Probability of Detection Assessment for a Guided Wave Structural Health Monitoring System

Seth S. Kessler, Ph.D. | Gregory Jarmer, Ph.D.

1 September 2015 | Metis Design Corporation

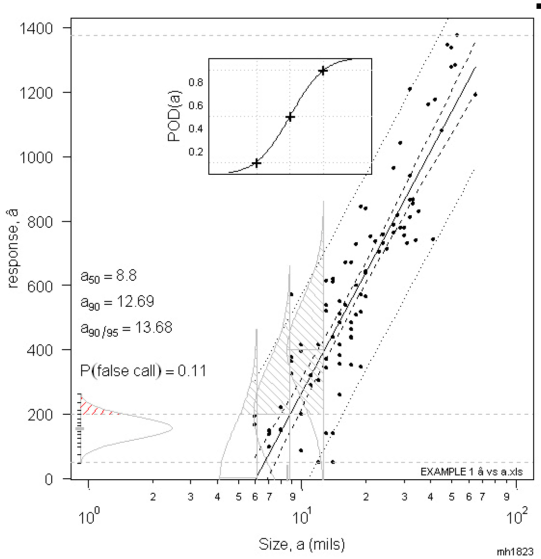
metis design

structural health monitoring
multi-functional materials
lean enterprise solutions

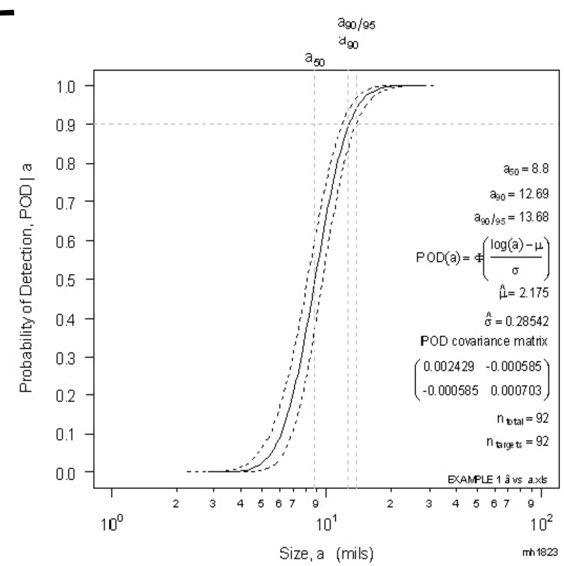
205 Portland St • Boston, MA 02114 • 617.447.2172 • http://www.metisdesign.com

Damage Tolerant Design & Probability of Detection

- Damage tolerant approach common for DoD/commercial design
  - ➢ Requires definition of minimum detectable flaw size
  - ➢ Requires inspection interval set to find minimum flaw with safety factor
- $a_{90/95}$ is flaw size found 90% of the time with 95% confidence
  - ➢ MIL-HDBK 1823A establishes guidelines for NDE reliability assessment
  - ➢ Probability of Detection (PoD) method presented to determine $a_{90/95}$



Experimental Data



PoD Curve

PoD for Structural Health Monitoring

- Desire to establish accepted approach to capture PoD for SHM
  - Based on MIL-HDBK-1823A as written, not historical implementations
  - Accommodate SHM while maintaining overall reliability standards
  - Exploit models & advanced statistical approaches to minimize specimens

- SHM methods differ from NDE methods
  - SHM sensors are generally integrated into a structure permanently
  - SHM monitors an area, not a point: PoD a function of distance/orientation
  - Sources of variability: inspectors & placement vs bonding & temperature

- Close examination of why $a_{90/95}$ is the traditional benchmark
  - Allows for high reliability with maximum inspection interval
  - Designed to maximize availability, minimize tear-down/inspection costs
  - SHM allows for repeated inspection at no cost, can $a_{xx/95}$ be used instead?
  - Independence/dependence of inspections will be the deciding factor

PoD Experiment Design

- Aerospace structures have many sources of variability
  - Uncertainty in response due to damage
    - Fatigue crack(s) size and orientation
  - Uncertainty in response due to geometry
    - Change in contact condition at joints
    - Propagation paths can change in thickness
    - Bolt and fastener torque at connections

    Boundary Conditions
  - Uncertainty in response due to operational environment
    - Strain condition (payload), temperature, humidity (absorption in composite)
  - Uncertainty in response due to sensor bond line degradation
- Group sources of variability
  - Pre-Test Variables: Manufacturing and preparation of specimen
  - Test Variables: Geometry and operational environment
- Isolate effect of variables through controlled building-block

Pre-Test Variables

- Variation due to manufacturing & preparation of specimen

Variable	Operation Range	Control Method	Effect
Part Fabrication	± 0.005″	Machining tolerance	Random
(LxWxH) Dimension	±0.005″	-	-
Starter Notch	±0.005″	-	-
Bonding of Array	-	Installation Jig	Random
Transducer Response (D31)	±30%	Random Selection From Lot	-
Position	±0.05″	Bonding Jig	-
Adhesive Bond Line	±0.001″	Impedance Tests	Random

- Variables explored before specimens are mechanically fatigued
- Adhesive bondline is anticipated as most important variable
  - ➢ Installation kit to minimize variability (tool + triggerbond + 2-part epoxy)

