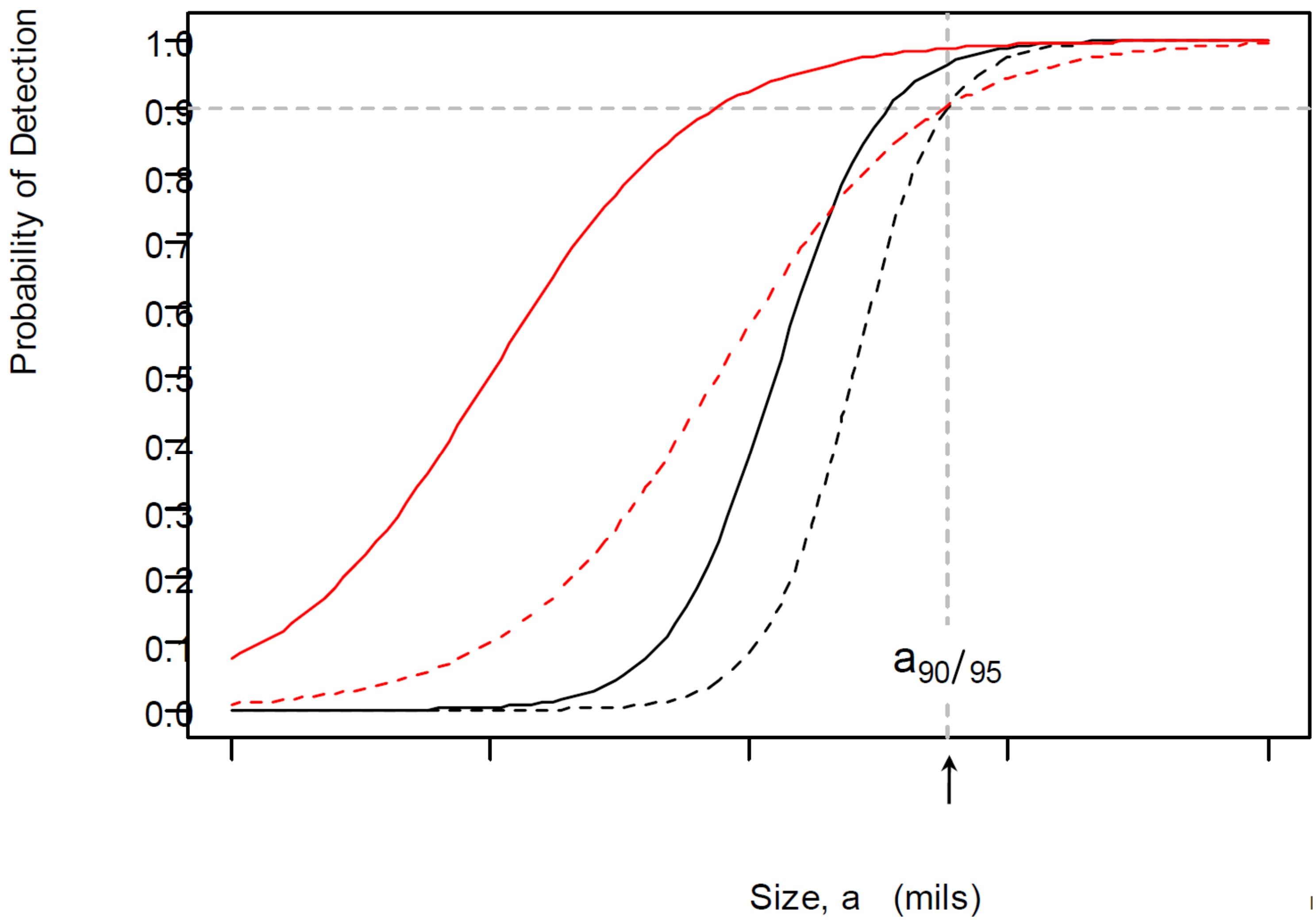
( —— Ideal sizing; - - - - +/- 0.5 mm; — — +/- 1 mm; —— Safety limit against undersizing; □ Surface flaw scatter; ◆ Embedded flaw scatter)

Nordtest. 1998. *Guidelines for NDE Reliability and Descriptions, NT Techn Report 394. 1998.*

* Figure from: Ducharme et al., "Automated ultrasonic phased array inspection of
fatigue sensitive riser girth welds with a weld overlay
layer of corrosive resistant alloy (CRA)" (2012).

* http://www.ndt.net/article/ndtnet/2012/1_Ducharme.pdf

# Why a single number summary, $a_{90/95}$, is an incomplete NDE summary [Annis]



# Quality Metrics for Damage Localization / Characterization

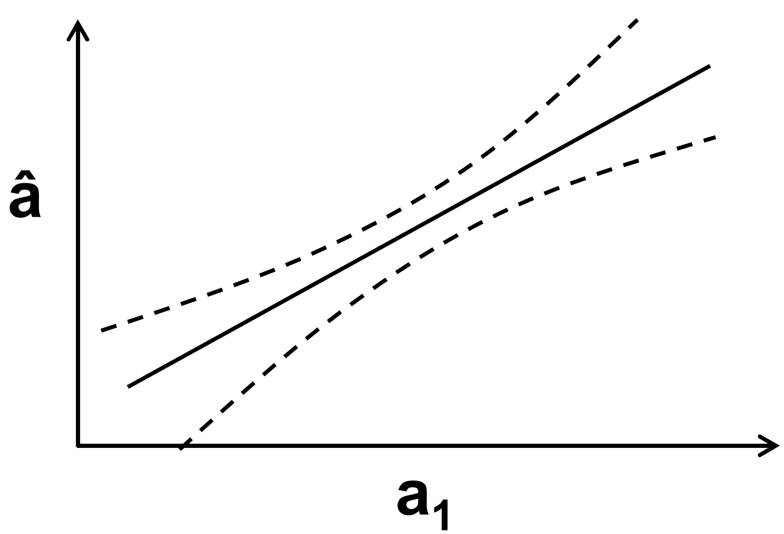
## Review of Evaluation Methods (Metrics) for Characterization:

- **2) Parameter Estimation / Inversion Community:**
  - **Estimation Metrics (e.g. CRLB)**
  - Knopp et al, 2008, "Estimation Theory Metrics in Electromagnetic NDE"
    - **Issue: These metrics are often purely model-based. Do not naturally address parameters/conditions not well-defined by models.**
- **3) Uncertainty Quantification Community (Models, MAPOD)**
  - **Verification & Validation (Emphasis on Scientific Computing)**
  - **Stochastic Numerical Methods (e.g. Polynomial Chaos)**
  - **Bayesian Calibration**
  - SIAM – UQ12
  - **<u>Error Estimate with Uncertainty Bounds</u>**
    - **Challenge: Quality metric is an evaluation of error with *uncertainty bounds* given the full application context (experiment + simulation)**
- **4) Foundations for Quality Metrics for NDE/SHM Characterization:**
  - **Sensitivity Analysis in Inverse Methods [Aldrin et al, 2009]**
  - **MAPOD for SHM / Radiance Program [Aldrin et al, 2009-2011]**

# Compare NDE ‘Ahat-vs-a’ POD and NDE Characterization Error (CE) Evaluations

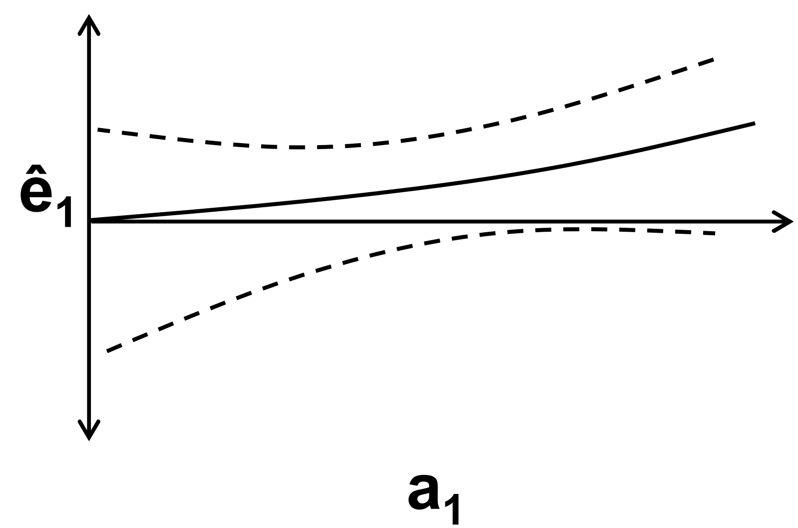
**<u>Ahat-vs-A POD Analysis</u>:**

- **Follow MIL-HDBK 1823A**
- **Perform evaluation studies**
  - **experimental measurements**
  - ***simulated* measurements**
- **Evaluate *model of measurement* ($\hat{a}_j$) with respect to flaw size ($a_k$)**
  - ***mean* model**
  - ***confidence* (uncert.) bounds**




**<u>Characterization Error Analysis:</u>**

- **Build on Protocol for NDE/SHM**
- **Perform evaluation studies**
  - **experimental *sizing results***
  - ***simulated sizing results***
- **Evaluate *characterization error* ($\hat{e}_j$) with respect to flaw size ($a_k$)**
  - ***error* model ($\hat{e}_j = \hat{a}_j$ - $a_j$)**
  - **uncertainty bounds**



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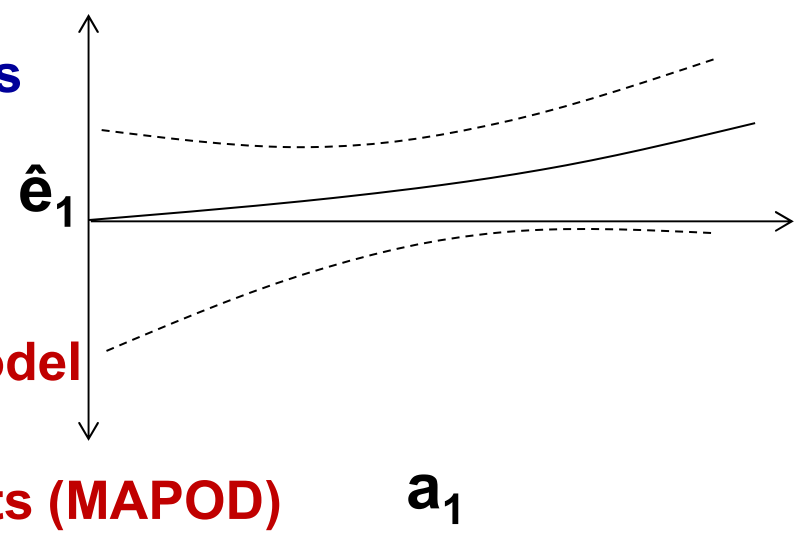
**Characterization Error (CE) Evaluation is Similar to Ahat-vs-A POD Assessment**



