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Calibration *vs* Calibration Verification for POD Studies & "Reliability"

30 October 2012

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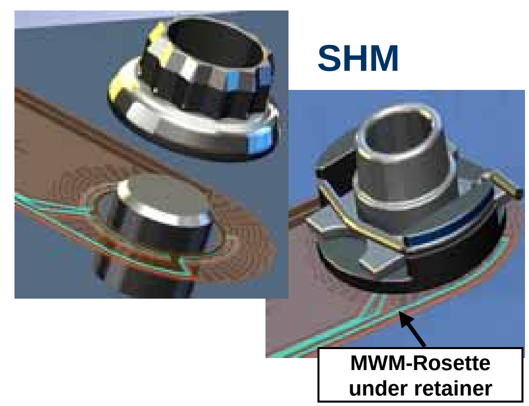


JENTEK issued and exclusively licensed patents include U.S. Patent #s 8,222,897, 8,050,883, 7,994,781, 7,876,094, 7,812,601, 7,696,748, 7,589,526, 7,533,575, 7,528,598, 7,526,964, 7,518,360, 7,467,057, 7,451,657, 7,451,639, 7,411,390, 7,385,392, 7,348,771, 7,289,913, 7,280,940, 7,230,421, 7,188,532, 7,183,764, 7,161,351, 7,161,350, 7,106,055, 7,095,224, 7,049,811, 6,995,557, 6,992,482, 6,952,095, 6,798,198, 6,784,662, 6,781,387, 6,727,691, 6,657,429, 6,486,673, 6,433,542, 6,420,867, 6,380,747, 6,377,039, 6,351,120, 6,198,279, 6,188,218, 6,144,206, 5,966,011, 5,793,206, 5,629,621, 5,990,677 and RE39,206 (other US/foreign patents issued and pending).

Outline

- **Reliability Related Definitions**
- **Technical Challenges (introduced by Rummel*) for Calibration Verification**
- **JENTEK Model-Based Calibration, Calibration Verification, and Measurement Approach**
  - For ET NDT
  - For ET SHM

  (using MWM-Arrays)

* Rummel, Ward, “Nondestructive Inspection Reliability - History, Status and Future Path”, 18th World Conference on Nondestructive Testing, Durban, South Africa, 16-20 April 2010

Definitions (by Floyd Spencer, with references to Ward Rummel)

- **Reliability** ***can be defined as***
  …the probability of a device (or process) performing its defined purpose ***adequately*** for a specified period of time, ***under the operating conditions encountered***

- **NDT Reliability** (from Rummel*)
  - Reproducibility – Calibration
  - Repeatability – ***Process Control***
  - Capability – POD

* Rummel, Ward, "Nondestructive Inspection Reliability - History, Status and Future Path", 18th World Conference on Nondestructive Testing, Durban, South Africa, 16-20 April 2010

Definitions (by Floyd Spencer) (cont)

- **Reproducibility (driven by Calibration, according to Ward Rummel)**
  …variability in the device (or process) caused by differences in the behavior of "components" (inspectors/instruments/probes/scanners….)

"Adjustments made to reproduce sensor gain may ***change the POD*** and off-sets may be necessary" (from Rummel *) – *in other words do the assumptions for your POD study apply to the inspection?*

- **Repeatability (driven by Process Control, according to Ward Rummel)**
  …variability within fixed "components" due to test – retest

- **Capability (equated to POD, according to Ward Rummel)**
  …measure of the ability of a process to achieve its objectives

Definitions (by Floyd Spencer) (cont)

- **Probability of Inspection (POI)**

  …probability that field inspection occurs under assumed conditions

  …in other words did your inspection meet the assumptions on which POD is determined

Law of total probability as applied to detection for field inspections

Pr(detect) =
Pr(detect | field inspection conditions "A") * Pr (field inspection conditions "A") +
Pr(detect | field inspection conditions "not A") * Pr (field inspection conditions "not A")

Pr(detect) = POD * POI + unquantified POD *(1 – POI)

Definitions (by Floyd Spencer) (cont)

- **Calibration (or standardization)**
  …comparison of NDT signal response to known flaw characteristics through the use of ***reference standards***

- **Calibration in Air or on unflawed parts**
  …for instrument only, requires ***verification on reference standards with known flaws***

- **Robustness = Reliability with an emphasis on**
  …a device (or process) performing its defined purpose adequately for a specified period of time, under the operating conditions encountered, ***where the operating conditions may vary significantly***

Calibration Verification

"If we intend to analyze data by assuming a linear increase in NDT response with increasing crack size, we are obligated to verify that the measurement system is producing the assumed response."*

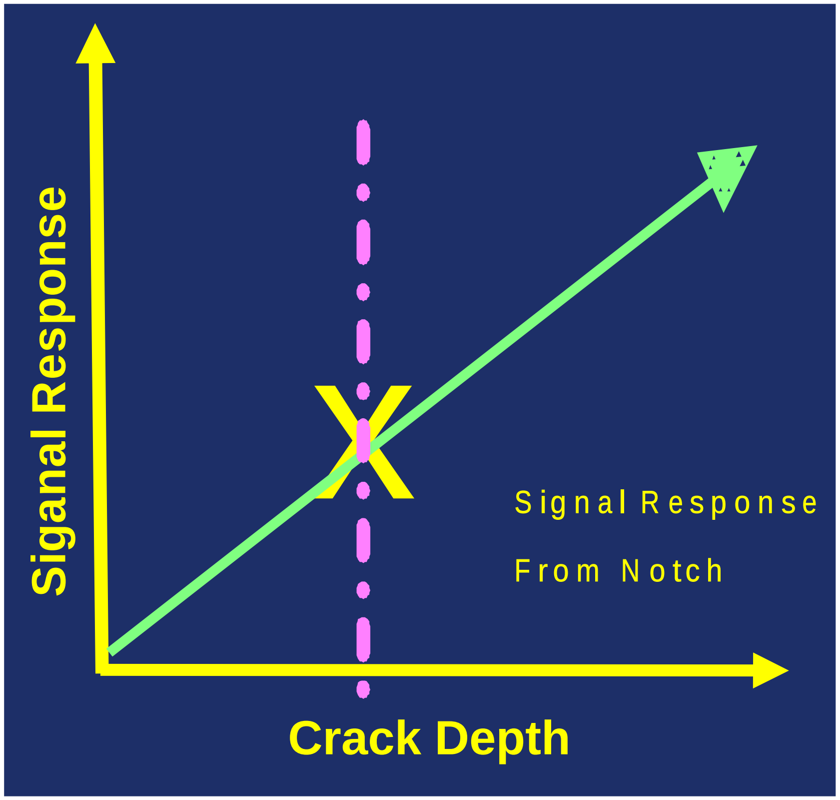
"Instrument calibration should be performed in accordance with manufacturer's instructions. A permissible instrument calibration is an air standardization with extensive and documented performance verification measurements per manufacturer's instructions."**

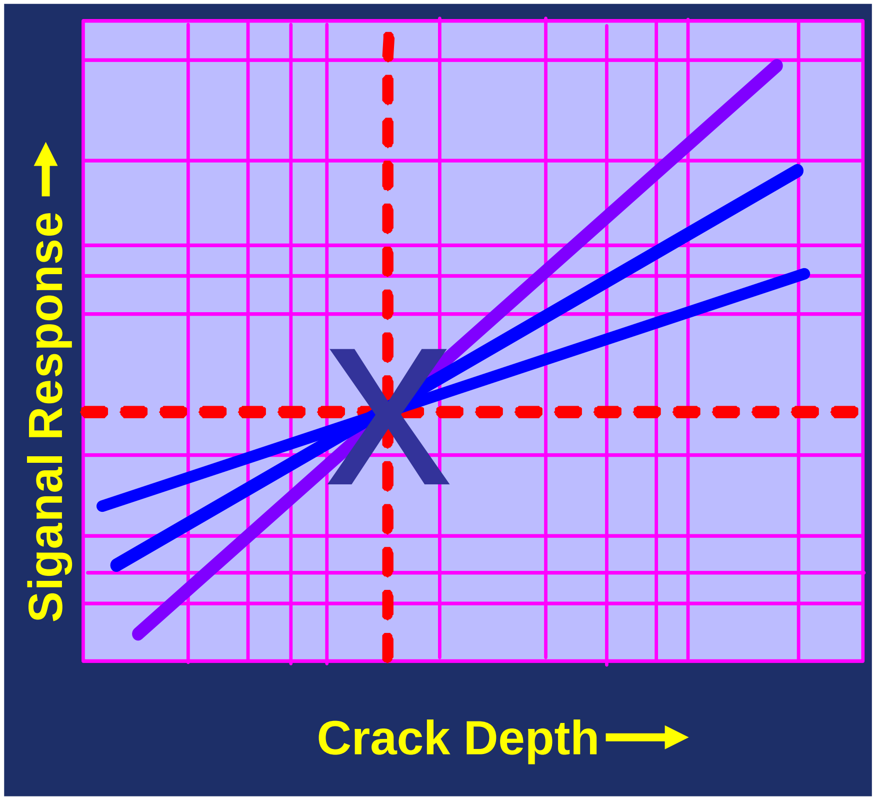
* Rummel, Ward, "Nondestructive Inspection Reliability - History, Status and Future Path", 18th World Conference on Nondestructive Testing, Durban, South Africa, 16-20 April 2010

**E2338 – 04: "Standard Practice for Characterization of Coatings Using Conformable Eddy-Current Sensors without Coating Reference Standards"

Ward Rummel's suggested approach

"…verify that the measurement system is
producing the assumed response,"
using a three point calibration verification with crack standards





* Rummel, Ward, "Nondestructive Inspection Reliability - History, Status and Future Path",
18th World Conference on Nondestructive Testing, Durban, South Africa, 16-20 April 2010

Calibration Methods (Which is More Robust?)

Conventional Calibration
("Standardization") on crack standards

How do we verify that the POD curve ("capability") we are assuming actually applies to the inspection we are performing?

What is a sufficient calibration verification?

What if your calibration standards have a different …? (e.g., roughness or paint thickness)

Model-Based Calibration, with Calibration Verification

Do Model-Based methods provide a more robust solution and means for ensuring that the POD curve assumptions are upheld?

What is a sufficient calibration verification?

Can we perform statistical process control on our NDT process?
e.g., monitor parameters that define/constrain the performance

The choice is to measure it (verify) or control it (trust)!

Technical Challenges (from Ward Rummel)

"Develop and apply multiple point calibration as a "STANDARD PROCEDURE" ***– is this enough?***

"Link use of predictive NDT performance models to NDT procedure CALIBRATION and NDT acceptance criteria" ***– is this better?***

* Rummel, Ward, "Nondestructive Inspection Reliability - History, Status and Future Path",18th World Conference on Nondestructive Testing, Durban, South Africa, 16-20 April 2010

JENTEK's Model-Based Approach

- Model-Based Calibration and Measurement Methods
- Calibration Verification on Crack Standards or actual service hardware with verified defects, if available
- Calibration verification at each inspection location, to ensure that the POD assumptions are still valid

…without this last step, do you really know if your POD (capability) assumptions still apply?

JENTEK's Model-Based Approach (continued)

- Spatial filtering and data processing to achieve*:
  - Linear crack response vs. crack size over range of interest
  - Constant variance within accepted bounds over range of interest
- Must include false indication rate with all POD curves and when comparing performance, **# of false alarm opportunities must be the same**

*the above conditions underlie the properties necessary for POD estimation as reflected in MIL-HNDBK 1823 and can often be achieved with appropriate transformations of signal responses and crack sizes. POD may be estimated without these assumptions being true, but will require methodologies beyond those presented in 1823.