Test Variables

- Variation due to geometry & operational environment

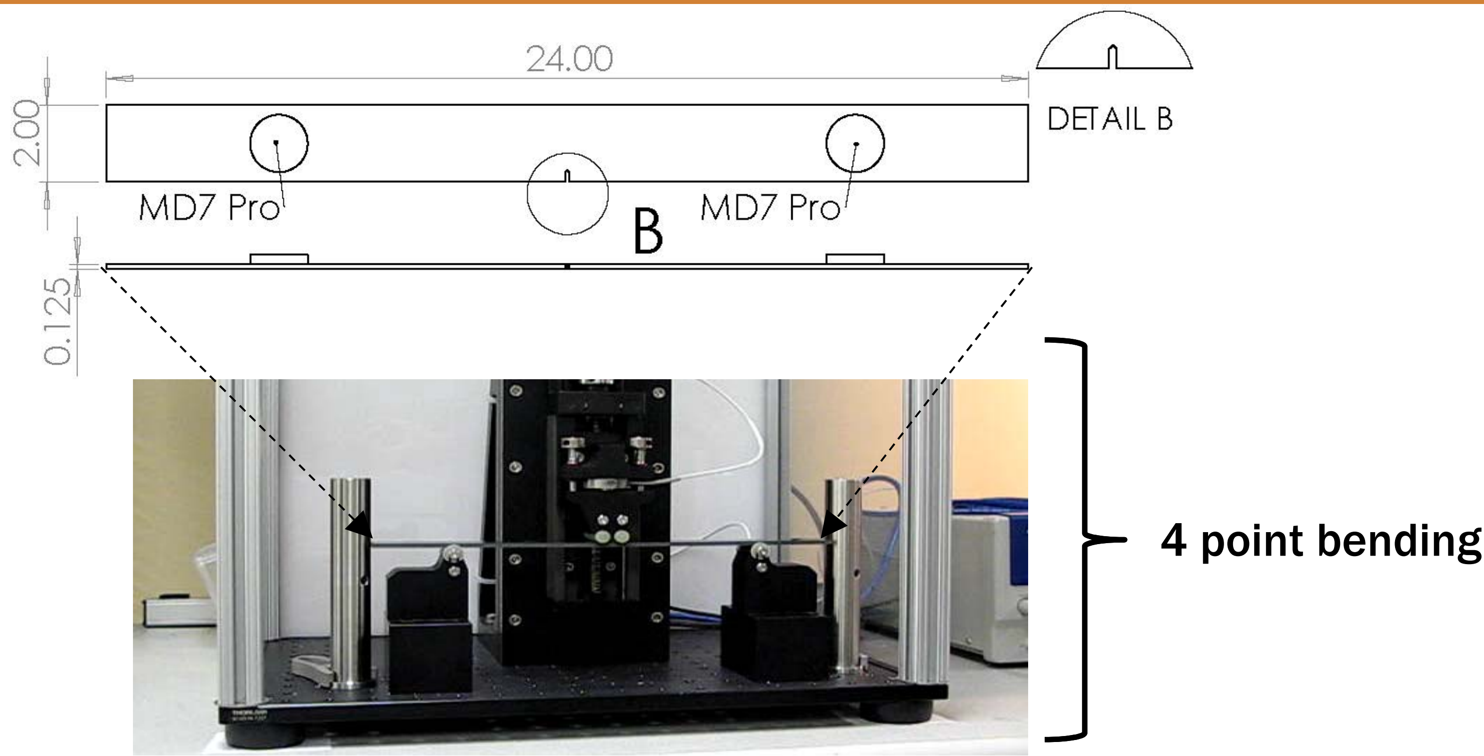
Variable	Operation Range	Control Method
Temperature	32^oF to 100^oF	Environmental Chamber
Subset #1	80^oF	-
Subset #2	85^oF	-
Subset #N	TBD^oF	-
Humidity	Absolute scale	Environmental Chamber
Crack Size	0.015 to 0.22 inches	4 Point Bending
13 Test Specimens	-	Digital Image
Strain State	Weight on Wheels	Unload/Constant
Boundary Conditions	NA	Simply Supported
SNR Calibration	-	DAQ Setting
Frequency	10-500 kHz	-
Interval	TBD	-
Number of Averages	2^x = 256,512,1024	-
ADC Gain	10,20,50	-
Inspection Process		DAQ Setting
Continuous and at each crack size interval	During Fatigue and at set crack sizes	-

- Operating range for inspection is representative
  - Propose stain condition: Weight on wheels
  - Propose temperature range: 32 to 100^oF
    - Test values limited by available environmental chamber