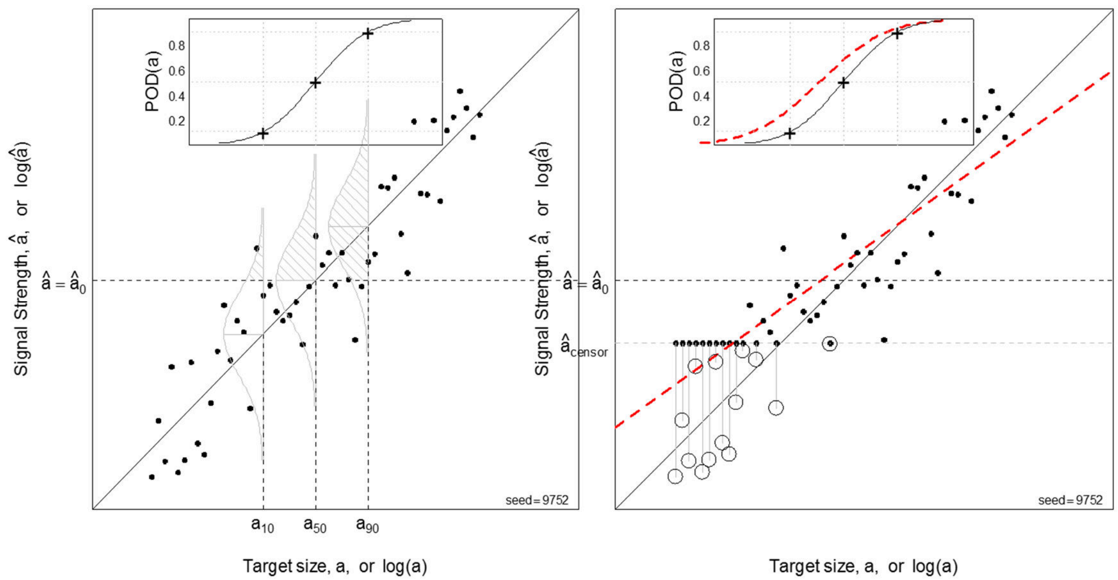

**Differences:**

- **Complex multi-dimensional error model**
- ***Simulating 'characterization' more complicated* than NDE measurements (MAPOD)**

# What's Missing in NDE Capabiltiy Evaluation? [Annis et al., Mat Eval. 2015]

**Understand implicit statistical assumptions in regression analysis:**

1. ***The model must look like the data!***
2. **The response must be continuous and observable.**
3. **The model must be linear in the parameters.**
4. **The variance must be homoscedastic (uniform variance)**
5. **The observations must be uncorrelated:**
   - **with respect to time**
   - **with respect to space**
6. **The errors must be Normal**



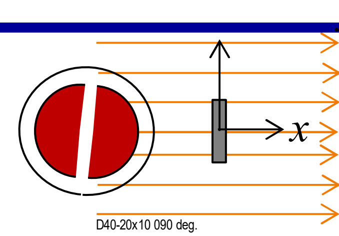

Replacing censored values with the censoring value skews the result anticonservatively.

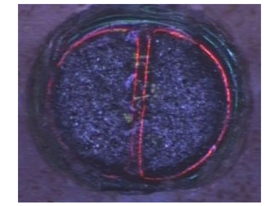
**If assumptions are not met, you need to pick a different 'correct' model!**

*"Simply not understanding the nature of the assumptions being made does not mean that they do not exist."* Frank et al (1993).

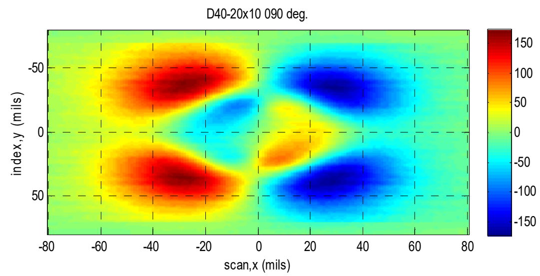
# Case Study - Model-based Inversion of EM Signals for Crack Characterization [Shell et al., QNDE 2014]

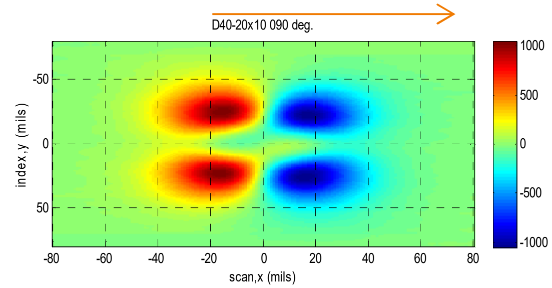
Parameters: 20x10x1.2 mil notch, D40 Probe, Tangential (90°) Orientation: 5°



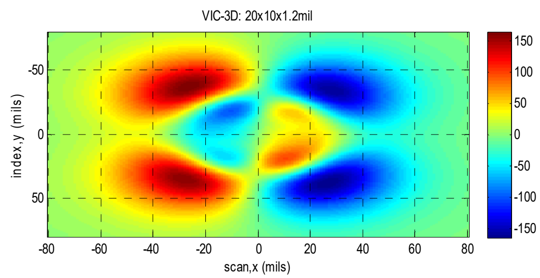



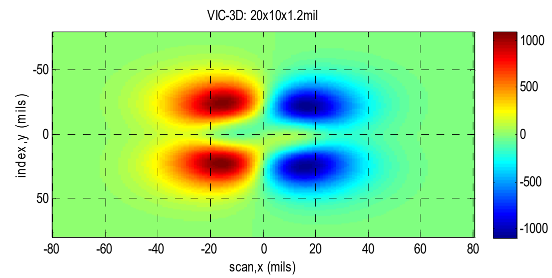
Experimental Data (Wyle):



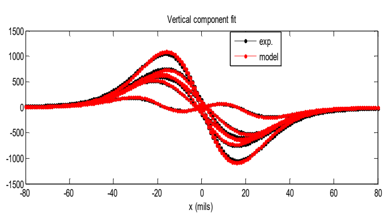



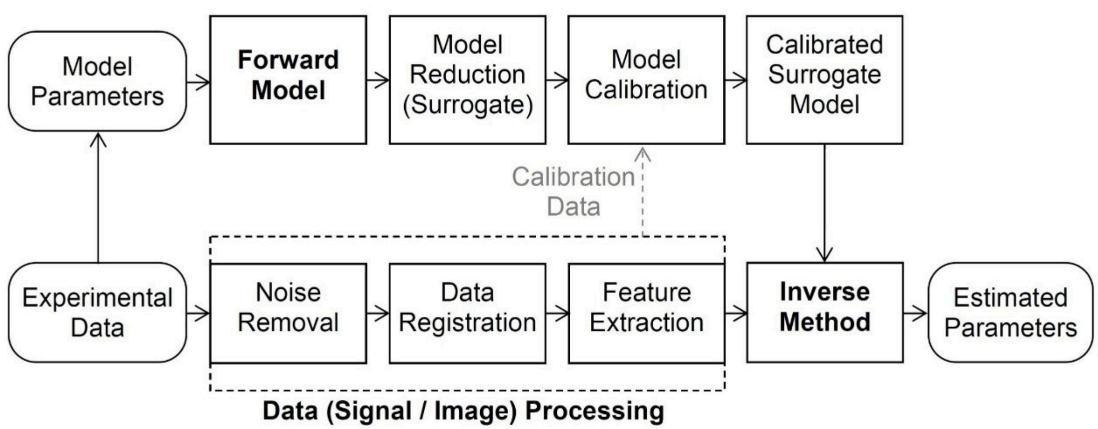

Model (VIC-3D©):




Inversion Process:

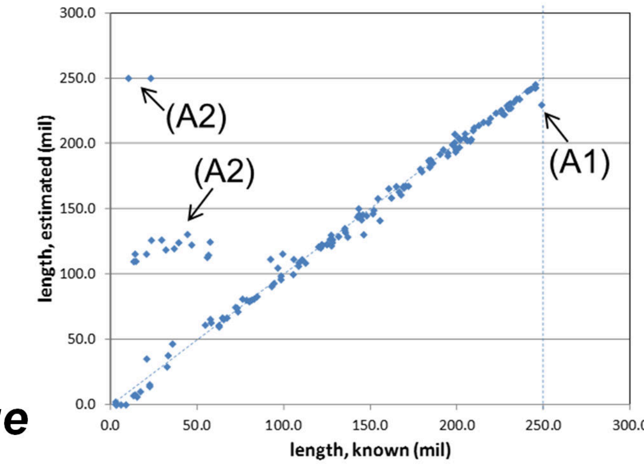



Characterization Case Study:
(a) crack length,
(b) crack depth,
(c) crack width,
(d) crack angle.

# Developing Characterization Error Models for Inversion Performance [QNDE 2013]

**Group Characterization Error Samples into Unique Data Classes:**

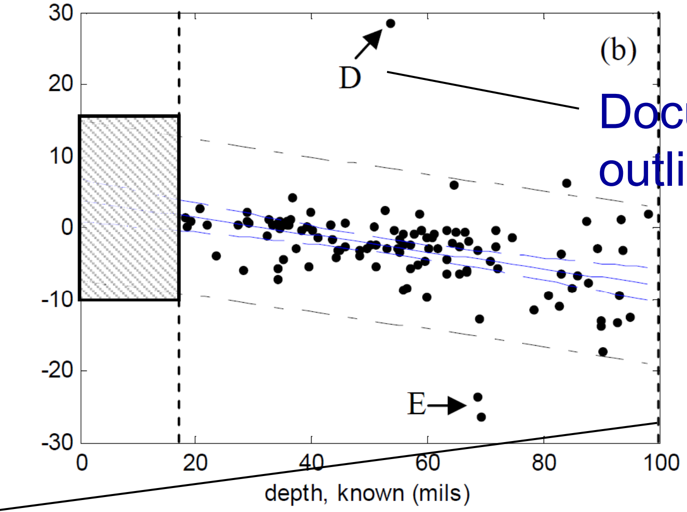



1. P(**good classification: with some error**)
    - **associated with linear ahat-vs-a model**
2. P(**poor classification: due to weak signals**)
    - correlated with ***small flaw geometry***
    - **associated with left 'censoring' in POD**
3. P(**poor classification: due to saturated signals**)
    - poor classification, ***signals smaller than true value***
    - **associated with right 'censoring' in POD**
4. P(**poor classification: conditions exceed inversion parameter constraint(s)**)
    - observed as ***'clusters' at specific parameter estimate plane bounds***
    - **analogous with 'censoring' in POD**
5. P(**poor classification: problem ill-posed / solution stuck in local minima**)
    - ***secondary 'clusters' in error plane***
    - **need for more complex POD models (mixture models, higher order)**
6. P(**poor classification: due to poor NDE technique** )
    - complete failure in sizing procedure
    - result ***independent of flaw parameters***
    - **associated with 'random missed call rate' in POD**

# Developing Characterization Error Models for Inversion Performance [QNDE 2014]

**A. Leverage Insight from POD Evaluation in Characterization Error Model Building:**

- **Censoring / constraints**
- **Interactions and mixture models**
- **Random missed classifications**