Model-Based Calibration (with MWM-Arrays)

Sensor in "air"

Shunt Tip

Air, Shunt Calibration (No Crack Standards) now a U.S. Navy and U.S. Air Force Standard Practice

Easy to Replace Cartridges:

- Sensor
- Shuttle
- Balloons

First Air Calibration Validation & Verification

1993 Materials Evaluation Paper, Goldfine, (Melcher)
Multivariate Inverse Method using Pre-computed Measurement Grids

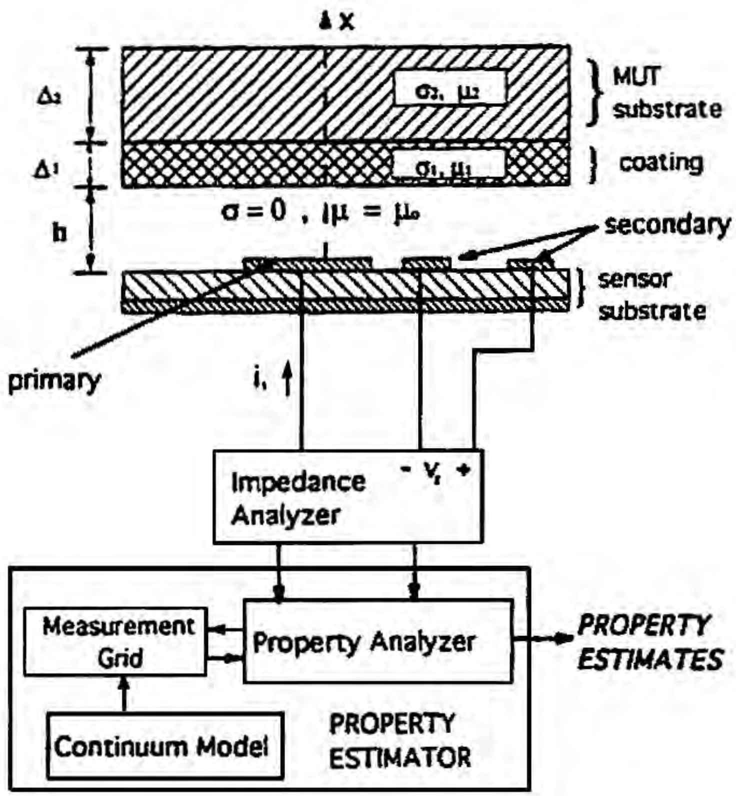


Figure 5—MWM prototype measurement system.

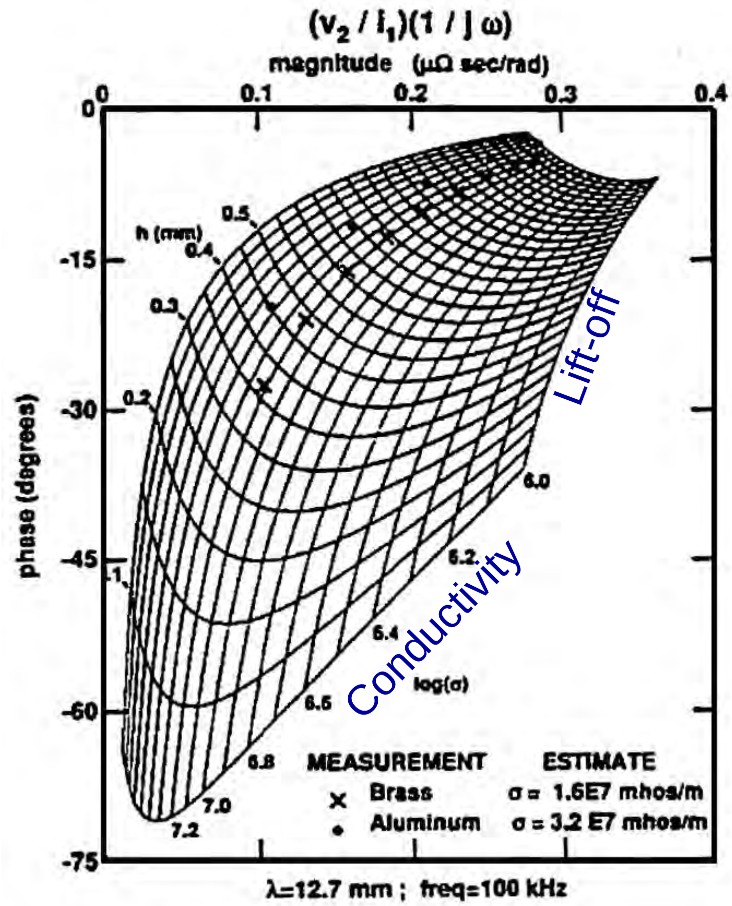
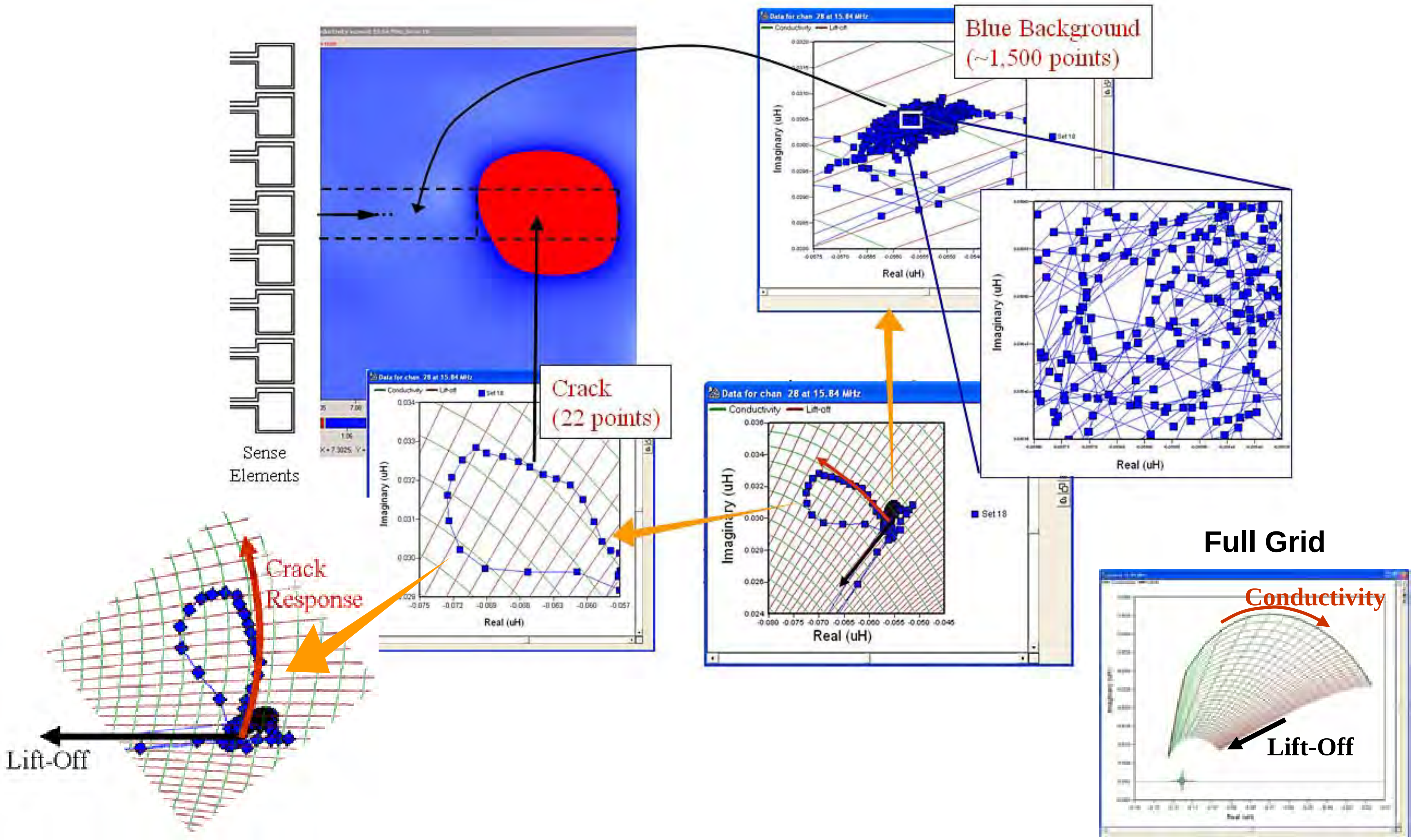


Figure 6—Property estimation grid for independent conductivity, σ, and liftoff, h, measurement (λ = 12.7 mm, f = 158 KHz).

Published, *Materials Evaluation* 1993

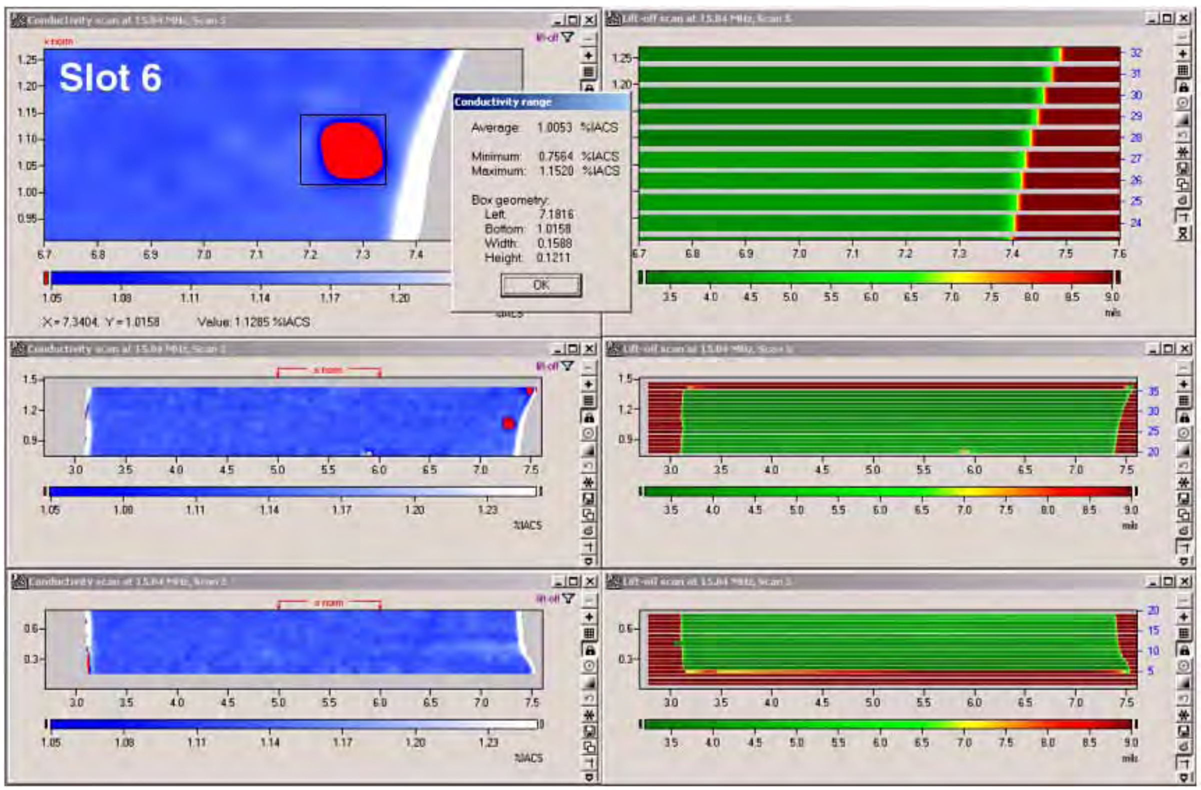
Model-Based Measurement/Inverse Methods
(with MWM-Arrays)

Rapid Data Processing with Grid Methods and "Air" Calibration



Model-Based Calibration Verification before, during and after inspections (with MWM-Arrays)