Outside of this regime do not inspect for damage

metis design

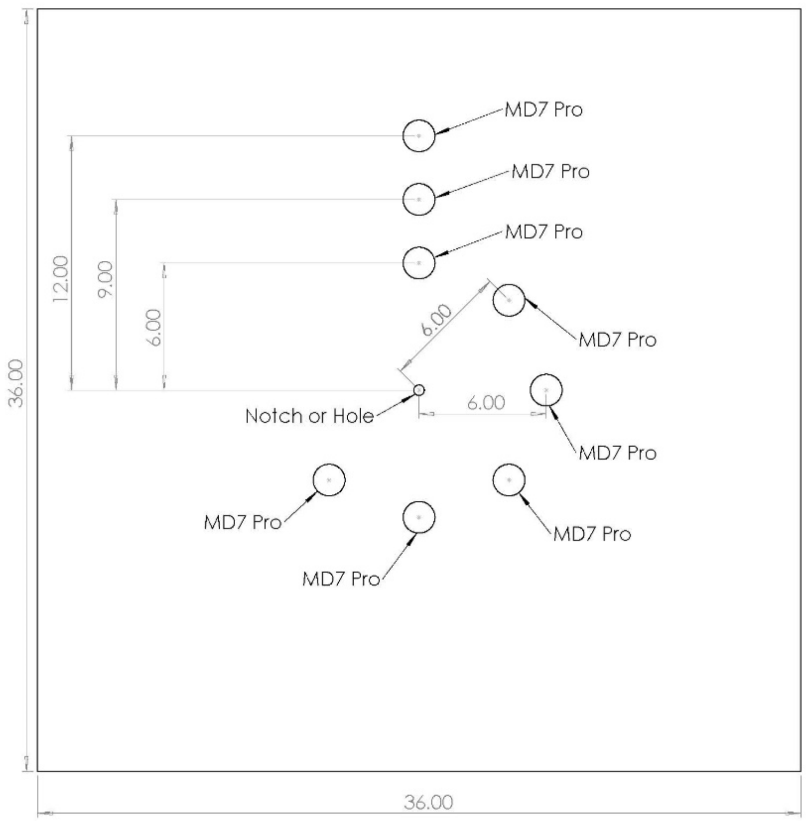
Sub-Specimen #1: 4-Point Bend Test



- Objective: Characterize sensor variability & wave mode scattering
  - Sensor bonded on each end for pitch-catch (PC) & pulse-echo (PE)
  - Can control operational environment with reasonable tolerances
  - Experience controlling fatigue crack growth in bending from edge notch

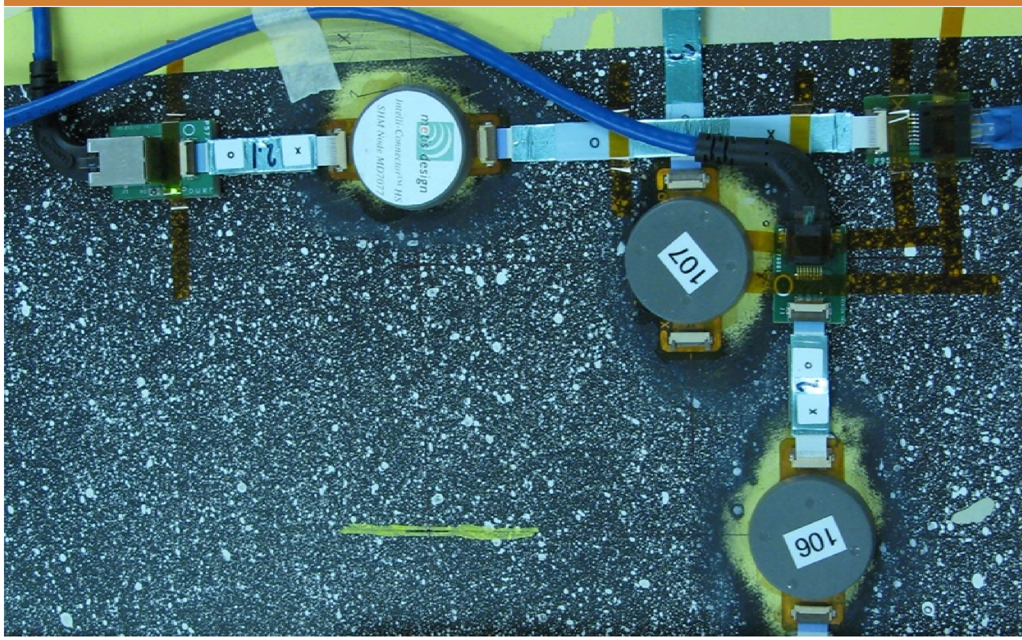
Sub-Specimen #2: Attenuation & Scattering

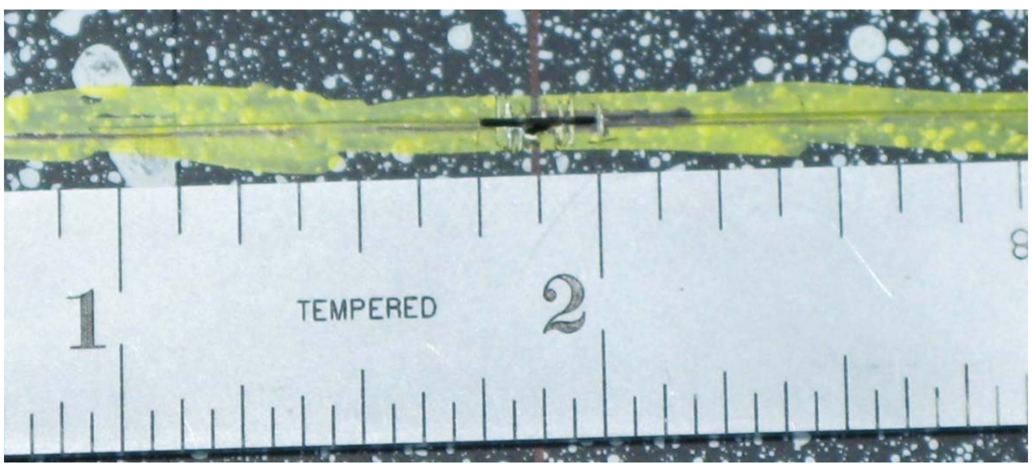
- Objective: Characterize attenuation & scattering from defect
  - ➢ Measure scattering from 0^o, 45^o, $90\ ^o$, 225^o, 270^o, 315^o with radius = 6”
  - ➢ Measure attenuation from at 6”, 9” & 12”
  - ➢ Expect to repeat test 3 times under 3 temperature conditions