Document outliers

***B. Critical to Check Assumptions in Characterization (Statistical) Model***

Define clear limits of error model fits

Consider confidence and prediction bound in fit

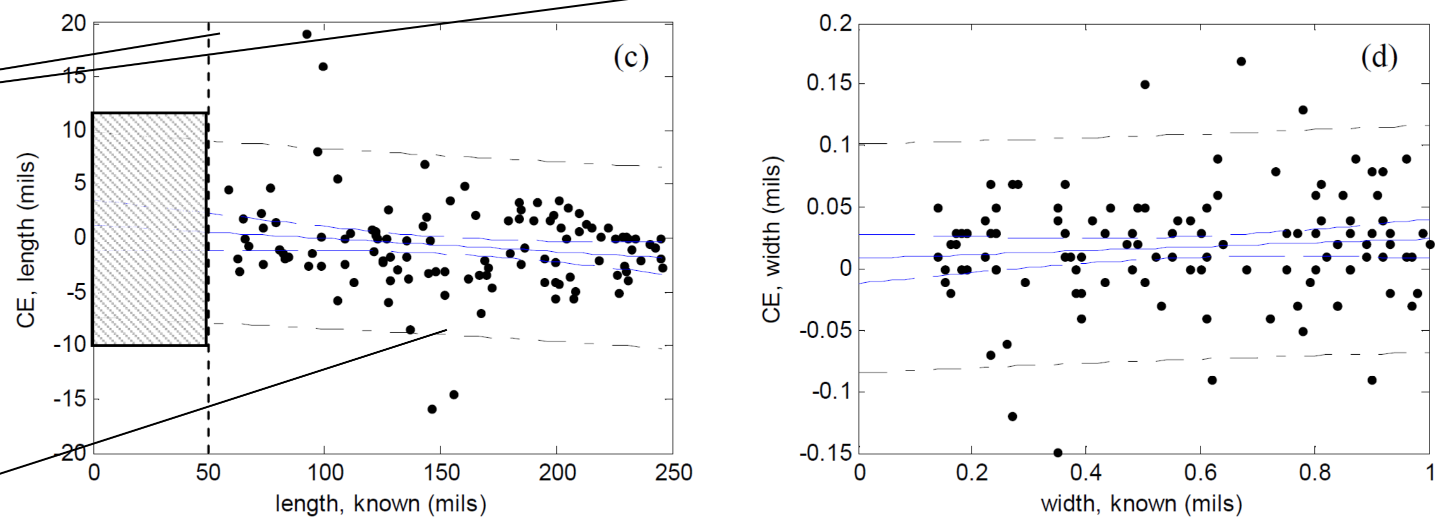
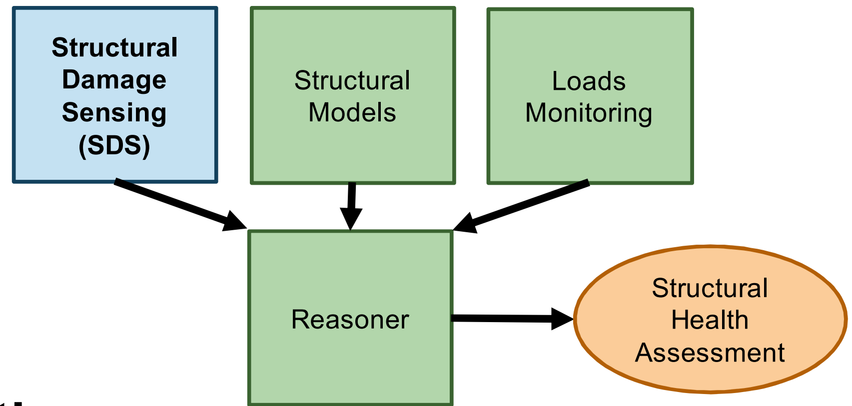



**FIGURE 4.** (a) RMS of characterization error for three crack dimensions with respect to varying estimated cross-sectional area of crack. Characterization error for censored inversion results for (b) crack depth, (c) crack length and (d) crack width. Plots include a linear model fit (solid line) with confidence bounds (dashed line) and corresponding prediction bounds (dash-dot line).

# Verification and Validation of Structural Damage Sensing Systems

- **Structural Damage Sensing is a component of SHM**
- **SDS System Certification <u>requires</u> Qualification Testing that includes Capability (Reliability) Validation**



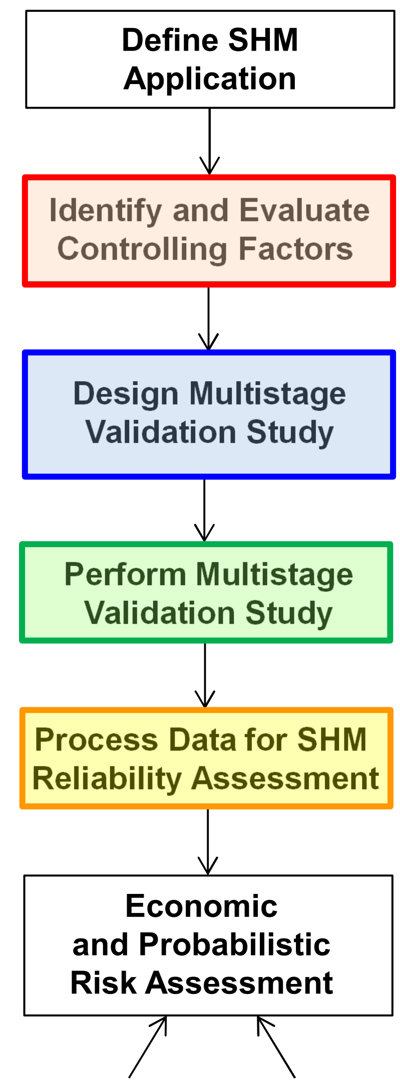

- **SDS System Verification and Validation:**
  - **Verification:** Demonstrate design requirements under *controlled conditions* (laboratory environment)
  - **Validation**: Demonstrate design requirements with *representative operational environment and user*
- **Required capability depends on expected application**
- **Validating SDS capability is a requirement for use of SHM in USAF structures managed via Aircraft Structural Integrity Programs (ASIP)**

# Probabilistic Reliability Assessment for SDS Systems

## Protocol comprises:

- Procedure for analyzing all pertinent **characteristics** of the SDS system
  - Identify all **critical factors** that affect system performance
- **Multistage** approach for system validation
- Modeling and experimental methodology for efficiently addressing a **wide range** of damage and operational conditions
- Effective methods for evaluating **metrics** of capability and reliability depending on system type and function (***uncertainty propagation***)

**Primary Protocol**



# Analyzing Pertinent Characteristics of an SDS System

## SDS System Characteristics

- **Type of Damage Sensing**
  - Direct / active, Passive, Indirect
- **SHM System Output**
  - Damage detection, localization, characterization
- **Coverage and Sensor Location**
  - Local, semi-global (sub-structure), or global
- **Measurement Type**
  - Eddy current, ultrasonic, vibration, pressure
- **Time of Data Acquisition (DAQ)**
  - During flight, select condition, on ground
- **Location of DAQ Hardware**
  - On the ground or onboard the aircraft

## SDS Data Analysis

- **Data Classification Approach**
  - Human interpretation only (human factors)
  - Automated signal classification (software certification)

**Structure Characteristics**

**Damage Characteristics**

## SDS Maintenance and Process Controls

- **System Maturity** (input data for assessment)
- **Secondary Inspections and Maintenance** (combined POD / False call assessment)
- **SHM Process Controls**
  - Maintain calibration, detect sensor failure
  - Redundant sensors systems coverage
- **SHM System Maintenance**
  - Repair scheduled or unanticipated
- **SHM Failure Modes Effects Analysis**

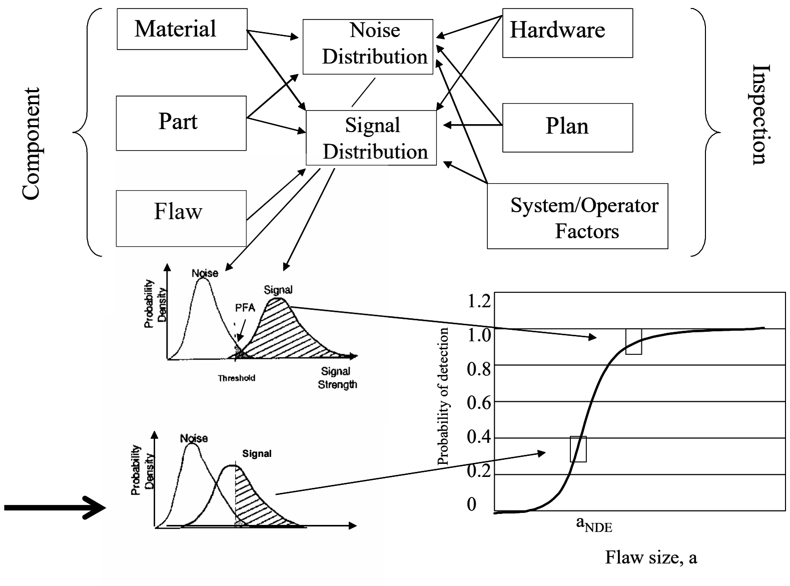
## Impact (on ASIP)

- **Criticality of the Damage State**
- **Credit Associated with SHM Application**
  - e.g. increase in maintenance cycle
- **Effect of Worst Case Occurrence (should SHM application fail)**

# Model Assisted
# Probability of Detection (MAPOD)

**Model Assisted POD (MAPOD) method:**

- Uses models to *minimize* the need for empirical samples to evaluate POD and False Call (FC) rate
- Consensus protocol developed by international working group [2003-11]
  - Transfer function (XF) and full model-assisted [Thompson, 2001]
  - Protocol added to MIL-HDBK-1823A (2009), Appendix H. See also www.cnde.iastate.edu/MAPOD/.

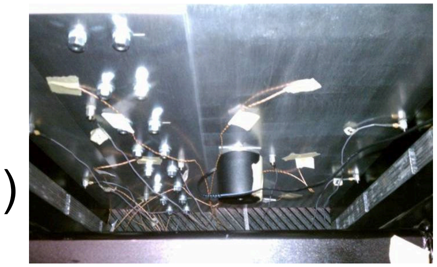



- Feasibility of approach demonstrated for a number of ultrasonic and eddy current inspection demonstrations:
  - MAPOD/WG Demonstrations [Forsyth, 2008]: XF and FMA[1] examples
  - PICASSO EU project: Several successful POD validation cases

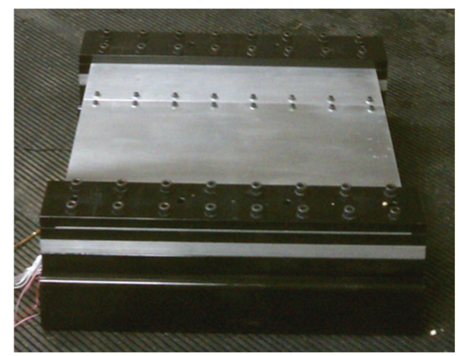
1. J.C. Aldrin, J. S. Knopp, E. A. Lindgren, K. V. Jata, “Model-assisted Probability of Detection (MAPOD) Evaluation for Eddy Current Inspection of Fastener Sites”, Review of Progress in QNDE, (to be published, 2009).

# Demonstration Study – Define SHM System

<u>**SDS System Characteristics:**</u>



- **Type:** Direct damage detection using active sensing
- **SHM System Output:** Damage detection call
- **Coverage and Sensor Location:** Semi-global (sub-structure)
- **Measurement Type:** **Vibration (low frequency) response**
- **Time of Data Acquisition (DAQ):** While aircraft is on the ground
  - **Vary temperature (gradients), loading/unloading, boundary cond., fastener torques**
- **Location of DAQ Hardware:** Onboard the aircraft



<u>**Structure Characteristics:**</u> **Include joints in test article**

- **Center joint with sites for simulating damage growth**
- End conditions with optional shims (to change boundary)