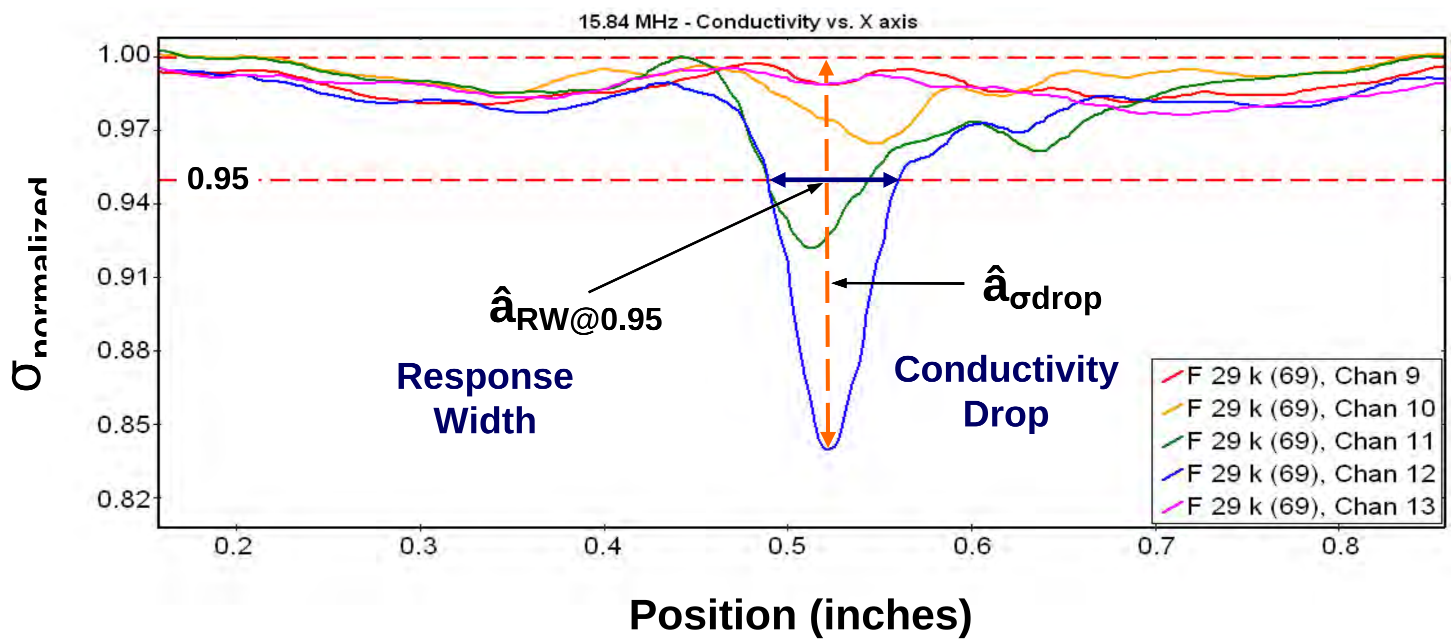
- In use at NAVAIR Depot since April 2005
- Disks with verified cracks detected, several of these verified large and small cracks **not detected by conventional ET and LPT**
- No false indications above threshold after over 7000 inspections



â Definitions for MWM-Array crack response

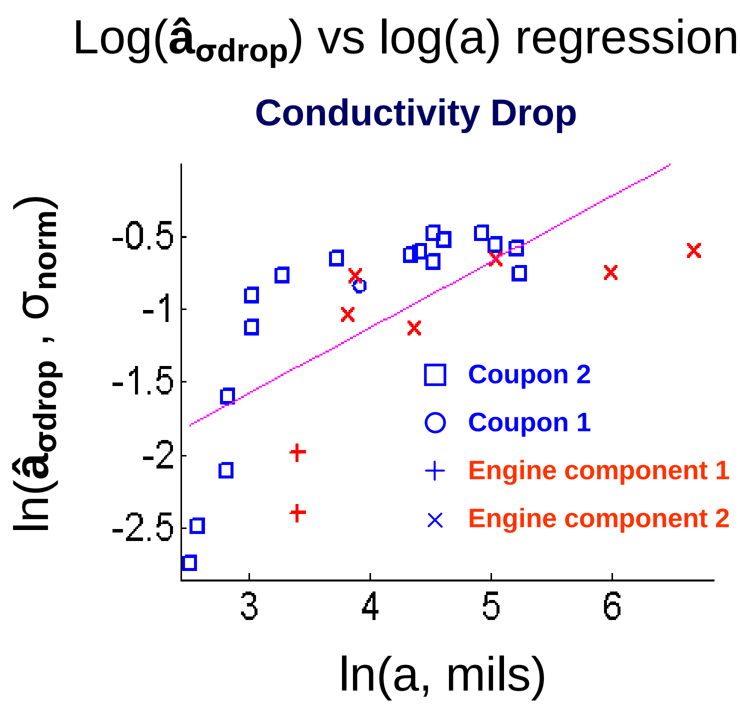
$\hat{a}_{\sigma drop}$ *vs* $\hat{a}_{RW@0.95}$

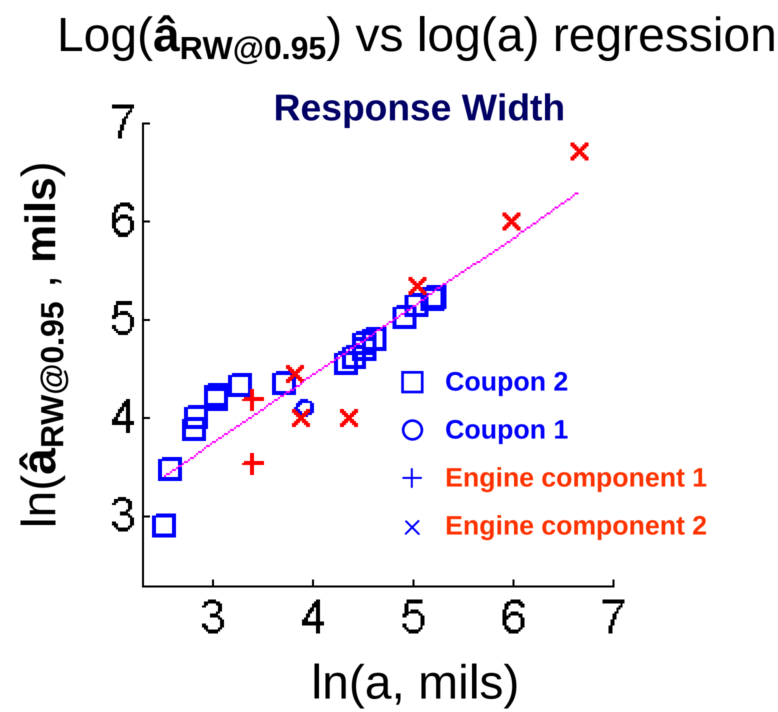
Coupon Fatigue Crack Response (16.9 mils)



â vs a Plots for Service Parts and Coupons

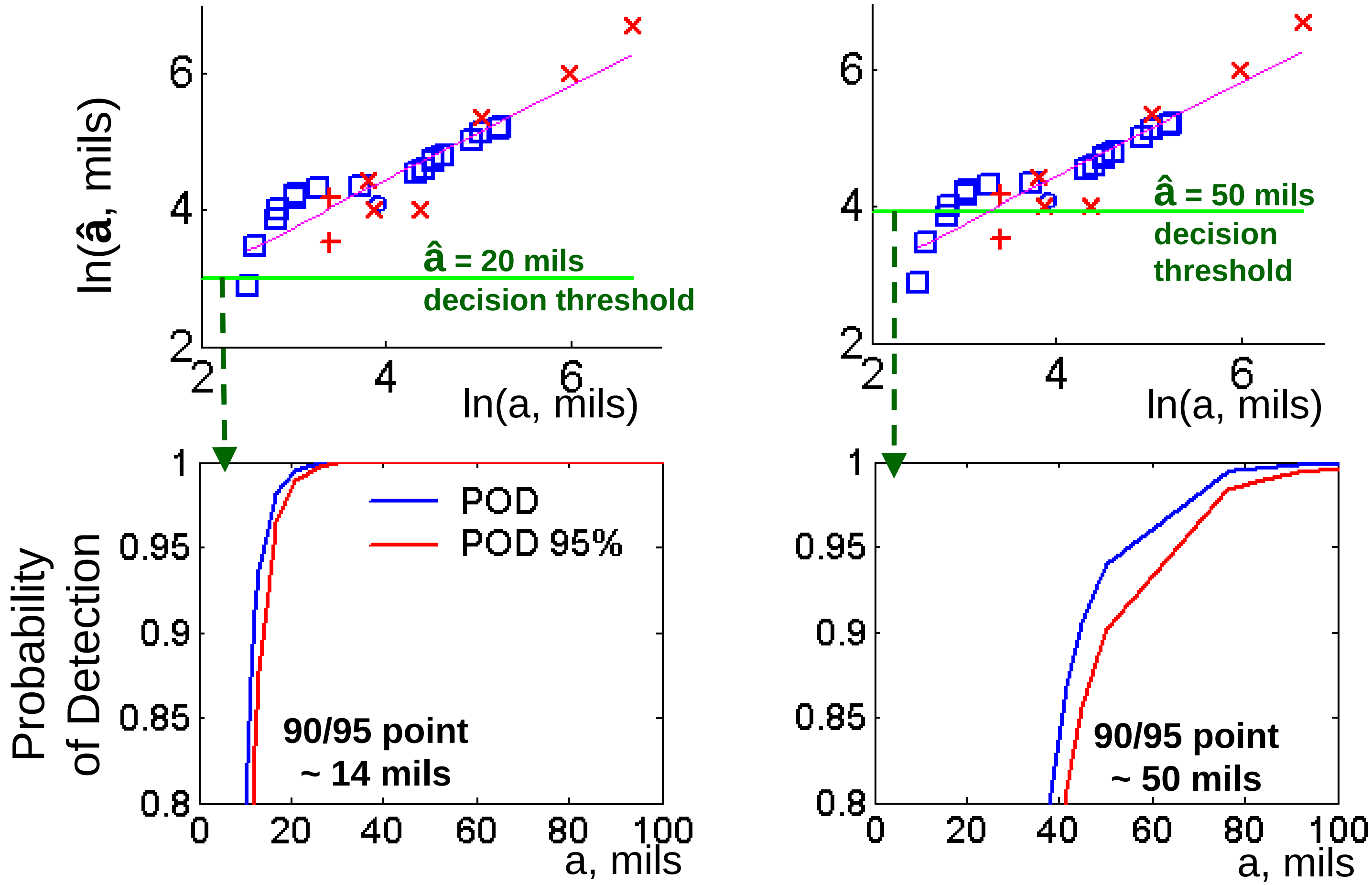
$\hat{a}_{\sigma drop}$ *vs* $\hat{a}_{RW@0.95}$





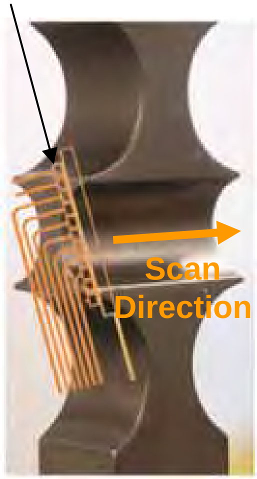
Note: Crack length correlates better with the $\hat{a}_{RW}$ (the response width).

POD Curves Generated using $\hat{a}_{RW@0.95}$ vs a Data

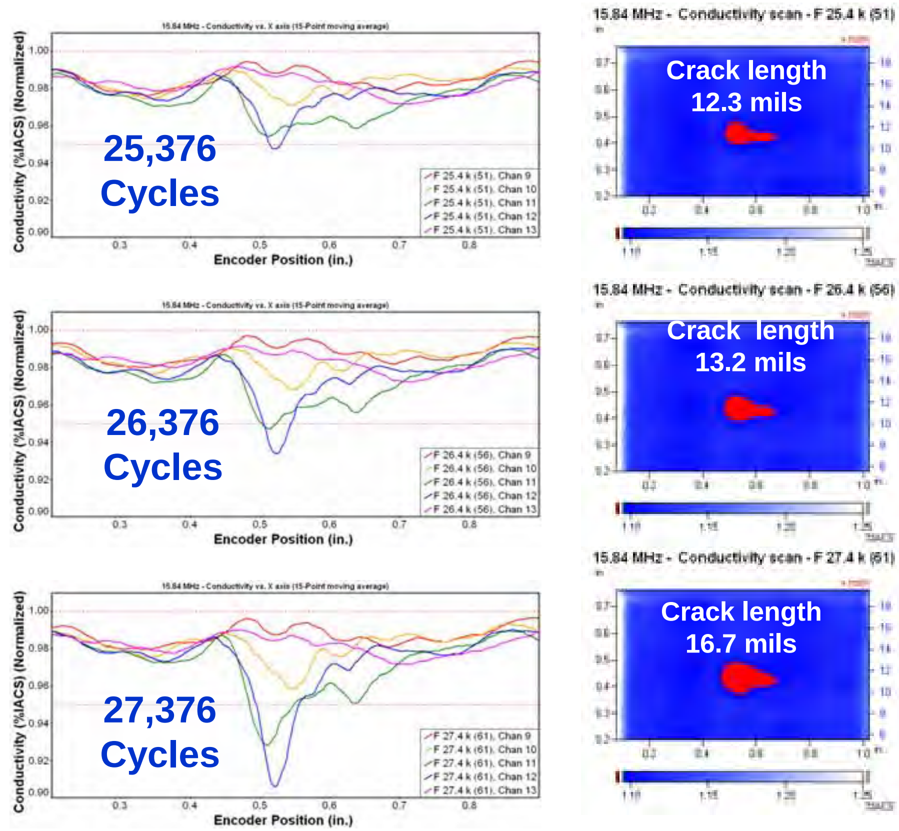


Note: Thresholds set above 0.04 inch for the $\hat{a}_{RW@0.95}$ response result in high confidence (~95%) that the same size crack lengths are detectable with high probability (~0.9).