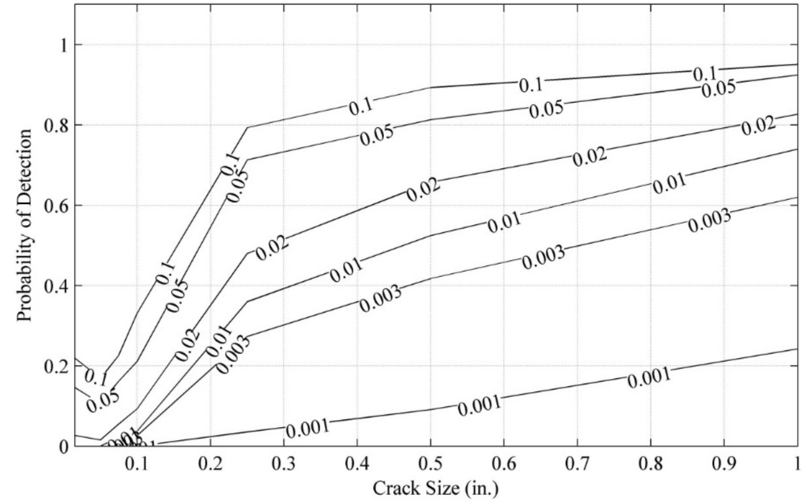
metis design

Course PoD of Al/Honeycomb Panel with Notch

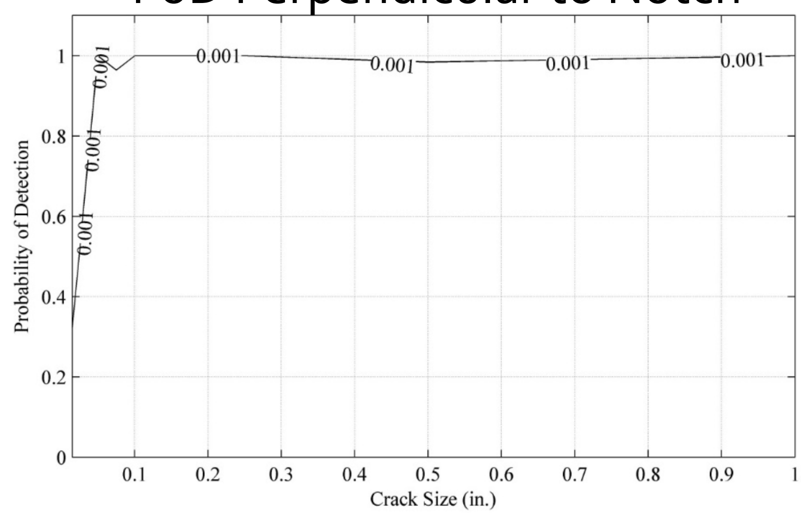




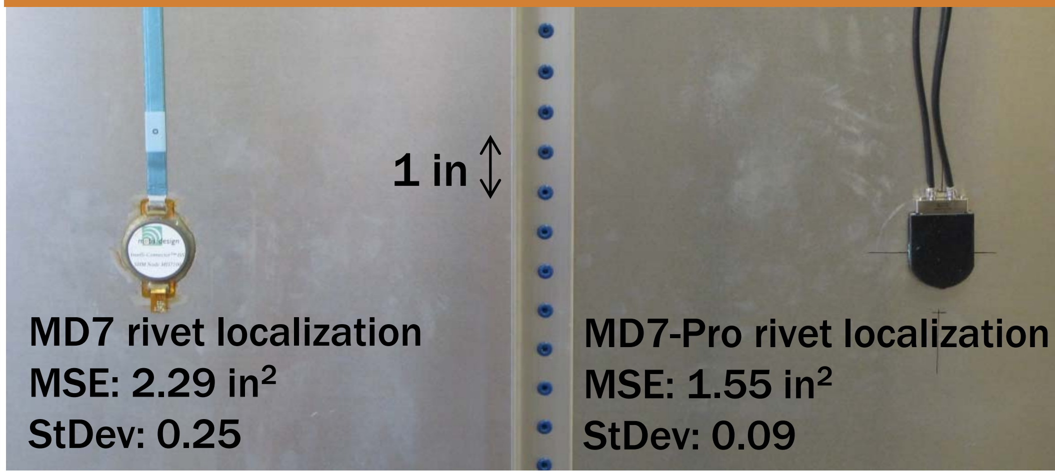
PoD Parallel to Notch

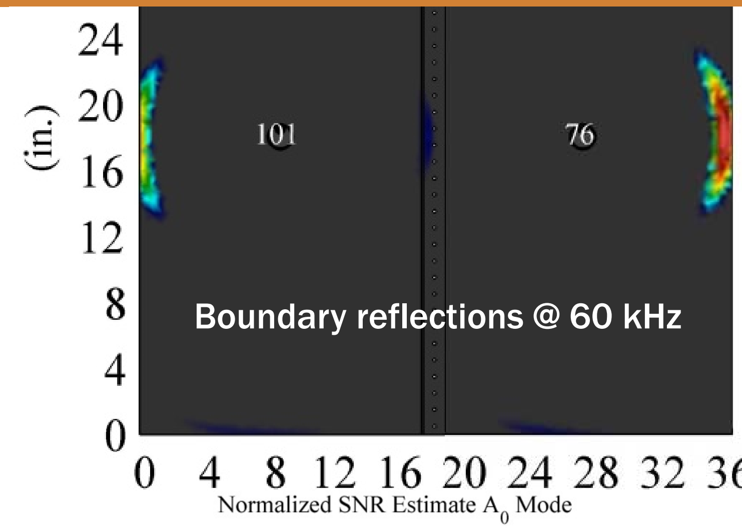


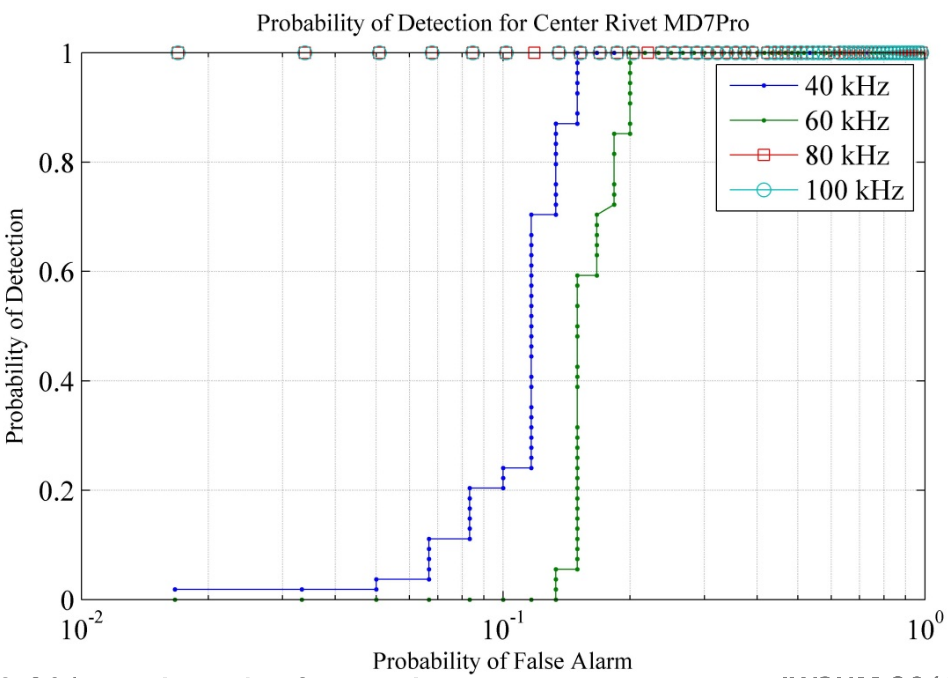
PoD Perpendicular to Notch

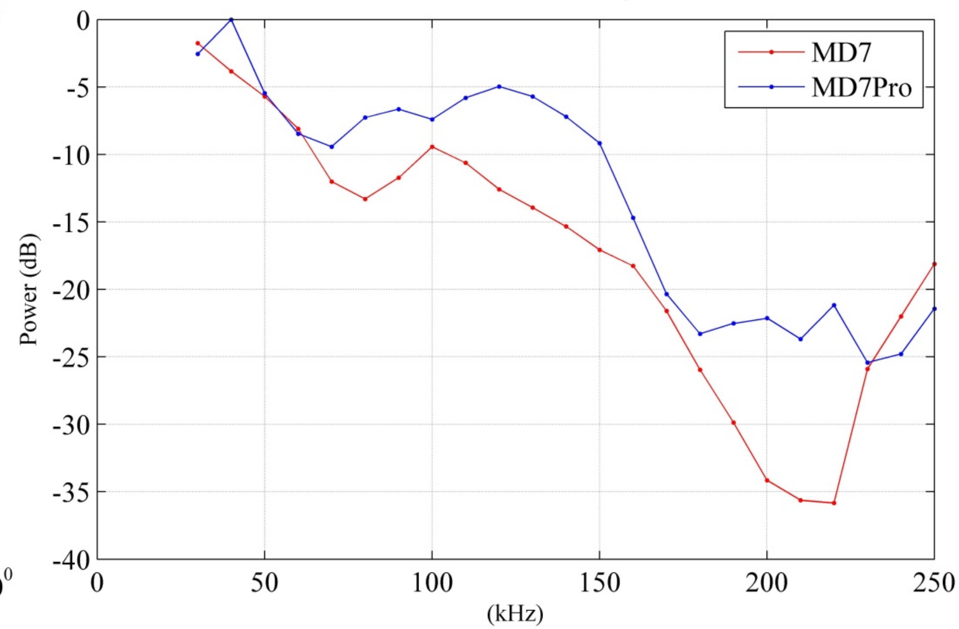


Course PoD for Al Plate w/Missing Rivets on Rib









Minimizing Required Test Matrix for PoD

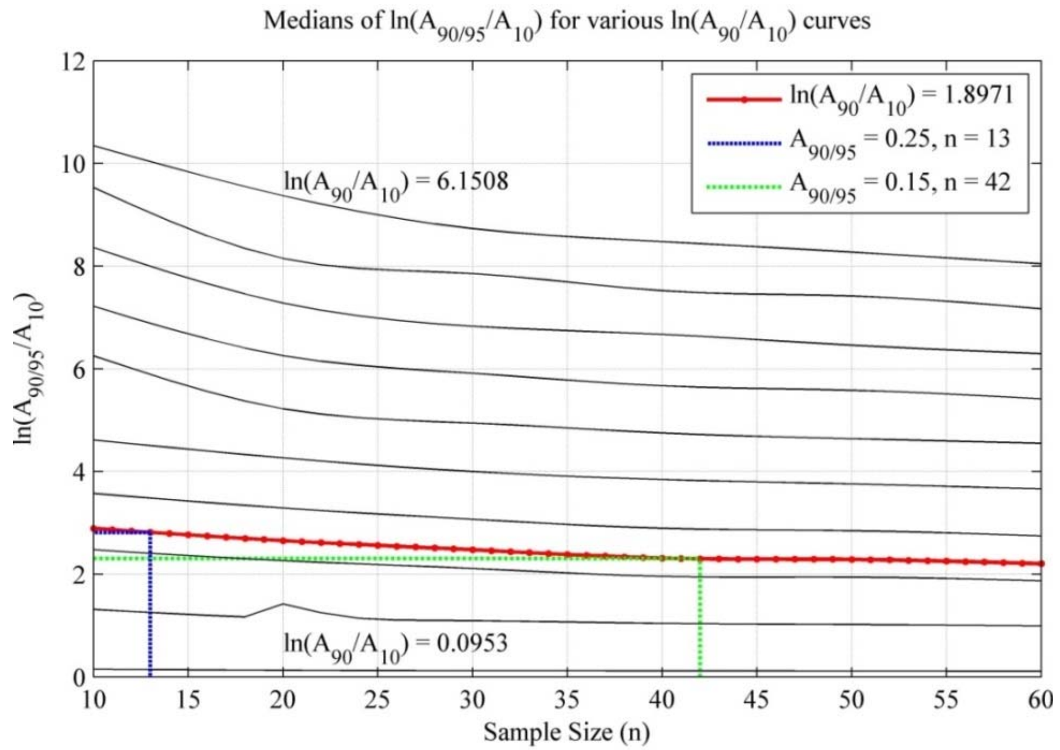
- Need "sufficient" # of specimens to fit PoD & determine $a_{90/95}$
  - HDBK essentially says to "consult a statistician"
  - Suggests 40-60 tests with equal number of undamaged specimens
- SHM relies on permanent installation
  - Reducing required sample size is driven by cost of disposable components
  - Also not practical to test many complex representative test articles
- Simulation methods exist to determine optimal sample size*
  - Monte Carlo based algorithm