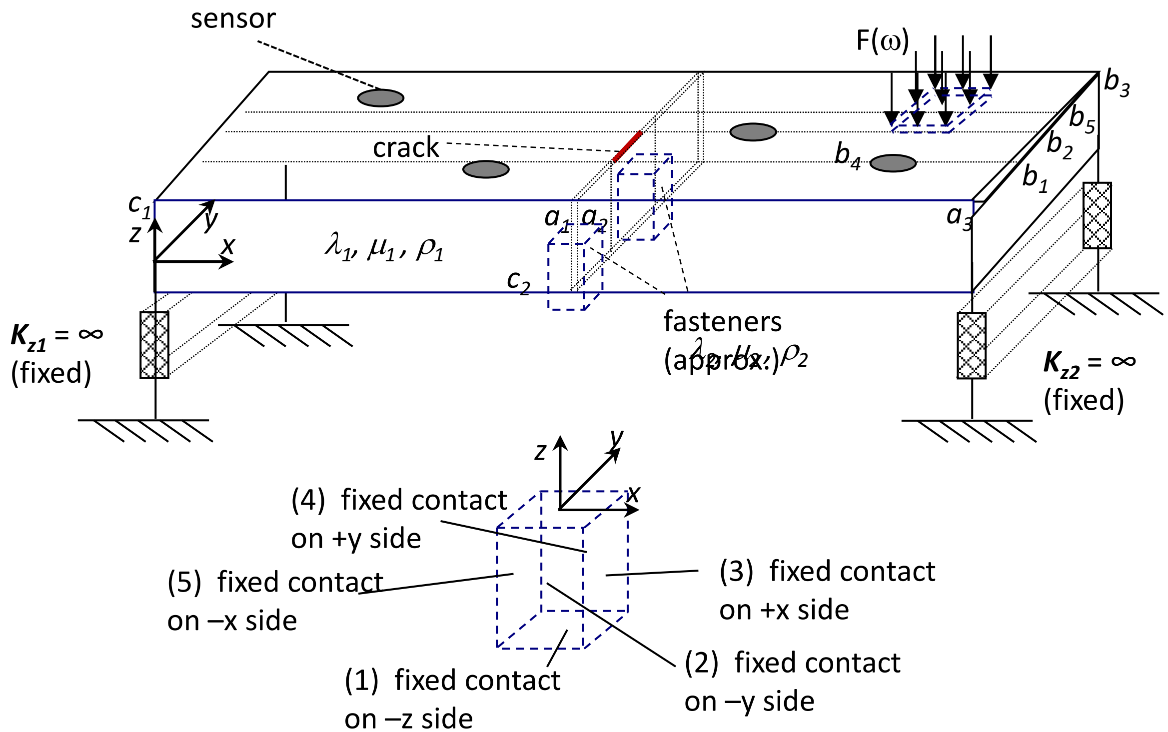
<u>**Damage Characteristics:**</u>

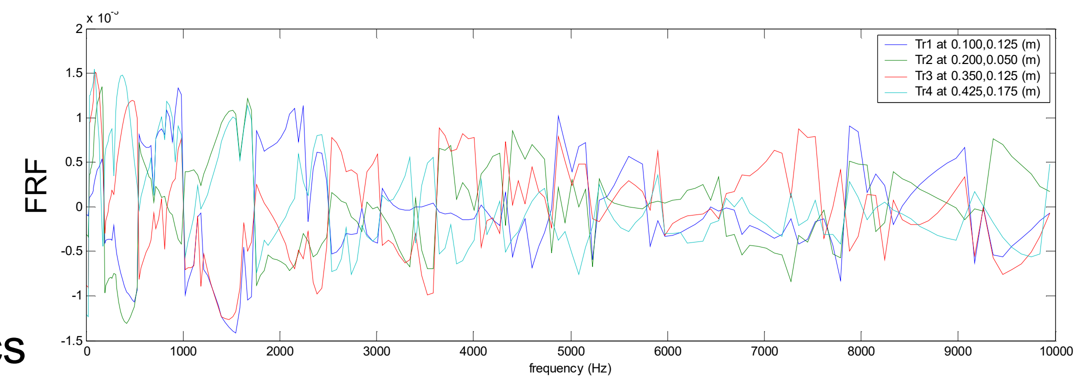
- **Damage Types (Failure Conditions) to Detect:** **(Large) fatigue cracks**
  - **Approximate crack growth by cutting notches**
  - **Fastener removal necessary for growing flaw** ***(must maintain equal torque, verify damage metric change not due to changes in boundary conditions)***

# Simulated Sensitivity Analysis for Representative Low Frequency Global Vibration-based Damage Sensing

**Parametric Study**

- Frequency
- Source Excitation
  - location
  - orientation
  - distribution
- Sensor(s)
  - location
  - orientation
  - measurements
- Crack (notch) length
- Temperature (elastic property variation)
- Boundary conditions
  - Fastener stiffness
  - Fastener contact
  - End stiffness
- Detection algorithms / metrics
- Characterization algorithms / metrics



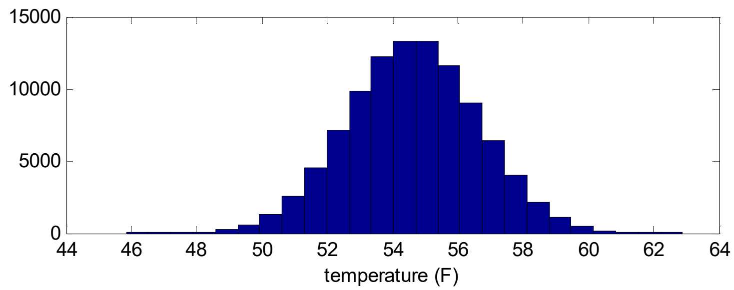



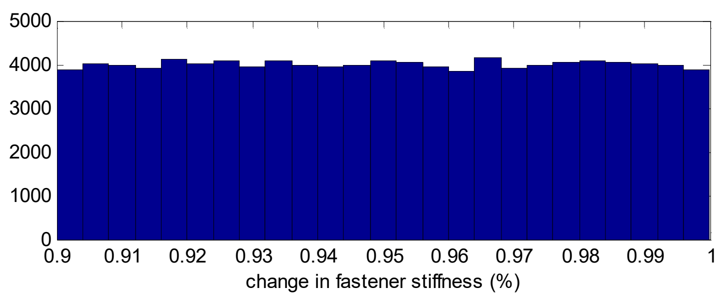
# Simulated Sensitivity Analysis for Representative Low Frequency Global Vibration-based Damage Sensing

## Determine Output Variance on Damage Measures (POD) Given Uncontrolled Environmental Variables and Uncertainty

### Input Parameters with Variation

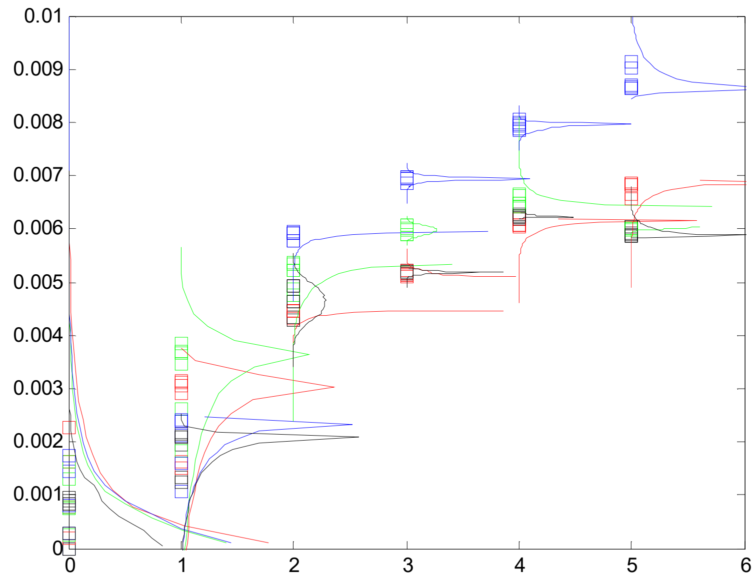
- Temperature : (elastic property variation)
- Boundary condition: Fastener stiffness

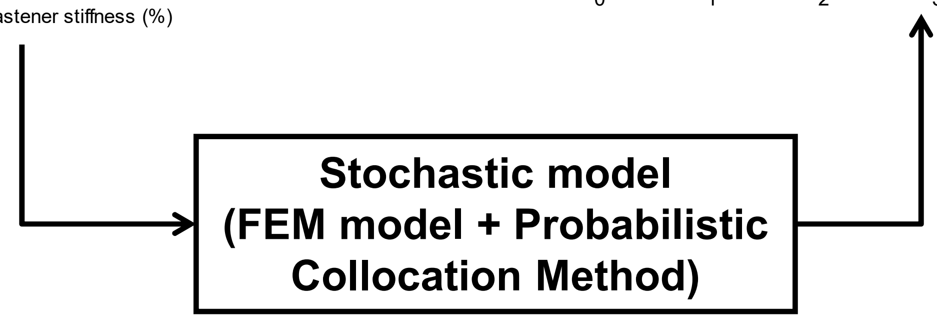



### Output Results

- Damage metric 'distributions' as a function of transducer location and crack length



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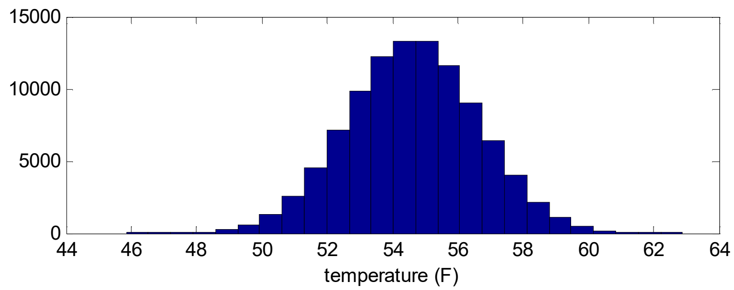
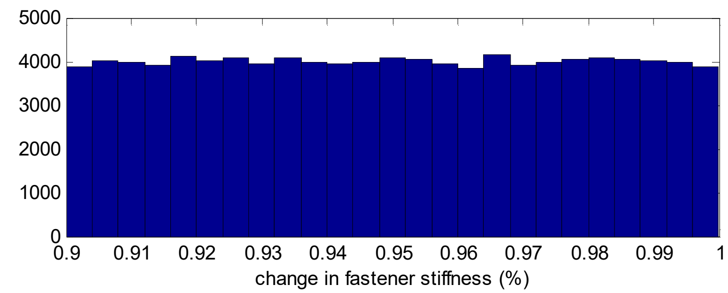
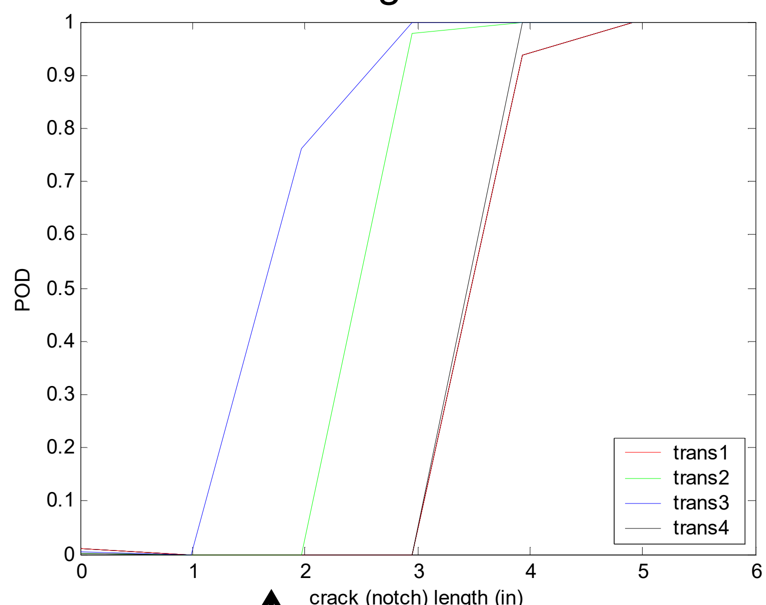


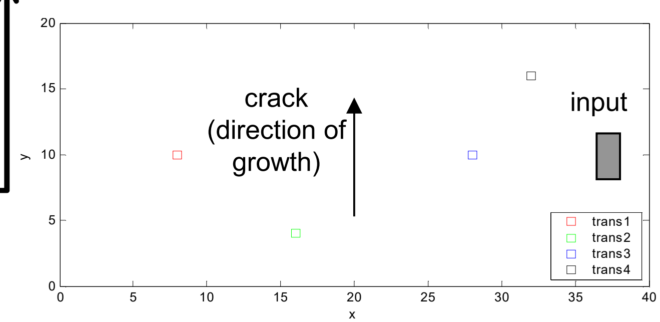




**Stochastic model (FEM model + Probabilistic Collocation Method)**

### Output Results

- POD for varying transducer location and crack length



# Demonstration Study – Identify and Evaluate Controlling Factors

**Primary Protocol**

- Define SHM Application
- Identify and Evaluate Controlling Factors
- Design Multistage Validation Study
- Perform Multistage Validation Study
- Process Data for SHM Reliability Assessment
- Economic and Probabilistic Risk Assessment

**Sub-tasks**

Evaluate **Potential Contributing Factors** (Part, Environment, Loading, SHM system)

Is **Variability** (Range) and **Uncertainty** (Confidence Bounds) of Factor Known?