Automated â vs a Data Generation using Multiple Coupons



Interval	Total Cycles	a, mils
0	0	0
2	6,000	3.9
11	27,376	16.7
12	29,041	16.9
25	41,000	186.6

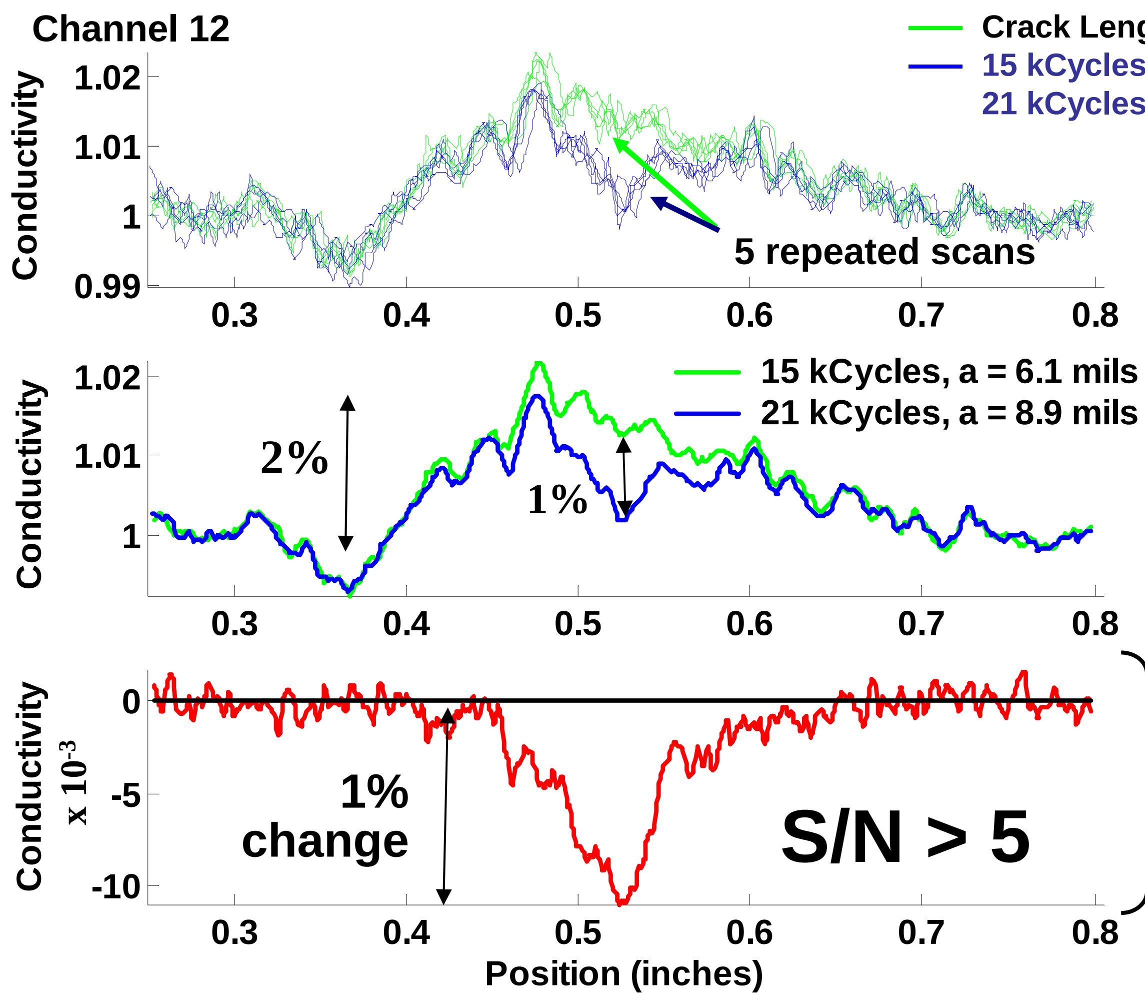


See also: Goldfine, et al, Defense Working Group 2011; Goldfine and Sheiretov, ENDE Conference 2009.

Difference Imaging or Baseline Subtraction

Improves Signal-to-Noise Levels to Reliably Detect Smaller Cracks

Titanium



Titanium Alloys

Average of 5 repeated scans

Difference between averaged responses for

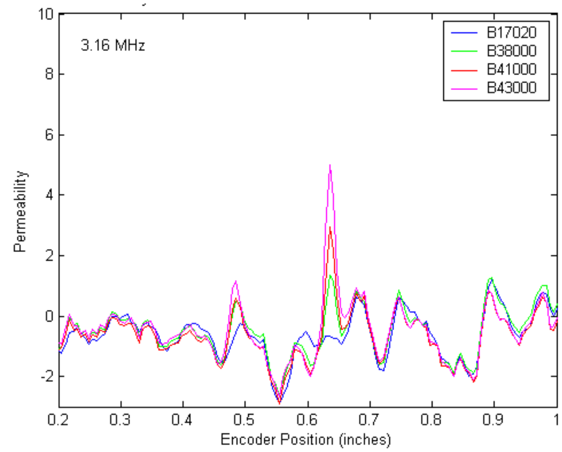
2.8 mil growth in crack length

Difference Imaging or Baseline Subtraction

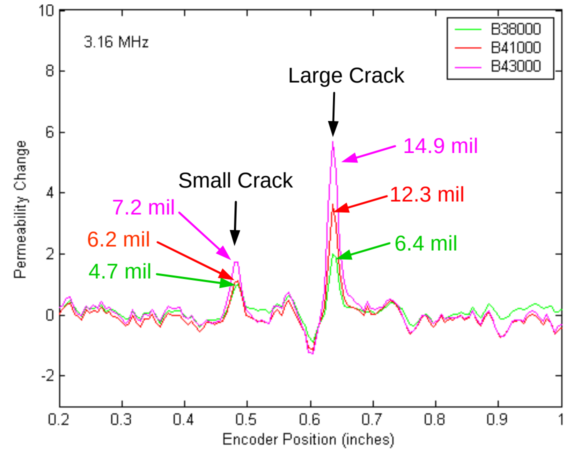
Improves Signal-to-Noise Levels to Reliably Detect Smaller Cracks

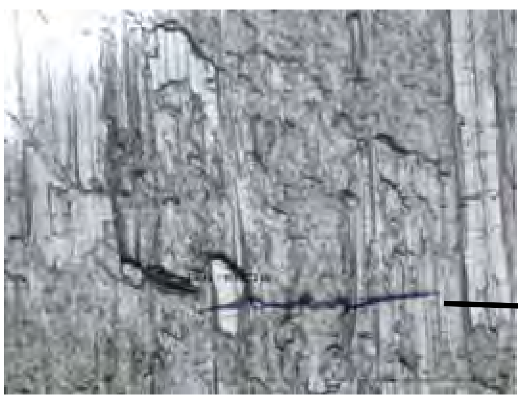
A514 Grade B Steel

Raw data

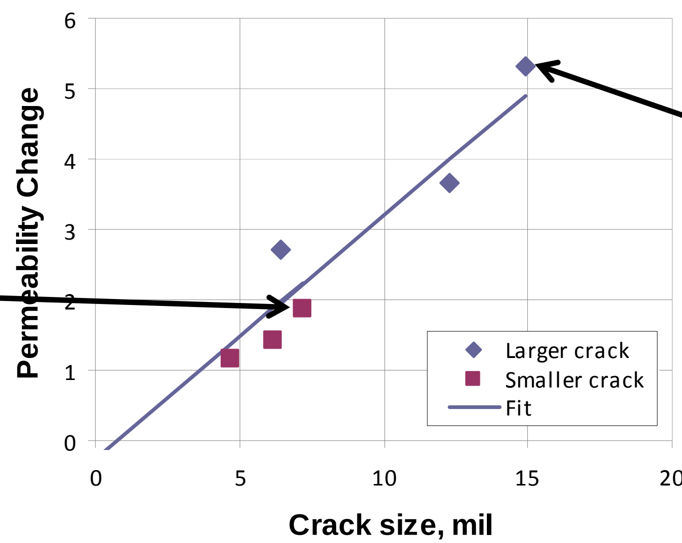


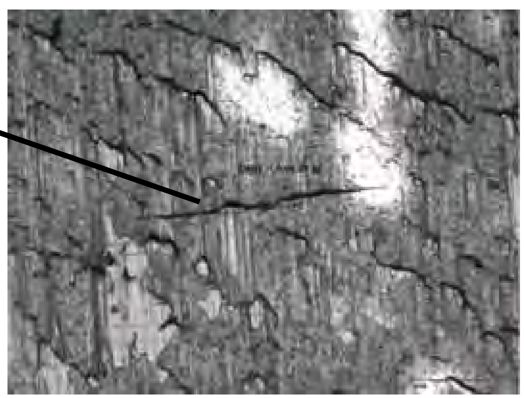
Data with baseline subtraction





Crack on front side at 43,000 cycles



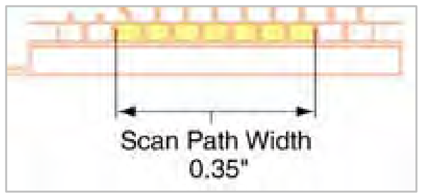


Crack on back side at 43,000 cycles

Example: Reliability for Bolt Hole Inspection

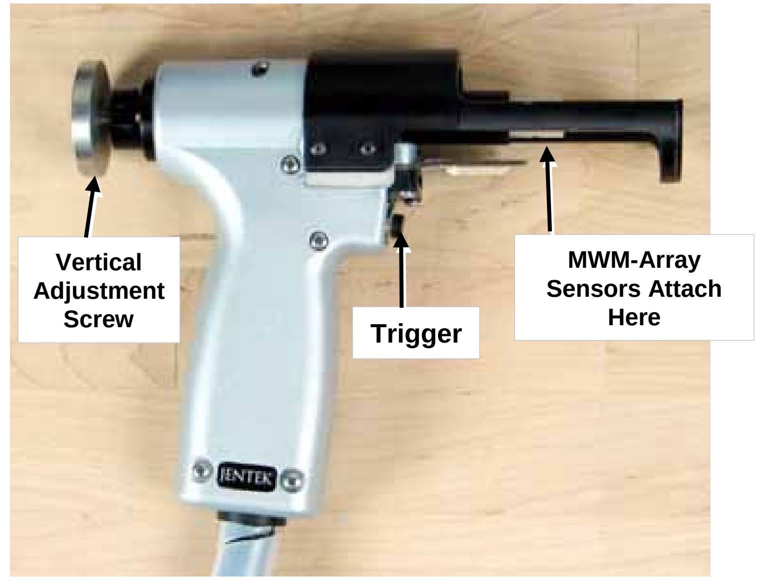
- C-Scan Imaging using MWM-Arrays
- Detection of Cracks at Edges with edge location correction
- Spatial Filtering for Cracks at Edges