  - Determines distribution of $a_{90/95}$ values & optimal # of test specimens

*Song, Xiaolan, Pradipta Sarkar, and William Veronesi. "Virtual Inspection: Optimum Sample Size for POD Experiment." *Quality Engineering* 14, no. 4 (June 18, 2002): 623–44. doi:10.1081/QEN-120003563.

Determining Optimal PoD Test Matrix

- **Simulation Inputs:**
  - Fixed a_{90} = 0.1''
  - Fixed a_{10} = 0.015''
- **Case #1**
  - Desired $a_{90/95}$ = 0.25''
  - Resulting sample size n = 13
- **Case #2**
  - Desired $a_{90/95}$ = 0.15''
  - Resulting sample size n = 42
- **Propose Specimens**

Specimen Name	Quantity
#1: 4 Point Bend Test	13
#2: Attenuation and Scattering	3
#3: I Beam	3
#4: I Beam with Ribs	2
#5 Final Specimen: I-Beam w/ribs & splice plate	1



Reduced Inspection Intervals with SHM

- SHM has no cost for reducing the inspection interval
  - Assuming independence, overall effective probability of detecting a crack increases with more inspections; allows for reduced instantaneous PoD
  - Example of independent inspections:

One Inspection	***Inspection #1*** *PoD = 90%, P_{FA}=1/1000*				***Equivalent*** *PoD = 0.9000* *P_{FA}=1/1000*
Two Inspections	***Inspection #1*** *PoD = 90%, P_{FA}=1/1000*	***Inspection #2*** *PoD = 90%, P_{FA}=1/1000*			***Equivalent*** *PoD = 0.9900* *P_{FA}=1/500*
Four Inspections	***Inspection #1*** *PoD = 70%, P_{FA}=1/1600*	***Inspection #2*** *PoD = 70%, P_{FA}=1/1600*	***Inspection #3*** *PoD= 70%, P_{FA}=1/1600*	***Inspection #4*** *PoD= 70%, P_{FA}=1/1600*	***Equivalent*** *PoD = 0.9919* *P_{FA}=1/400*

- False alarm rate repercussions will be the major driving factor
- If dependent, equivalent PoD function of given operational state

Independence of Repeated Inspections

- General consensus is that 2 NDE inspections taken a year apart are considered independent (how do we know if this is true?)

Two Inspections

Jan. → Feb. → Mar. → Apr. → May → June → July → Aug. → Sept. → Oct. → Nov. → Dec.

- Are three inspections considered independent?