Can **Influence** of the Factor be Evaluated Using Simulated and/or Experimentation?

**Approaches**

- Prior work
- Elicit expert opinion
- Baseline experiments
- Designed experiments
- Simulated studies
- Inverse methods

**Assess SHM System Sensitivity to Following Factors:**

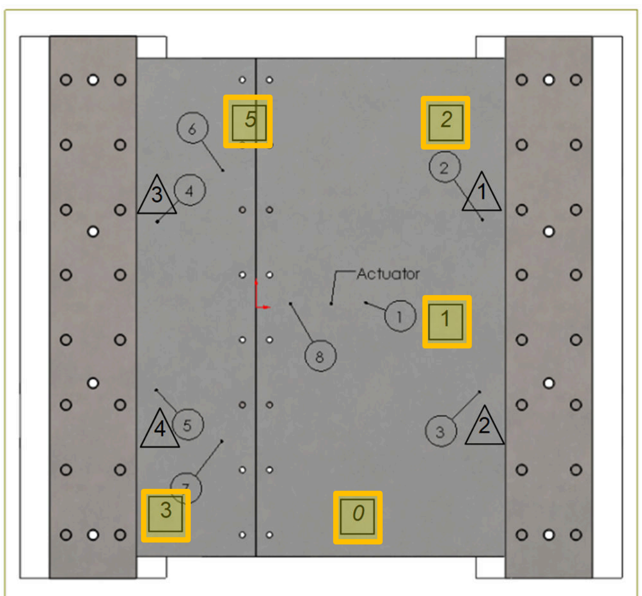
A. Loading and Unloading
B. Fastener Torque
C. End Condition Variation (Stress)
D. Temperature Variation and Temperature Gradients
E. Bond Quality and Sensor Performance
F. Ambient Noise (from Test Chamber on / off)
G. Sensitivity to Flaw Growth

# Evaluate Controlling Factors – Temperature Variation and Gradients

**Temperature Study:** Test article placed in Thermotron temperature chamber

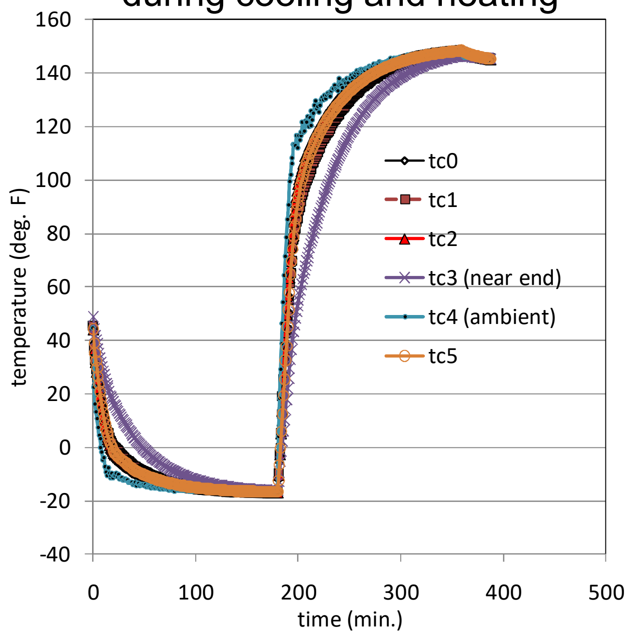
- Temperature testing performed from -20°F to 150°F
- Temperature compensation algorithms are necessary for damage metric
- Significant temperature gradients also observed during study
  - Some gradients considered extreme (>45°F) due to end ‘ thermal sinks’
  - Need to make estimate of expected gradients ‘in the field’ (10-20°F ?)

Thermocouple locations

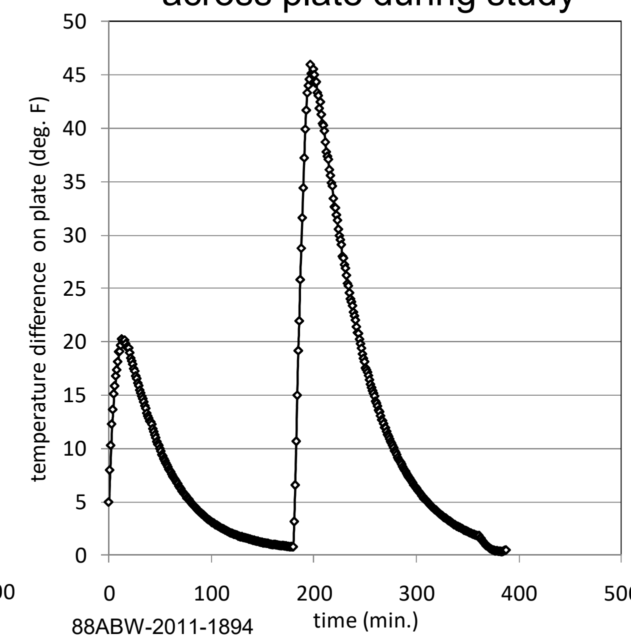



4 (in air on top side)

Temperature response on plate during cooling and heating




Peak temperature difference across plate during study

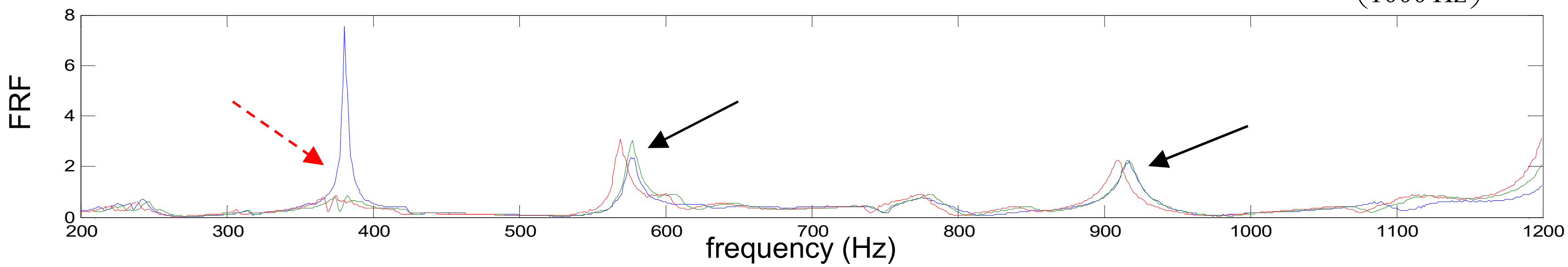



88ABW-2011-1894

# Temperature Compensation Algorithm

**Issue 1:** Varying shift wrt frequency in FRFs with temperature changes

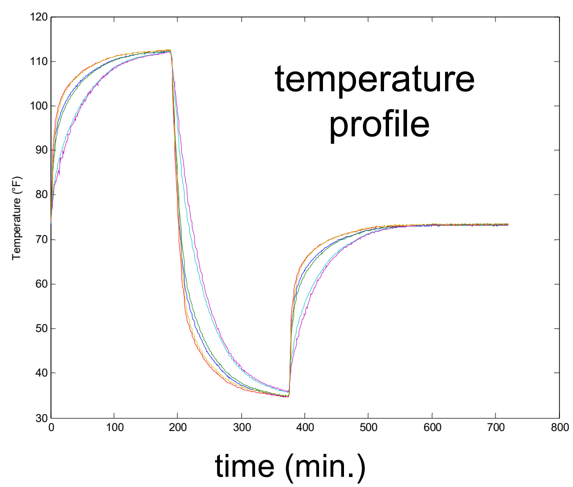
➢ ***Fit nonlinear model*** with bias and slope corrections: $f_{new}(f) = f + \left(\frac{\phi_1}{1000\text{ Hz}}\right) f + \phi_0$