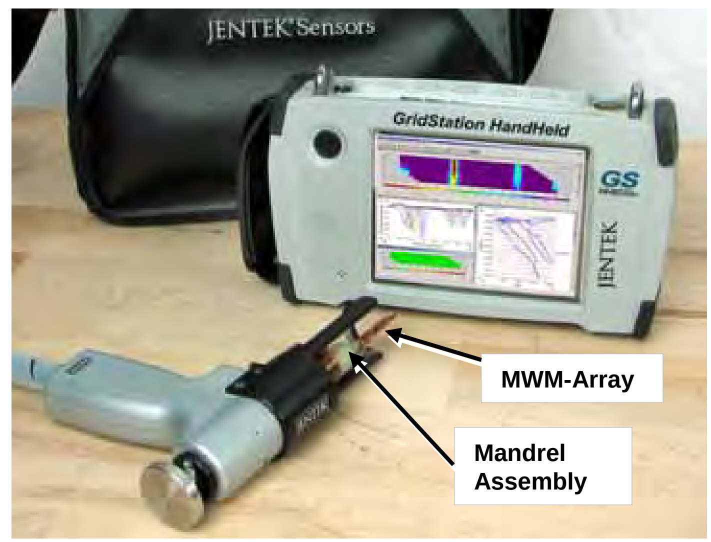
FA43
Sensor
Detail



Mandrel Assembly with interchangeable MWM-Arrays

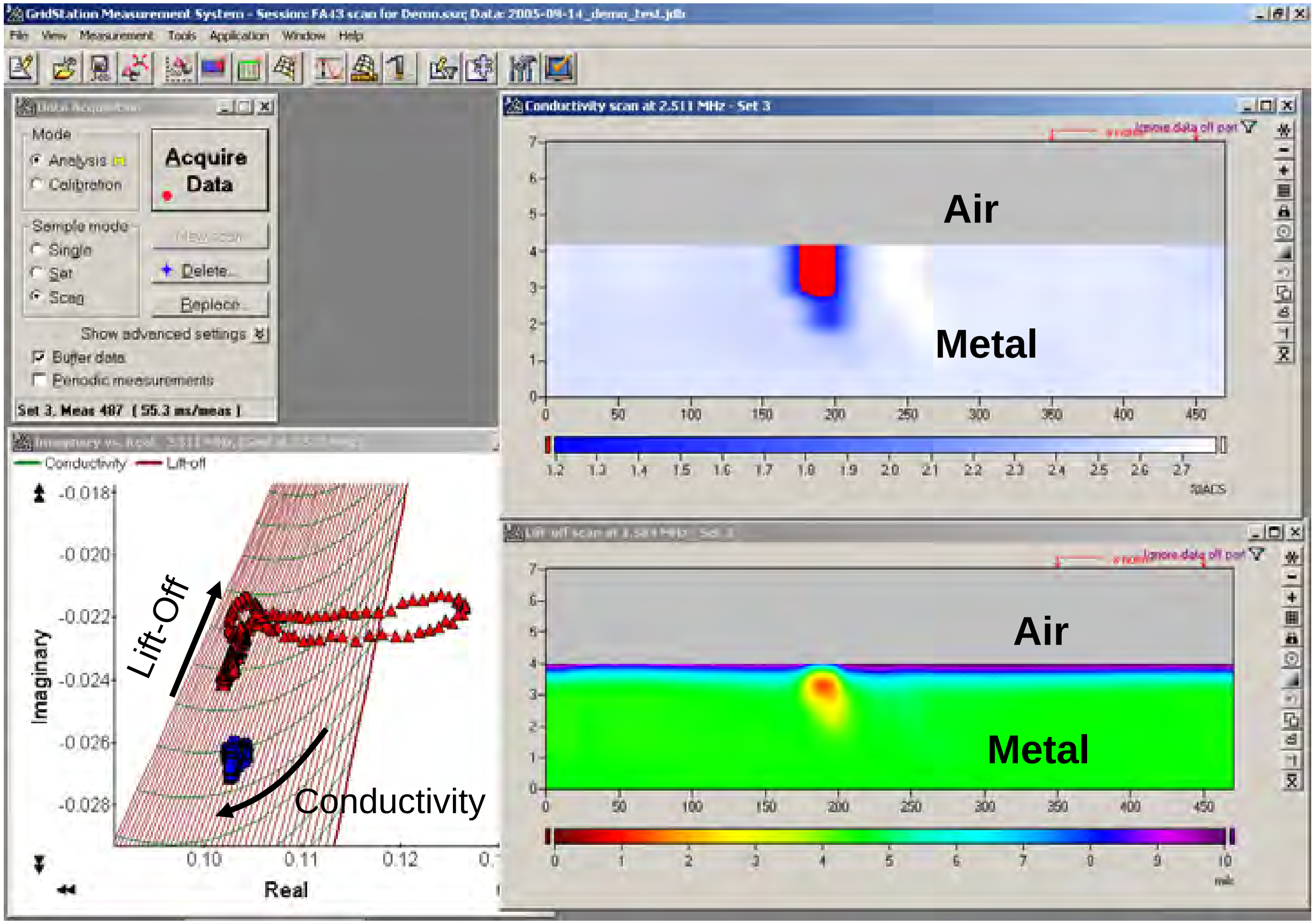
FA166 FA182 FA43



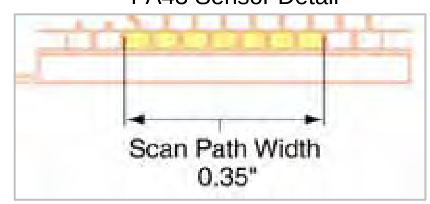


Correcting for Edges and Other Interferences

GridStation Conductivity/Lift-Off Images (Unfiltered)

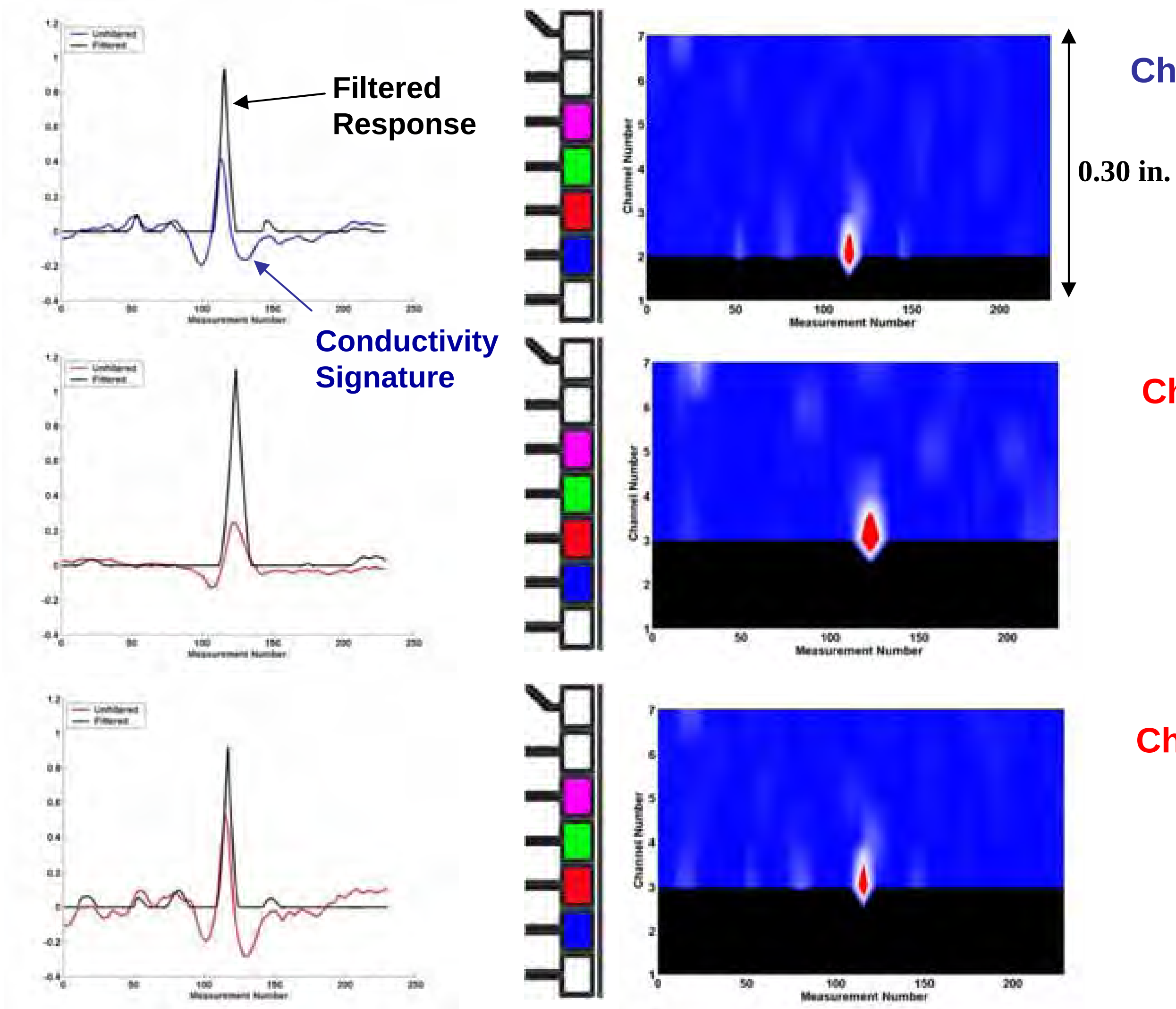


FA43 Sensor Detail

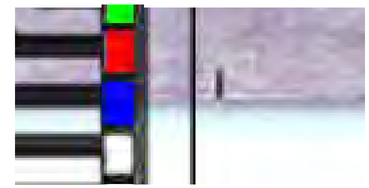


Detection of Cracks at Edges

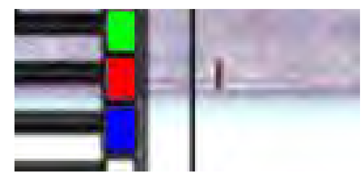
Edge location correction, and Spatial Filtering, using Signature Libraries