Three Inspections

Jan. → Feb. → Mar. → Apr. → May → June → July → Aug. → Sept. → Oct. → Nov. → Dec.

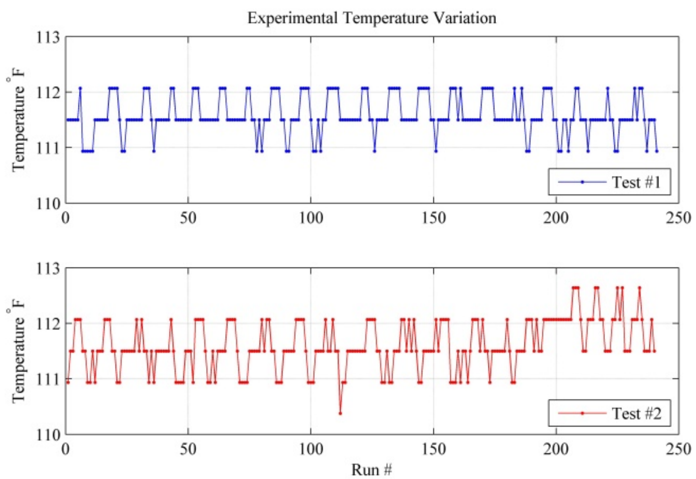
- Independence: a function of interval/operational environment
  - Boundary conditions, strain state, temperature all vary over interval

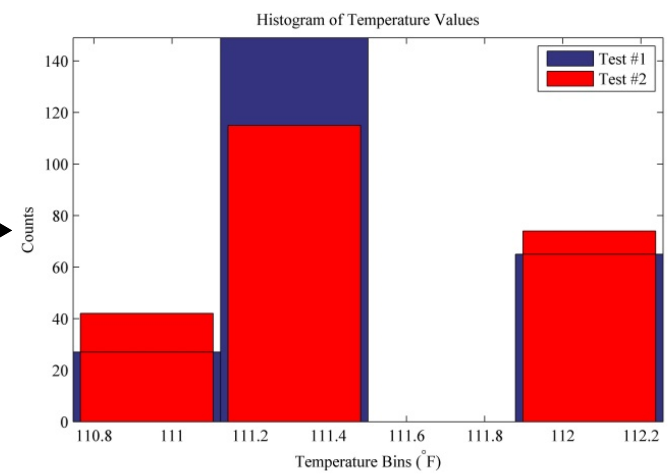
Operational Environment

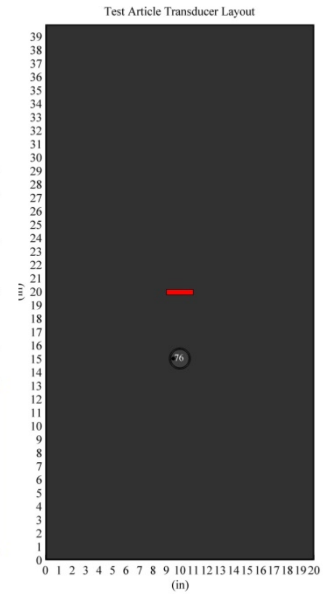
- Need to statistically test for independence between PoD and change in operational environment

Chi Square Independence Test

- Hypothesis test to determine if two variables are independent
  - ➢ Measures how well an observed distribution of data fits with the distribution that is expected if the variables are independent
- Test if PoD is independent of temperature
  - ➢ Test article is a metallic plate with honeycomb core
    - — Interrogate notch in pulse echo, damage 0.25” notch
  - ➢ 500 runs over several days
    - — Sub-divide by days: Test #1 = day 1, Test #2 = day 2
    - — Divide temperature into ranges of ~1^{o}F







metis design

Chi Square Independence Test Matrix

$P(A \cap B)$ $\qquad P(A) = \frac{220}{451}$

Observed Data

Temperature Ranges (Bin Centers)

Test #	111°F	111.5°F	112°F	T>112°F	*Total*
1	21	138	0	61	220
2	42	115	0	74	231
Total	63	253	0	135	451

$P(B) = \frac{63}{451}$

Expected Data

Temperature Ranges (Bin Centers)

Test #	111°F	111.5°F	112°F	T>112°F
1	30.7	123.4	0	65.9
2	32.7	129.6	0	69.1

$$P(A)P(B)*451 = P(A \cap B)*451$$

- Temperature varied all other parameters constant
- Using observed data calculate expected data assuming independence

$$P(A)P(B) = P(A \cap B)$$

- Compare observed and expected values

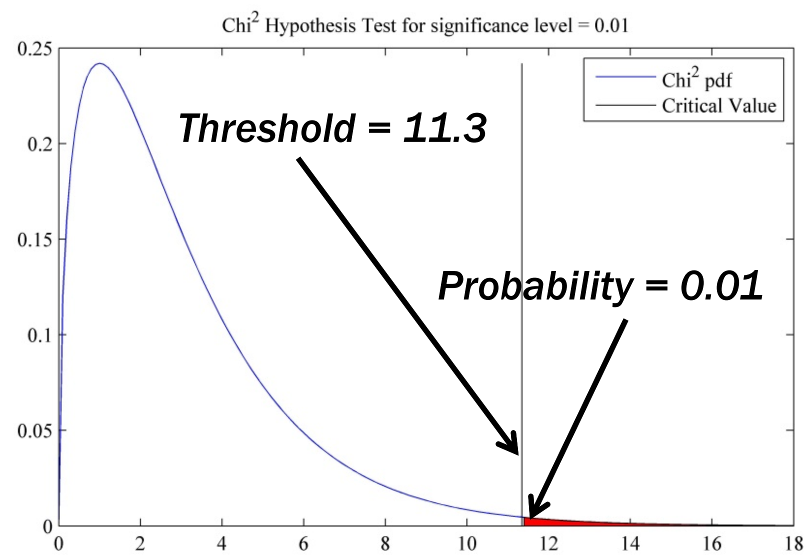
$$\chi^2 = \sum \frac{(Observed - Expected)^2}{Expected}$$