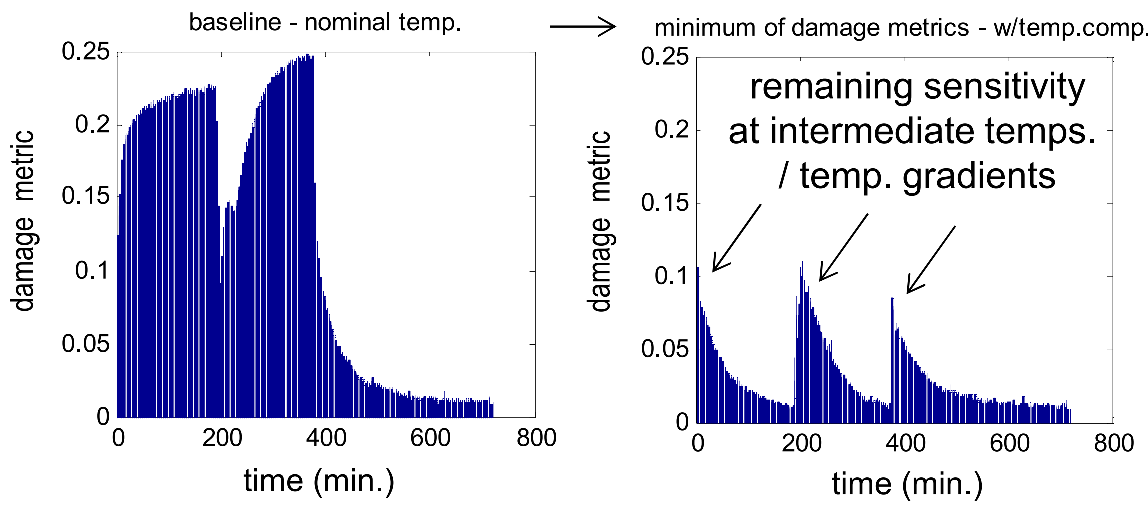



**Issue 2:** Temperature variation also produces shape changes in FRFs

➢ ***Use three references*** (FRFs) addressing different temperature bands

**Study:** Vary Temperature - Up to 112°F, Down to 32°F, Return to 75°F

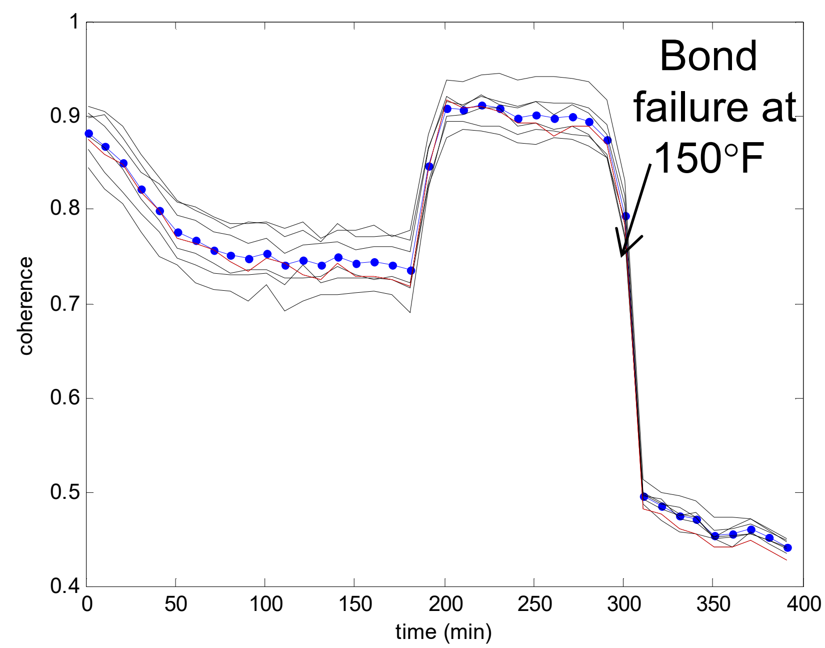


# Evaluate Controlling Factors – Bond Quality and Sensor Performance

**Observations:**

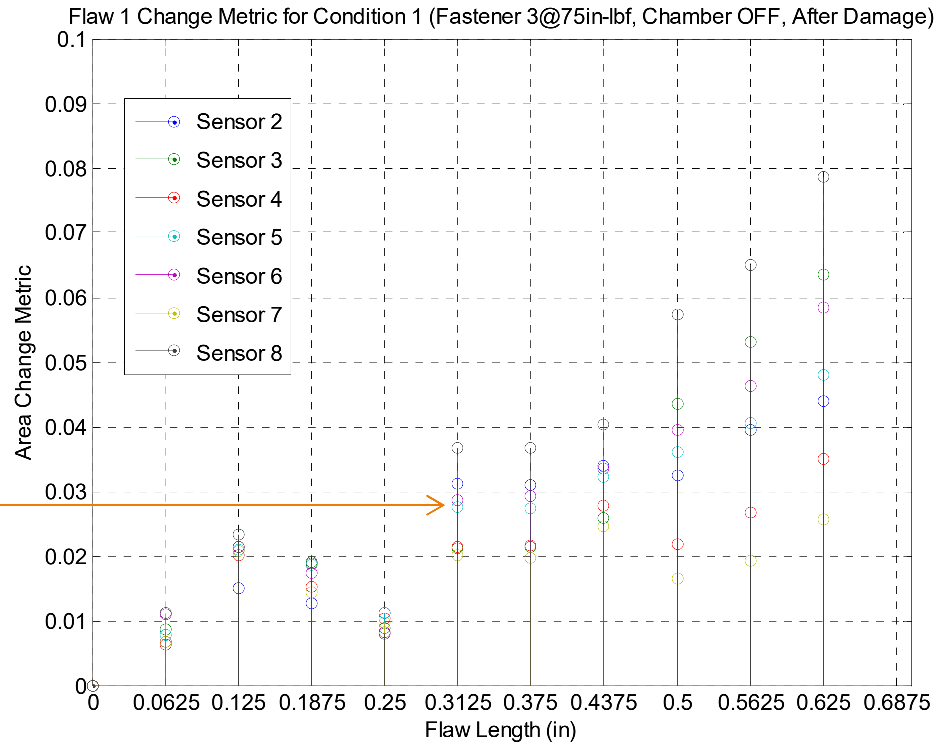
- Several accelerometer bonds failed during temperature testing
- Failure was observed at prolonged exposure to 150°F
- Coherence measures can be used to track sensor failure (example below)
  - Differences were observed with sensor ‘in partial contact’ and ‘in air’
- One of the sensor failures was the reference accelerometer (#1)
- *Losing the reference sensor is especially detrimental to performance of vibration-based SDS system (FRF)*
- SHM computer algorithms need to detect failures and schedule repairs
- Validation studies should include bond failure and repair as varying condition



# Evaluate Controlling Factors – Sensitivity to Damage

**Observations:**

- Damage grown at 1/16" increments up to 0.688" at only one site to verify sensitivity (thin saw blades provided by NIAR)
- Simulated flaw growth (SFG) attempted to mimic forcing of plate structure without creating damage – *no significant effect on damage metric*
- Sensitivity observed to certain notch increases, but trend not linear
  - sensitive to first notch cut
  - significant drop after fastener installed and removed (FIR)
  - Metric grows with larger notches
- *Jump observed after two week delay in testing – 'still in noise'*
- Larger cuts will be applied for validation studies



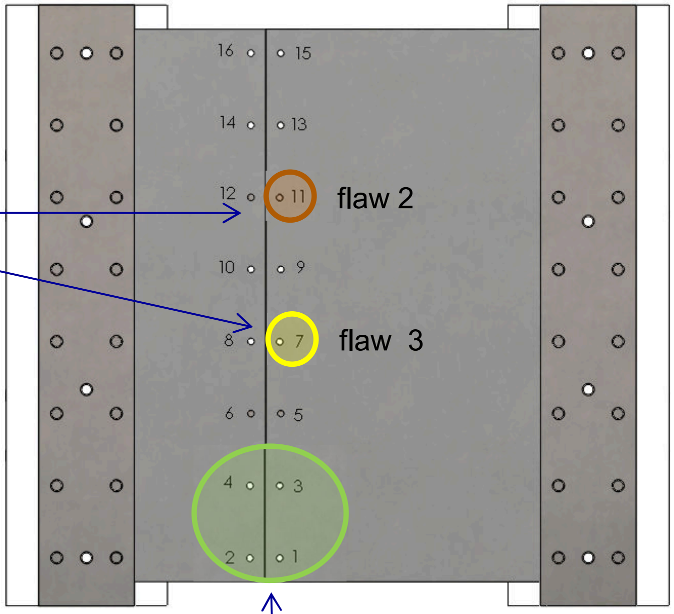
# Design of Validation Study

**Demonstration Study: Focused on Single Stage**

- Phase II – Laboratory Testing of Relevant Structures / Environment
- Assumption: Key SDS Factors can be Demonstrated in Single Study

**Factors in Study:**

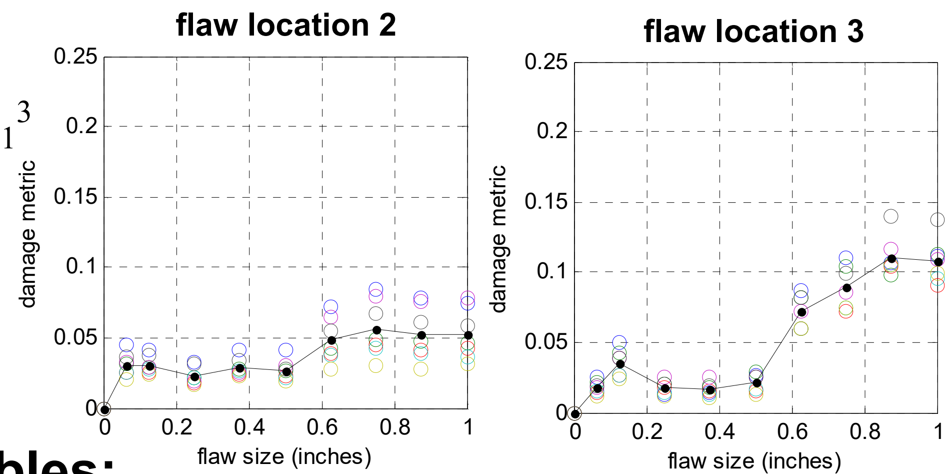
- Flaw growth (notch):
  - First cut: 0.063", Second to 0.125", repeat 0.125" cuts to 1.00" (10 levels)
  - At two fastener locations with relief notches
- Environmental conditions: (ambient 72°F)
  - Temperature variation (32°F to 112°F)
  - Temperature gradients (<10°F)
  - Ambient noise (chamber on / off)
- Boundary conditions:
  - Loading / unloading mass on structure (10 lb)
  - Fastener removal and reinstall (75 in-lbs +/- 10 in-lbs) – 'simulate maintenance'
- Sensor conditions: Evaluate accelerometer bond reinstallation (ref., second)



# Measurement / POD Model

## 1) Model Flaw Length and Location:

- **Length:** $dm = \beta_0 + \beta_1 * a_1 + \beta_2 * a_1^2 + \beta_3 * a_1^3$
- **Sensitivity to location must be addressed in model** [Compare *combined and separate* measurement model fits]




## 2) Model for Secondary (Envir.) Variables:

- Normalized mean temperature ($a_3$), and absolute value $|a_3|$
- Normalized temperature gradients ($a_4$),
- Abs. difference between temp. and nearest reference ($a_5$)
- Ambient noise level ($a_6$),

**Include in measurement model / regression fit (ANOVA)**

## 3) Model Impact of *Random* Conditions (Change from Before vs. After):

- *Sensor failure**
- Sensor bond degradation
- Sensor replacement
- Minor fastener loosening
- Local maintenance action (fasteners uninstall/install)
- Added mass
- Structure load / unloading

**Perform separate statistical tests for significance**

# Measurement / POD Model

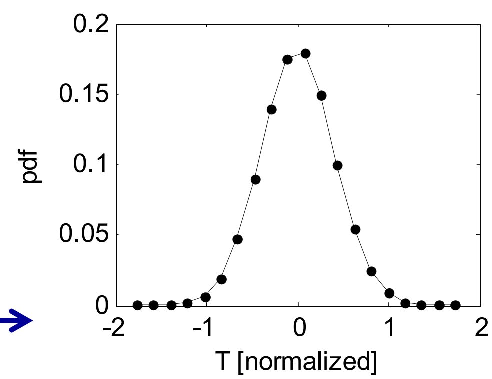
**Input Parameters Types**:

- Controlled Parameters, $a_j$ ($N_j$)
  - Flaw size
  - Flaw location
  - Temperature Conditions
  - Ambient noise
- Uncontrolled Parameters, $a_k$ ($N_k$)
  - Boundary conditions
  - Flaw morphology

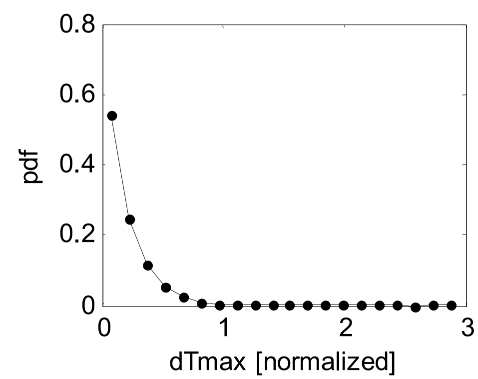
**Input Parameter Characteristics**:

- Expected Variation Represented as a *Distributions* (ex. *Gaussian*, Uniform, Gamma, Beta)
- *Uncertainty in Distribution Parameters (Not Addressed)*

**Level 1. Input Parameter Variability**




**Temperature (normalized)**




**Temperature Gradients (normalized, 10°F)**

**Input Parameters** → **Measurement 'Model'** → **Call Criteria** → **POD Model**

# Measurement / POD Model

## Fit Measurement ‘Model’ *(Using Empirical Data)*

- **Flaw length** ($a_1$): $dm = \beta_0 + \beta_1 * a_1 + \beta_2 * a_1^2 + \beta_3 * a_1^3$
- **Flaw location** ($a_2$)
  - Evaluate both ‘*combined*’ *and* ‘*separate*’ *flaw location scenarios* fits
- Normalized mean **temperature** ($a_3$), and absolute value $|a_3|$
- Normalized **temperature gradients** ($a_4$),
- Abs. **difference between temp. and nearest reference** ($a_5$)
- **Ambient noise** level ($a_6$),
- **Sensor status** (active, failed)