Channel 2, Lift-Off Factor = -0.69

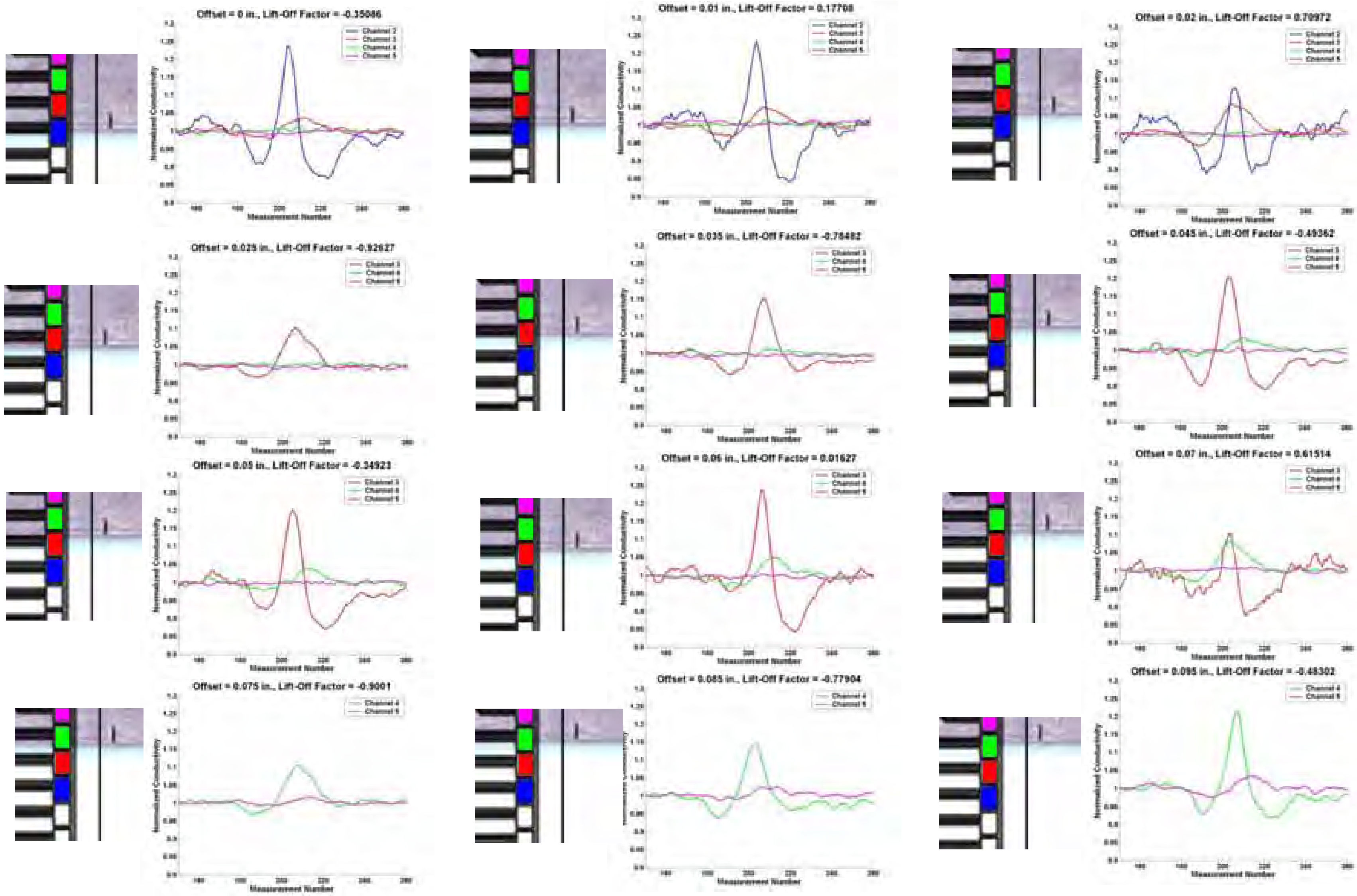


Channel 3, Lift-Off Factor = -0.96

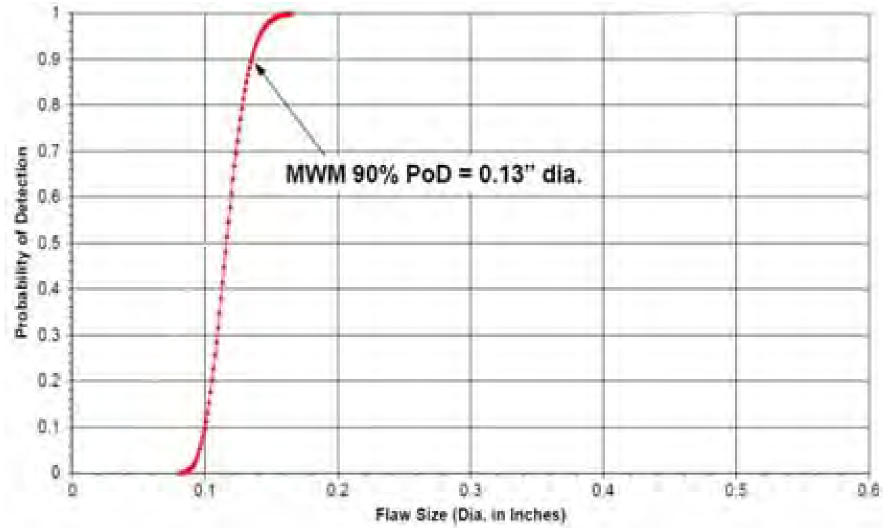


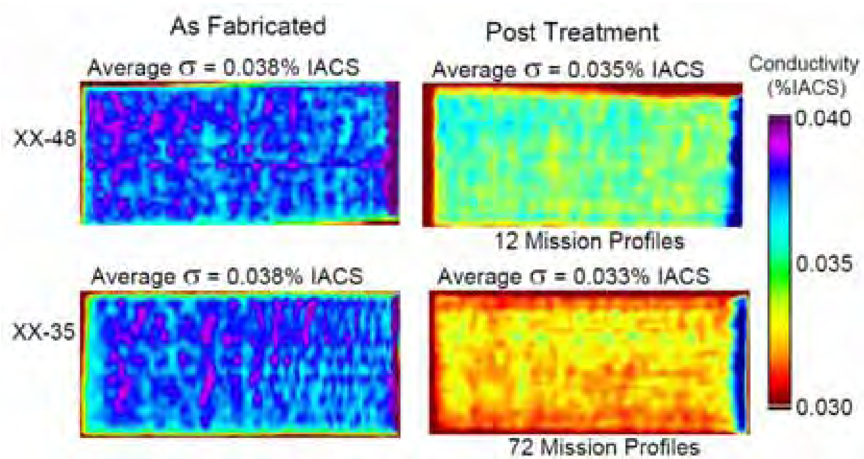
Channel 3, Lift-Off Factor = -0.47

Signature Library



Reinforced Carbon-Carbon (RCC) POD





Wincheski, B. Simpson, J., "Application of Eddy Current Techniques for Orbiter Reinforced Carbon-Carbon Structural Health Monitoring," CP820, Review of Quantitative Nondestructive Evaluation, Volume 25, PART B, pages 1082-1089, ed. by D.O. Thompson and D.E. Chimenti.

Engine Component

OEM & FAA - Approved Engine Component NDT with MWM-Arrays

AE SERIES PROPULSION SYSTEM
Service Bulletin Index

Rolls-Royce

LIST OF AE 3007A SERIES SERVICE BULLETINS

SB No.	Rev No.	Title	Compliance Category	Date	Models Affected	Module or ATA Locator
AE 3007A-72-386		See AE 3007A-A-72-386				
AE 3007A-72-388	1	Engine - 6th- thru 13th-Stage Compressor Wheel Knife Edge Seals - Jentek Eddy Current Inspection	8	09-May-11	7A, 7A1/1, 7A1/3, 7A1, 7A1E, 7A1P, 7A2, 7A3	72-37-00

"Technical aspects of the method are FAA approved."

MWM-Array
FA43 Sensor

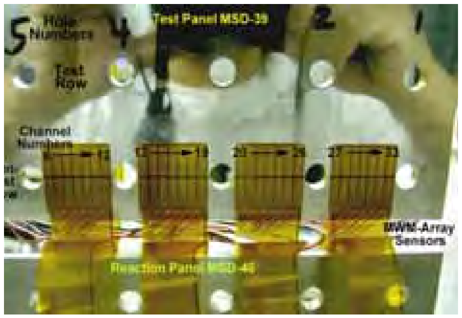
Reliability for Permanently Installed Eddy Current Sensors

- Embedded and Surface Mounted
- Linear MWM-Arrays and MWM-Rosettes
- Continuous Monitoring vs. Data Recording on the Ground Only