- Chi square value used in hypothesis test

Chi Square Independence Test Example

- Chi square test statistic has a Chi square probability distribution
  - Perform hypothesis test
    - Null hypothesis: PoD for test run and temperature are not associated
    - Alternative hypothesis: PoD for test run and temperature are associated
  - Choose power of test with significance level = 0.01
    - This sets the threshold\critical value
      - If test statistic > threshold: Reject null hypothesis
      - If test statistic < threshold: Do not reject the null hypothesis
    - Threshold value = 11.3
  - Test statistic = 10.1

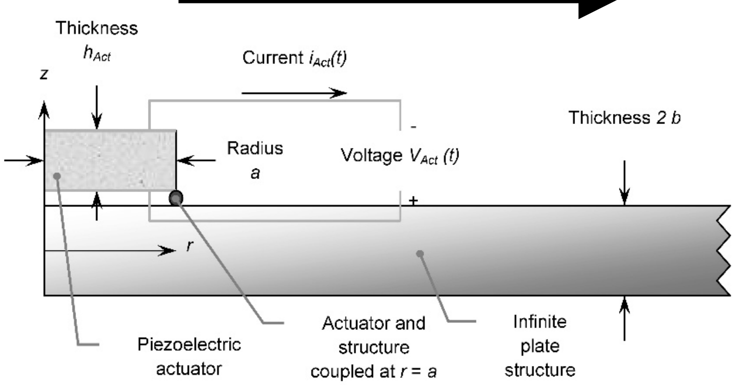
$$\chi^2 = \sum \frac{(Observed - Expected)^2}{Expected} = 10.1$$

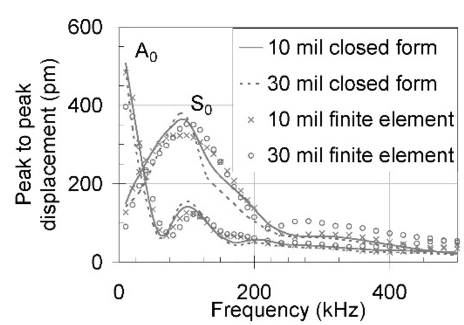


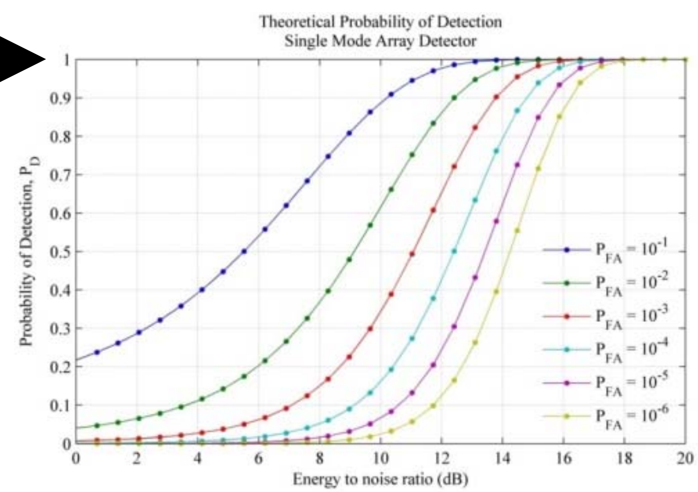
- Do not reject the null hypothesis
  - Test # & temperature are not correlated

Scaling Functions & Model-Assisted PoD

- Models necessary for efficient/comprehensive PoD calculation
  - Experimentally determining PoD curves as a function of damage size, orientation, distance not practical
- Form theoretical models & calibrate empirically
  - Signal processing methods derived from physics based model







- PoD driven by Energy-to-Noise ratio of scattered signal
  - Use scaling functions to calibrate PoD curves
  - Function of distance, orientation, and size of damage

Summary

- Differentiation between SHM & NDI for reliability assessment
  - SHM permanently installed at a point to cover an area, cost driver
  - Different variables effect PoD (temperature), no operator
- Proposed building block testing to isolate sources of variability
  - Increase complexity of each subsequent sub-specimen
  - Reduce physical test matrix size with models to minimize cost
- Repeated inspection is key to maintaining effective reliability
  - Impractical to maintain PoD of $a_{90/95}$ for entire SHM inspection range
  - Can reduce instantaneous test below $a_{90/95}$ if overall reliability maintained
  - Independence of repeated results will determine if this is allowed
  - Propose Chi Square method to test for independence
- Model-assisted PoD to accommodate flaw range & orientation

Technical & Business Contact

Seth S. Kessler, Ph.D. • President/CEO • Metis Design Corporation

617-447-2172 x203 • 617-308-6743 (cell) • skessler@metisdesign.com