**Level 2: Uncertainty in Model Parameter Estimate**

### Regression Analysis Example (R)

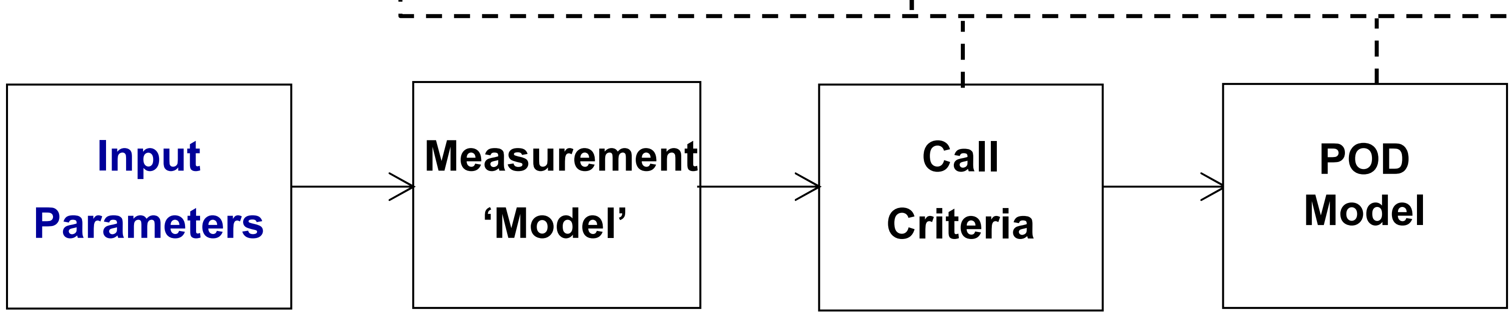
| | |
|---|---|
| Code: | `data.tmp <- read.csv('analy_ref1_flaw3.csv',header=FALSE)`<br>`x1 <- data.tmp$V1`<br>`x2 <- data.tmp$V2`<br>`x3 <- data.tmp$V3`<br>`x4 <- data.tmp$V4`<br>`x5 <- data.tmp$V5`<br>`x6 <- data.tmp$V6`<br>`x11 <- x1*x1`<br>`x111 <- x1*x11`<br>`y1 <- data.tmp$V14`<br>`frame1 <- data.frame(y=y1, x1=x1, x2=x2, x3=x3, x4=x4, x5=x5, x6=x6, x7 = x11, x8 = x111)`<br>`y.vs.x<- lm(formula = y ~ x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8, data=frame1)`<br>`summary(y.vs.x)` |
| Call: | `lm(formula = y ~ x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8, data = frame1)` |
| Residuals: | Min 1Q Median 3Q Max<br>-0.035835 -0.007133 0.001119 0.006437 0.026368 |
| Coefficients: | Estimate Std. Error t value Pr(>\|t\|)<br>(Intercept) 0.018921 0.003902 4.849 6.8e-06 ***<br>x1 -0.081361 0.041766 -1.948 0.05526 .<br>x2 -0.003323 0.003465 -0.959 0.34072<br>x3 0.010309 0.003690 2.794 0.00665 **<br>x4 -0.009321 0.005813 -1.603 0.11315<br>x5 0.032816 0.010755 3.051 0.00318 **<br>x6 0.005763 0.013645 0.422 0.67402<br>x7 0.373822 0.109798 3.405 0.00108 **<br>x8 -0.205131 0.072407 -2.833 0.00596 **<br>---<br>Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 |
| Diagnostics: | Residual standard error: 0.01303 on 73 degrees of freedom<br>Multiple R-squared: 0.9133, Adjusted R-squared: 0.9037<br>F-statistic: 96.07 on 8 and 73 DF, p-value: < 2.2e-16 |
| Significant Factors: | • `x1 <- data.tmp$V1`: Flaw size ($a_1$) (Part of flaw size model)<br>• `x3 <- data.tmp$V3`: Normalized mean temperature ($a_3$)<br>• `x5 <- data.tmp$V5`: Normalized temperature gradients ($a_4$),<br>• `x7 <- x11 <- x1*x1` Flaw size model term: $(a_1)^2$<br>• `x8 <- x111 <- x1*x11` Flaw size model term: $(a_1)^3$ |

**Input Parameters** → **Measurement ‘Model’** → **Call Criteria** → **POD Model**

# Measurement / POD Model

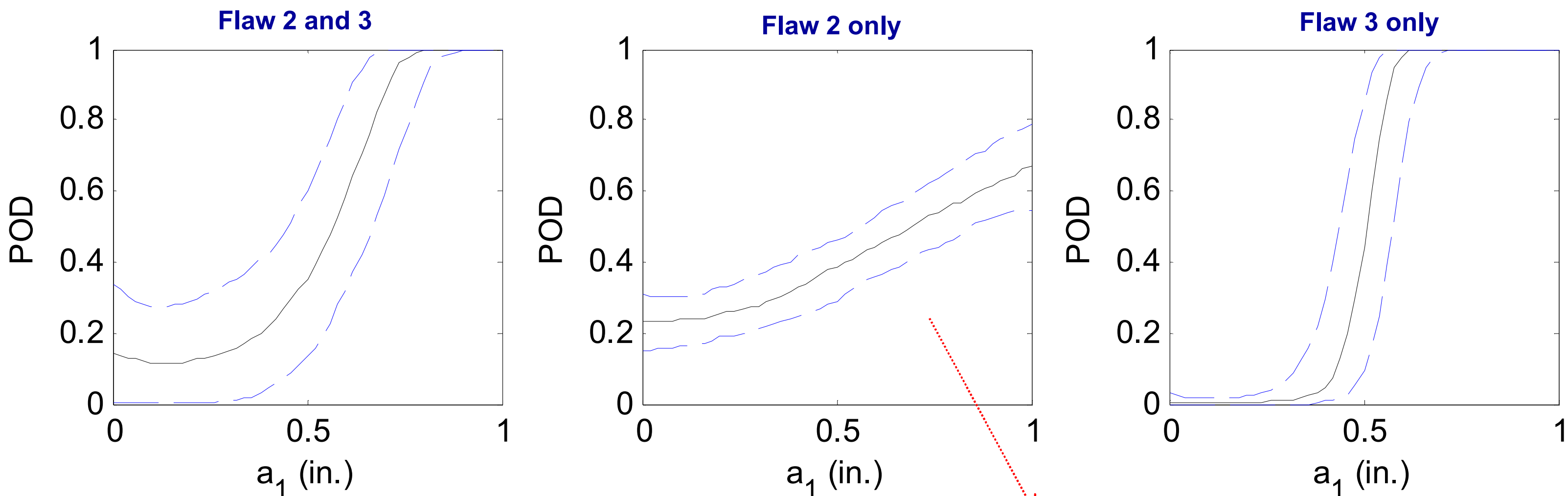
**POD Evaluation Process:**

- Apply threshold for call criteria ($dm$ > 0.06)
- Use second order probability analysis
  - Use two-level Monte Carlo simulation
    - Sample from Input Parameter Distributions (Level 1)
    - Perform Measurement Model Evaluation and Estimate Single POD Curve
  - Repeat Evaluation for Different Samples due to Uncertainty in Model Parameters (Level 2)
- Obtain 'Set' of POD Curves (*Uncertainty / Credibility* Bounds on POD Curve)
- Probability of False Call corresponds with POD curve result at $a_1$ = 0.



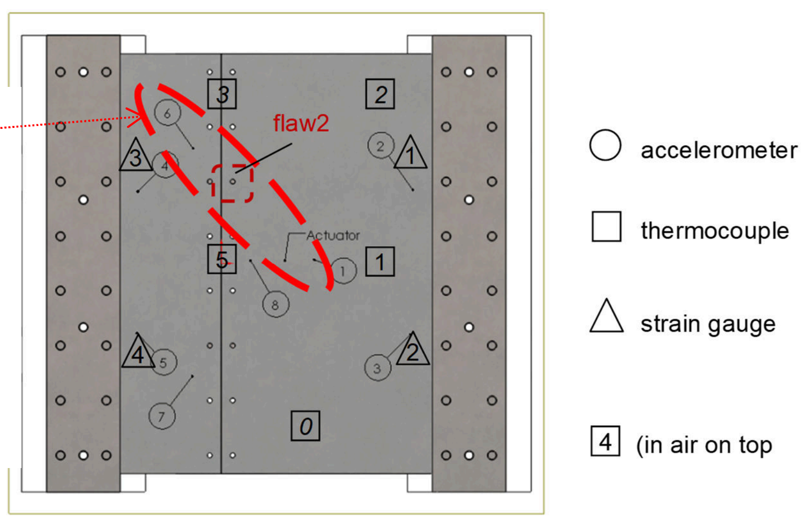
# POD Results – Sensitivity to Flaw Location

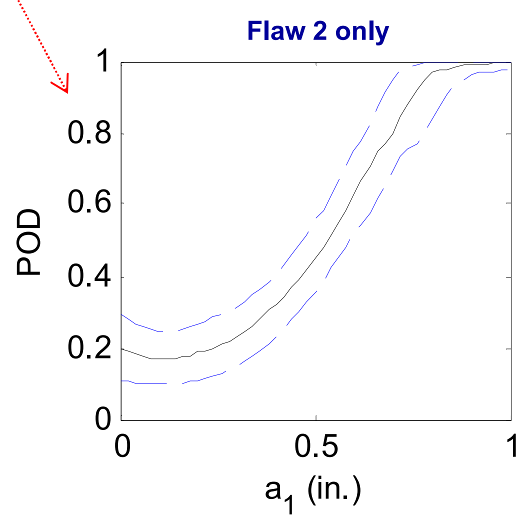
## POD Results: Dependency on Flaw Location




## Can Improve POD by Choosing *Optimal Sensor Configuration*:

Only use damage metric for accelerometer #6 (with reference #1)

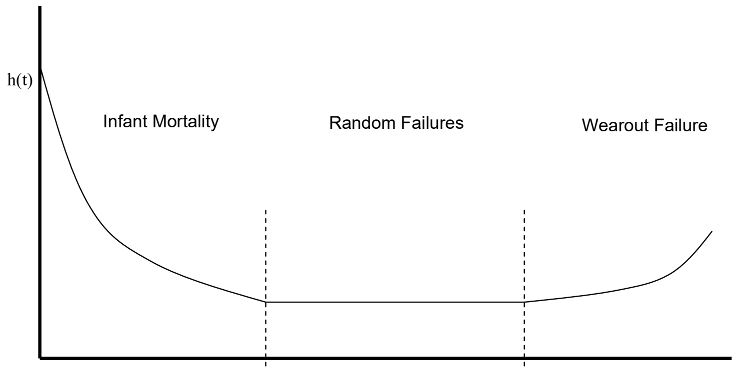


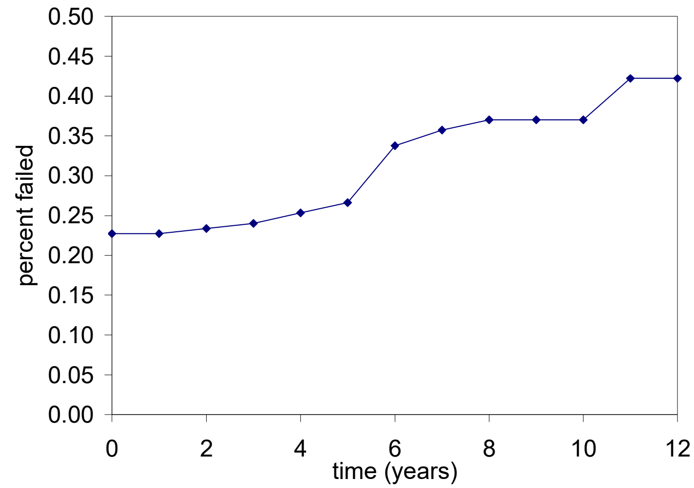



# POD Results – Impact of Sensor Durability

**POD Evaluation Must Address Known Sensor Durability Issues:**

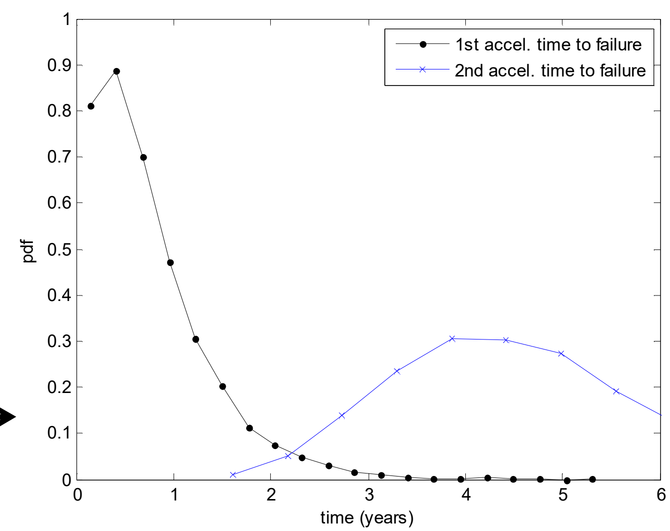
- **Issue demonstrated by percent of C–17 in-service strain gauge failures as a function of time** [Ware et al]
- **Bathtub Curve Model** [Meeker and Escobar]