Example Linear & Integrated Solutions

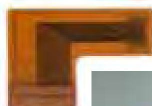
Example Linear MWM-Arrays

MWM-Array FA47

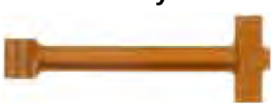


MWM-Array FA73

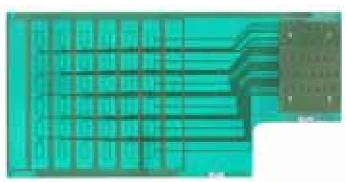
MWM-Array FA75



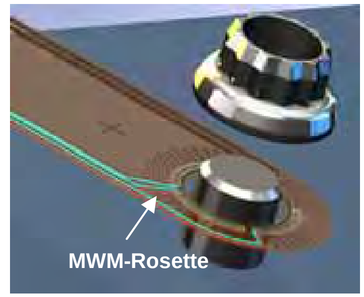
MWM-Array FA65

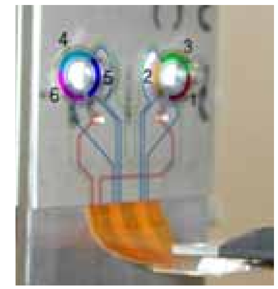


MWM-Array FA120



Example MWM-Rosettes & Integrated Solutions

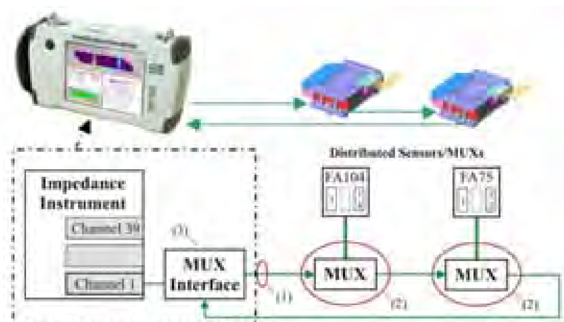




MWM-Array FA80

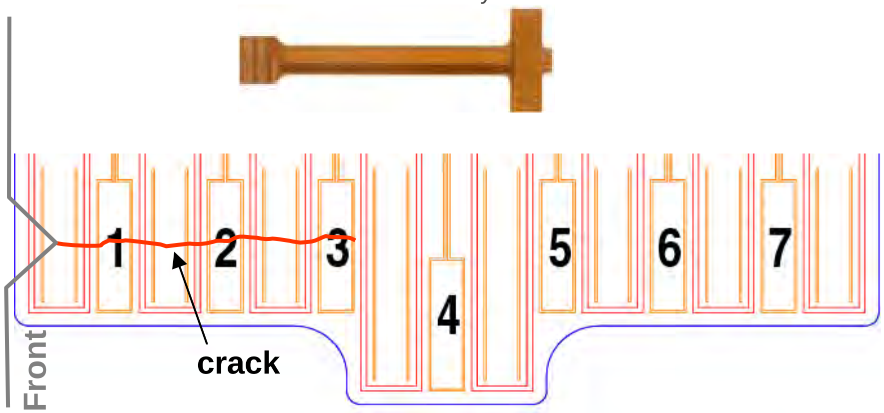
MWM-Arrays FA138, FA140

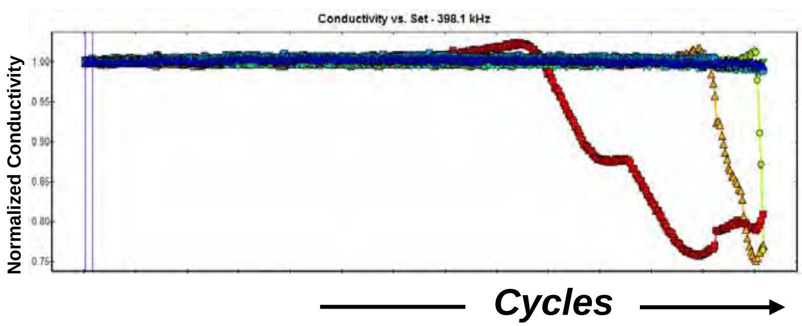
System and MWM-Array Sensor Mux Network



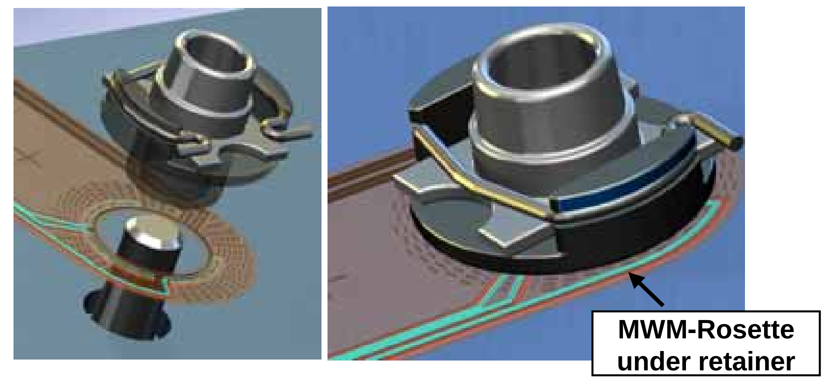
Linear MWM-Arrays

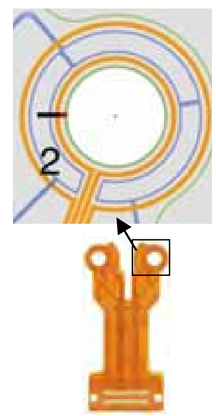
FA65 MWM-Array



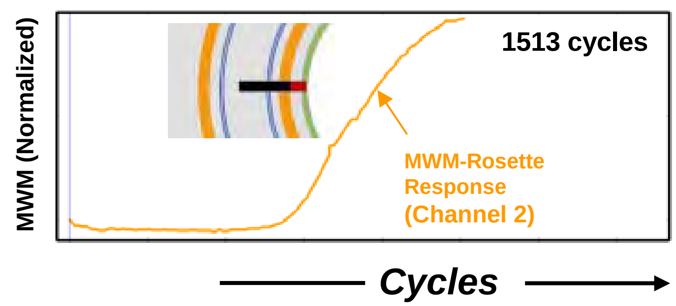


MWM-Rosettes





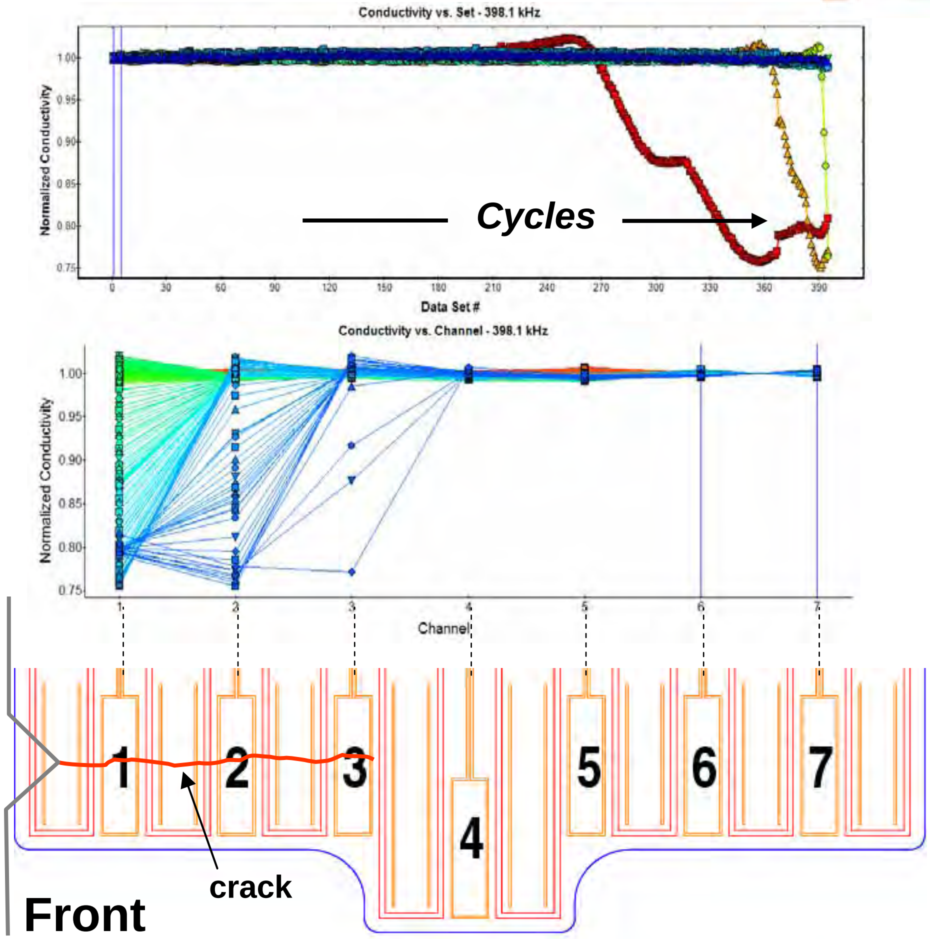
FA138 MWM-Rosette



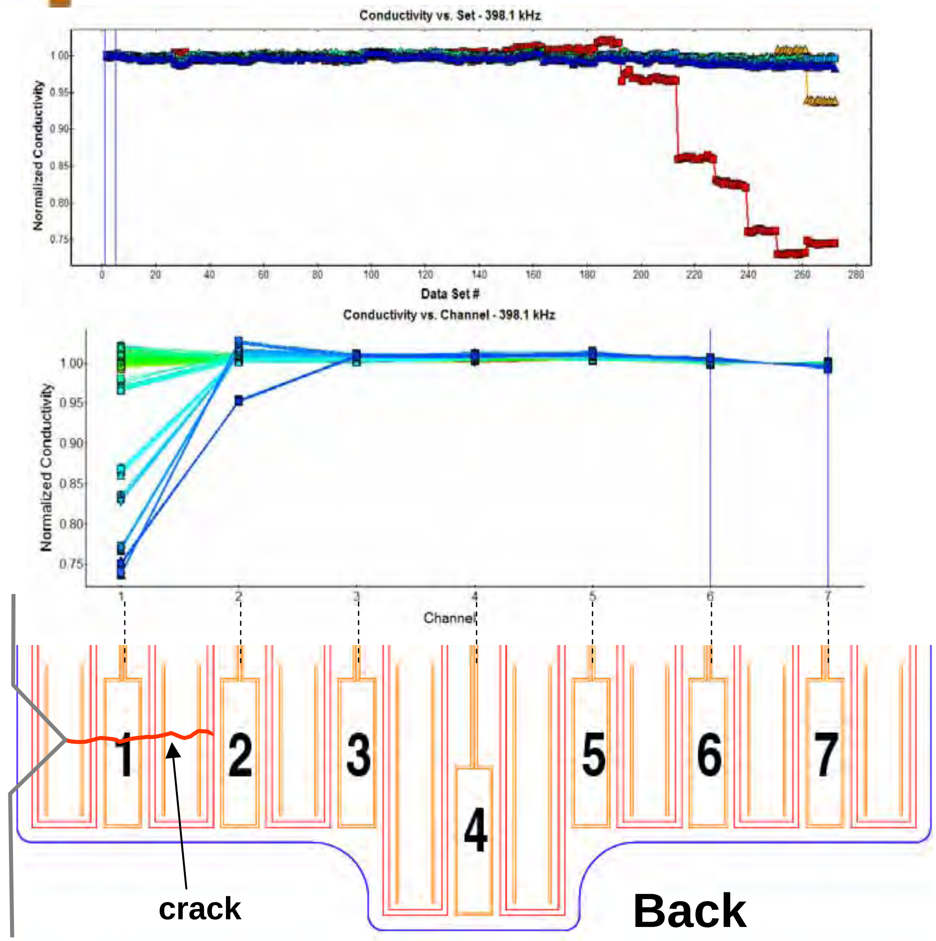
Linear MWM-Arrays & MWM-Rosettes can provide either continuous or scheduled inspection during fatigue or at rest

FA65 MWM-Array

Continuous monitoring



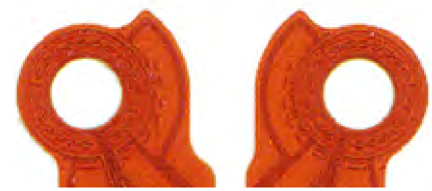
Scheduled inspections to simulate on-aircraft use



See also "Numerous Embedded Inductive and Capacitive Sensors for Corrosion & Fatigue," Aircraft Airworthiness & Sustainment (AA&S) Conference, Austin, TX, Presented May 2010.

POD Data Generation MWM-Rosettes

- MWM-Rosette (FA138) response monitored during fatigue test
- Determining actual crack sizes during testing
- Run multiple tests (e.g., 3-7 coupons)



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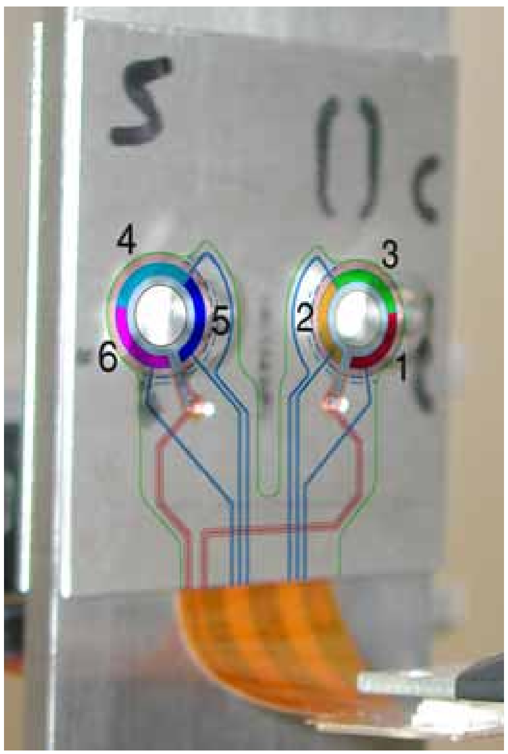
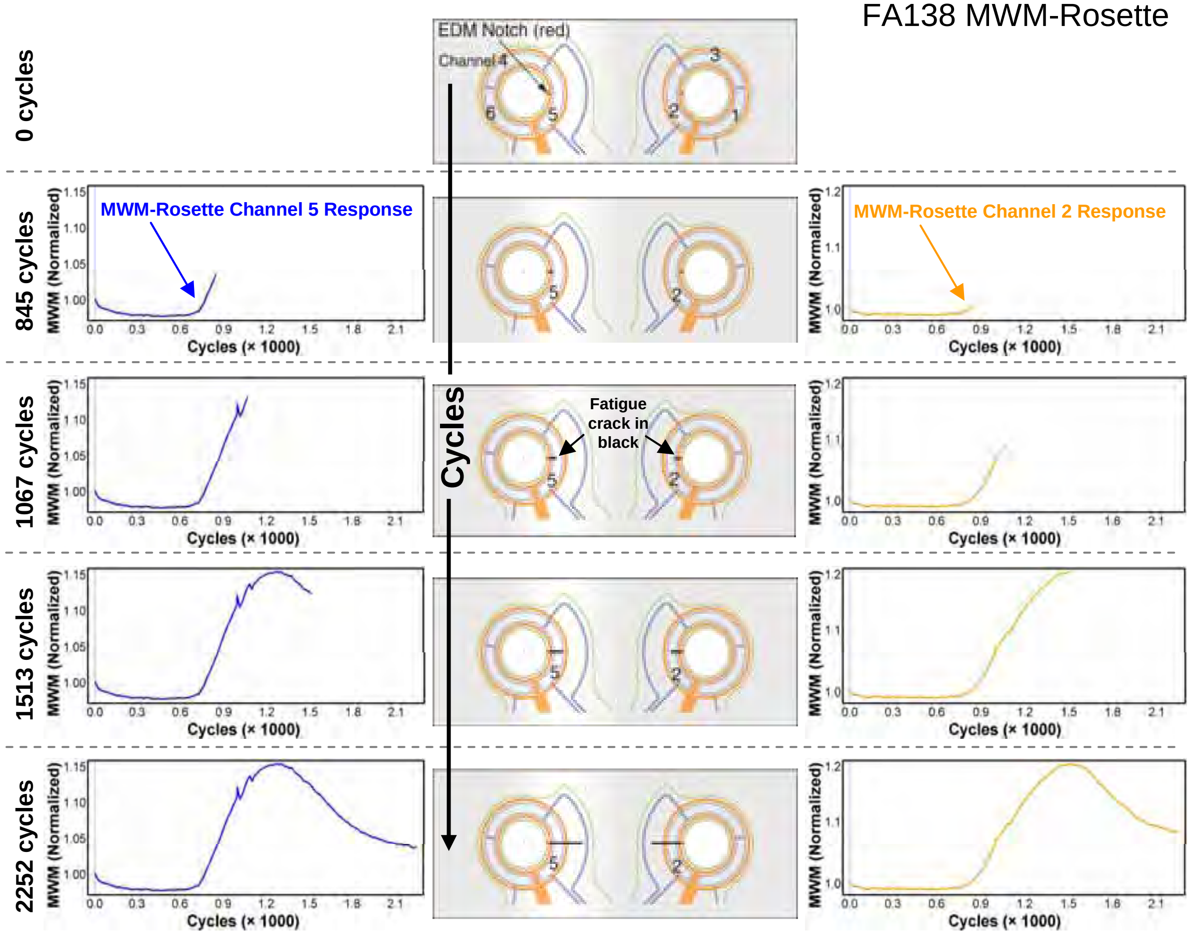