**Evaluation of Impact of Sensor Failure:**

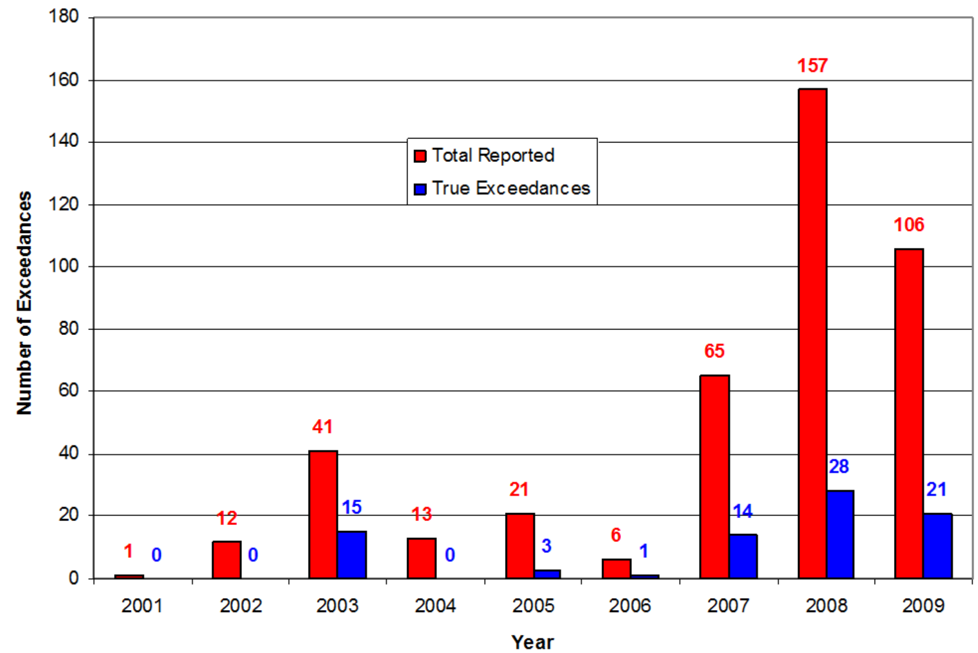
- **Evaluate changes in POD due to random sensor failure over time**
- **Explore failure of two sensors (25%) over first six years of service life**
- **Distributions of Time to Failure Considered in Evaluation**



# Consequence of SHM False Calls-
# KC-130J Exceedances

## Monitoring system:

- Sensors: Fuel Quality, Accelerometers, Differential Pressure, Discrete, Position
- 25 Parameters Measured




## Consequence of Indication

- All reported KC-130J exceedances require engineering disposition due tc
- Squadron sends SHM download files
- *Aircraft Structural Life Surveillance engineers* assess data/provide recommendation to Fleet Support Team (FST) *[engineering costs]*
- *FCs result in unnecessary inspections, affect aircraft availability*

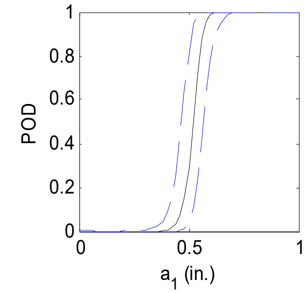
* Lindgren and Walbusser, "Experience/Lessons Learned using Flight Parameter Sensors on US Department of Navy C-130 Aircraft", Aircraft Airworthiness and Sustainment, (Austin, TX, 2010).

# POD Results – Impact of Sensor Durability

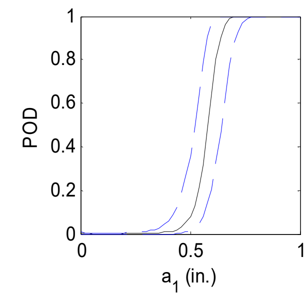
- **Sensor Scenarios with Corresponding Changes in POD and False Call Rate:**

**Scenarios Addressing Sensor Failure**

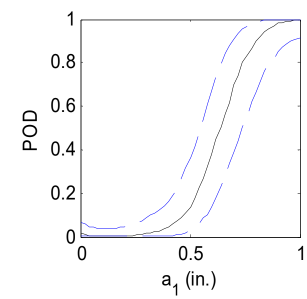
**Approach 1: (Best Sensitivity)**
- Use accel. #1 as reference
- Use accel. #6 as source



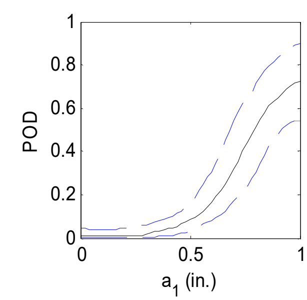

**Approach 2: (Accel.#6 Failure)**
- Use accel. #1 as reference
- Use median of active sensors




**Approach 3: (Accel.#1 Failure)**
- Use accel. #8 as reference
- Use median of active sensors




**Approach 4: (Accel.#8 Failure)**
- Use accel. #3 as reference
- Use median of active sensors

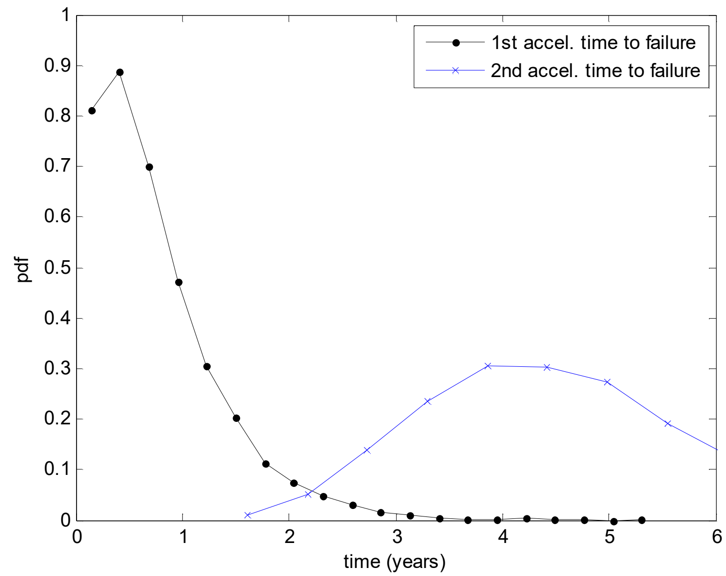


# POD Results – Impact of Sensor Durability

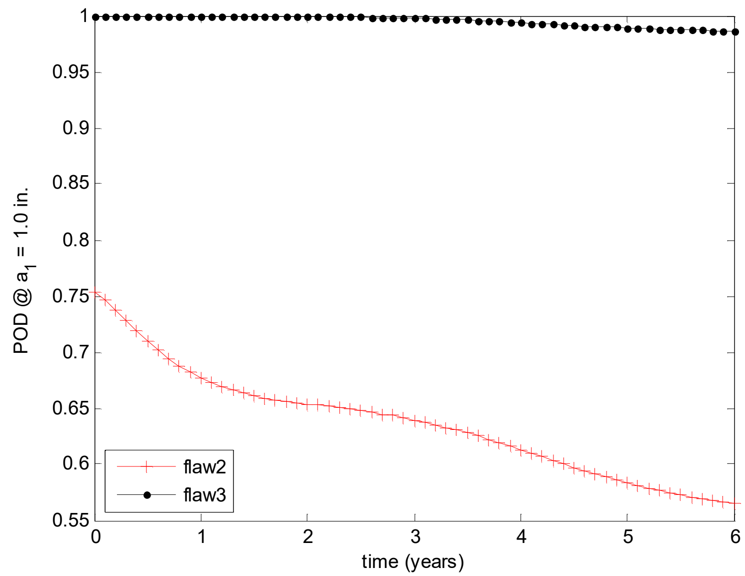
**Evaluation of Impact of Sensor Failure:**

- **Evaluate changes in POD due to random sensor failures over time**
- **Distributions of Time to Failure Considered in Evaluation**

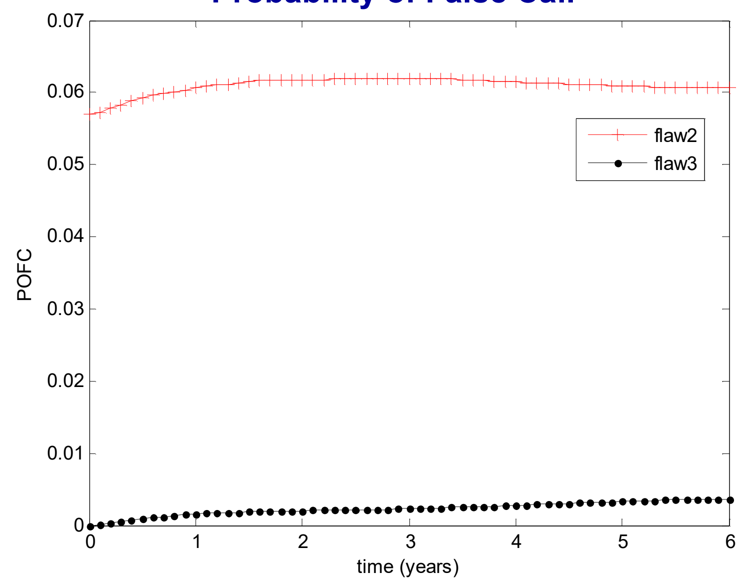
***Results:* *Mean* expected POD and POFC at a flaw size of 1.0 in *as a function of time***




**Probability of Detection**




**Probability of False Call**



# Summary of 'Best Practices' for NDE / SHM Characterization

- Characterization error analysis should follow standard practice for POD evaluation [e.g. **MIL-HDBK 1823A**]
  - **Must understand implicit statistical assumptions in regression analysis [Annis et al., 2015]**
  - **If assumptions are not met, *pick a different 'correct' model!***
- **Protocol presented for SHM capability evaluation**
  - **Thorough factor evaluation is critical for proper assessment [*environment, varying structure, sensor and damage state]***
- **Demonstrated 'need' for representative models in SHM capability evaluation** [empirical and/or numerical]
  - ***Certain flaw locations will require separate POD models*** **[global SHM]**
  - ***Feasible to evaluate impact of sensor failures on performance***
  - **Must address varying conditions and *model uncertainty (error)***

# Acknowledgements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  - Contract with Radiance Technologies, Inc., Contract Number: FA8650-09-C-5204
  - Research Initiatives for Materials State Sensing (RIMMS), Numerical and Computational Methods for Nondestructive Evaluation, (Contract: FA8650-10-D-5210, Independent Contractor Agreement 11-S7103-01-C1)