$\hat{a}$ vs a Response Model in Linear Range

MWM Crack Length Estimate = $\hat{a}$

$$\hat{a} = 1 + (b_0 + \varepsilon_s)\, a + \varepsilon_r$$

b_0 = Average **slope** for MWM response versus flaw size,

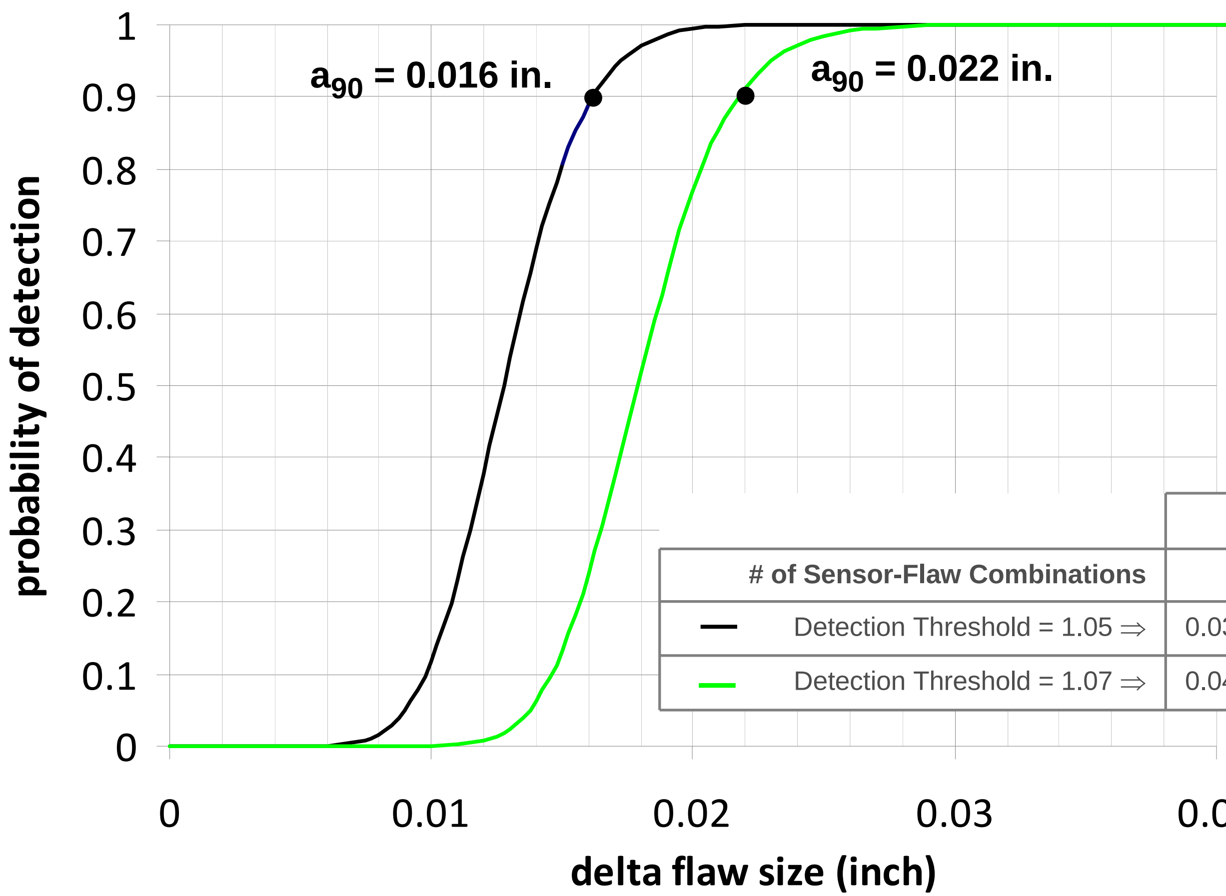
ε_s = Gaussian random variable with mean 0 and standard deviation σ_s (**sensor sensitivity, slope, variation**)

a = **Actual Flaw length**

ε_r = Gaussian random variable with mean 0 and standard deviation σ_r (**"glitches" from interrupted testing and other sources**)

First POD Curves for Embedded Eddy Current Sensors using Phase I Coupon Data

- Phase I data limited to 2 flaws
  b_0 est. = 3.920, σ_s est. = 0.400, and σ_r est. = 0.0082

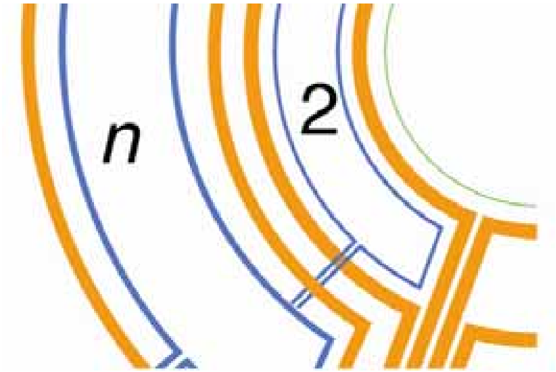


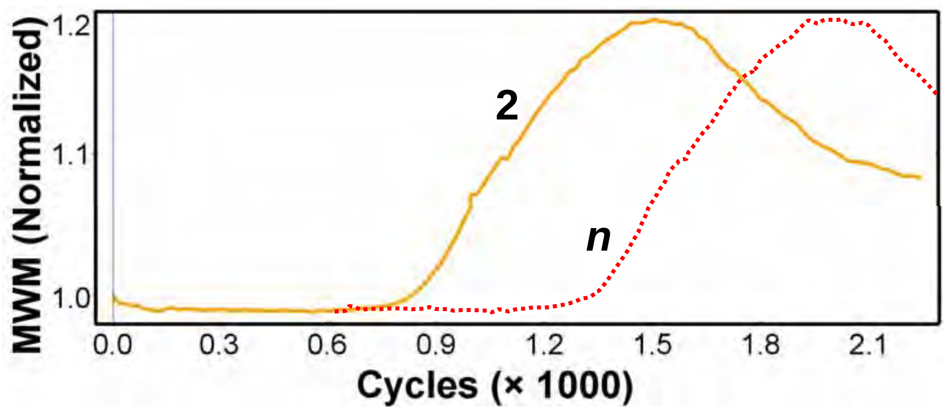
How many coupon tests do we need?

	$a_{90/95}$		
# of Sensor-Flaw Combinations	3	5	10
Detection Threshold = 1.05 ⇒	0.0306	0.0193	0.0173
Detection Threshold = 1.07 ⇒	0.0426	0.0265	0.0236

To Improve POD Curve Estimation

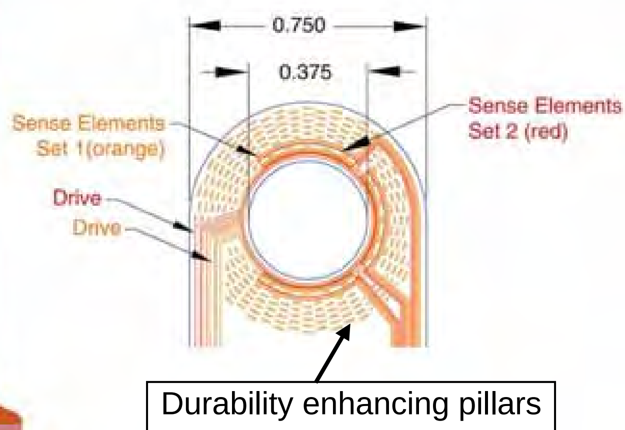
- **We can add another channel to expand linear range**

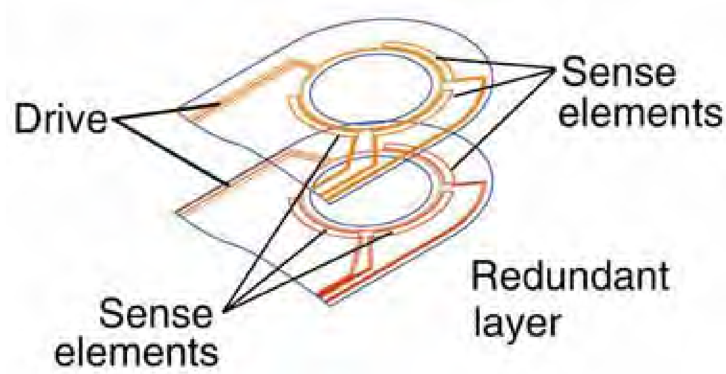




- **We can add redundant channels to improve noise suppression**

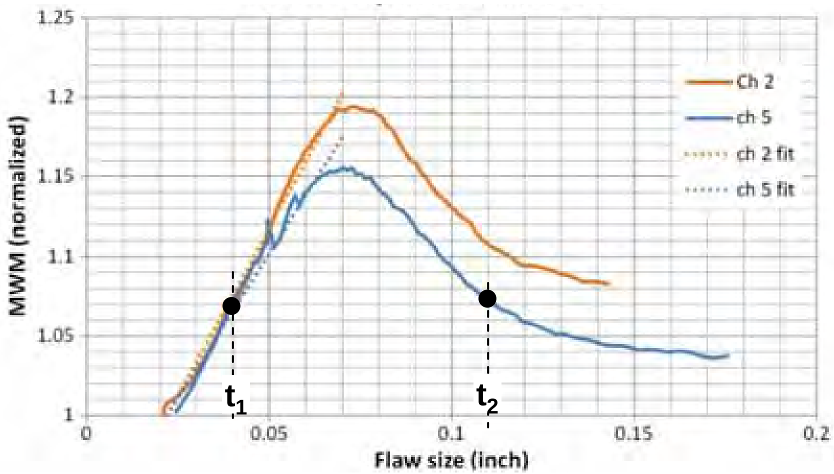
MWM®-Rosette FA158



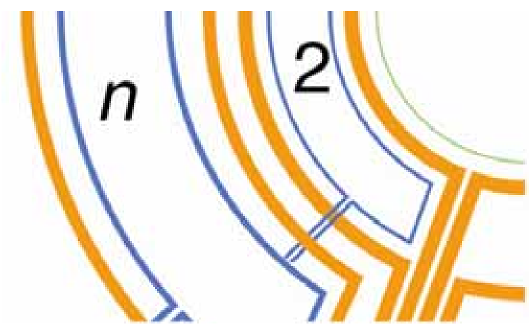


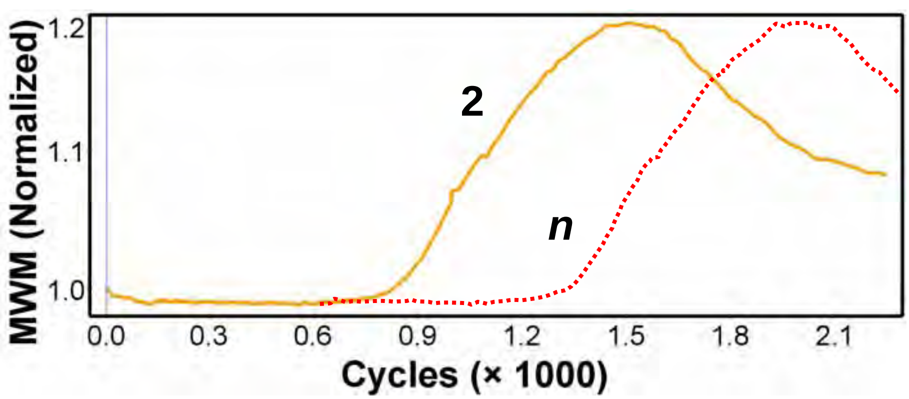
Caveats and Further Development

- POD form is valid only if able to determine which regime of the curve a single measurement occurs



- Can enable determination of regime with enhanced sensor design (e.g., add a channel)





JENTEK's Model-Based Approach is

- Model-Based Calibration and Measurement Methods
- Calibration Verification on Crack Standards or actual service hardware with verified defects, if available
- Calibration verification at each inspection location, to ensure that the POD assumptions are still valid

…without this last step, do you really know if your POD (capability) assumptions still apply?

Is POI ≅ 1.0 ?

Remember:

Pr(detect) = POD * POI + unquantified POD *(1 – POI)

Questions?