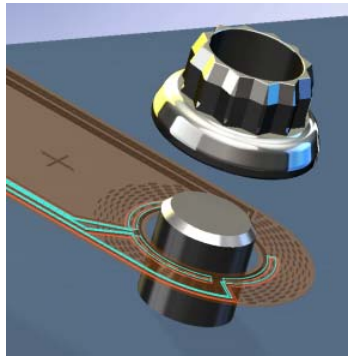
Flight Testing of Permanently Installed Eddy Current Sensors for IVHM



Neil Goldfine, David Grundy, Jennifer Marx, Brian Manning, and Chris Martin[1]
Floyd Spencer[2]
Chris Root, Albert Nguyen, and Cody Engstrand[3]
Paul Kulowitch and Adam Barrett [4]

1. JENTEK Sensors, Inc., Waltham MA 02453
2. Sfhire, Albuquerque, NM 87112-4924
3. NAVAIR, Fleet Readiness Center Southwest, San Diego, CA
4. NAWCAD, Patuxent River, MD 20670

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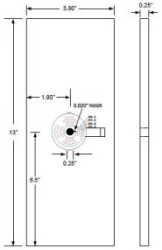
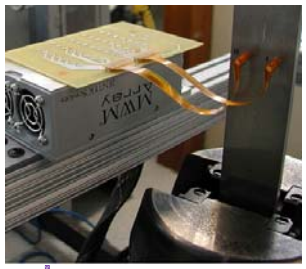
Historical MWM-Array Coupon Tests

Foil-Type Installed Eddy Current Sensors

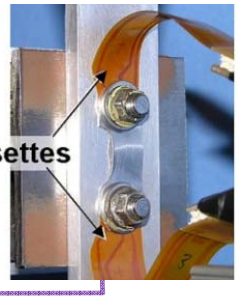
2001
Lockheed Martin Coupon Fatigue Tests[2,3]



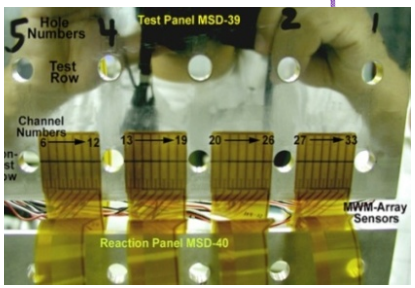
2004 - 2005
Northrop Grumman SIPS Program[1,4]



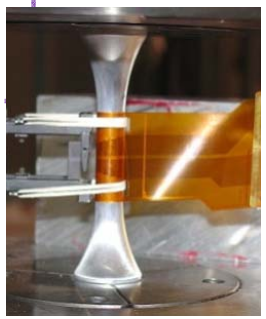
2006
U.S. Navy Phase II



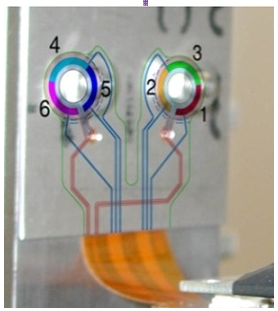
2001 — *2013*

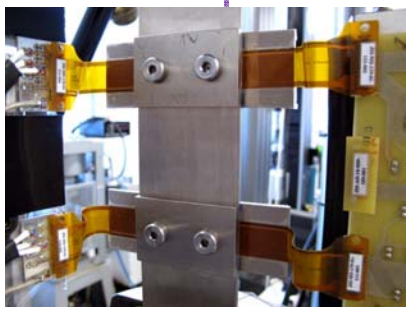


2004
Lockheed Martin MSD Coupon Fatigue Tests[1]



2004-2006
Northrop Grumman DARPA SIPS Program[1,4]





2009 - Phase I; 2012 - Phase II
U.S. Air Force

Sources:

[1]Neil J. Goldfine, et al, "Fatigue and Stress Monitoring with Magnetic Sensor Arrays," Annual Society for Experimental Mechanics (SEM) Conference, St. Louis, Missouri; June 2006.

[2]Neil J. Goldfine, et al, "Surface Mounted Periodic Field Current Sensors for Structural Health Monitoring," SPIE Conference: Smart Structures and Materials NDE for Health Monitoring and Diagnostics, Newport Beach, California; March 2001.

[3]Guadamuz, et al, "Application of the JENTEK "MWM" Sensor to Full Scale Structural Testing: A Case History," Poster, Aging Aircraft Conference, September 2002.

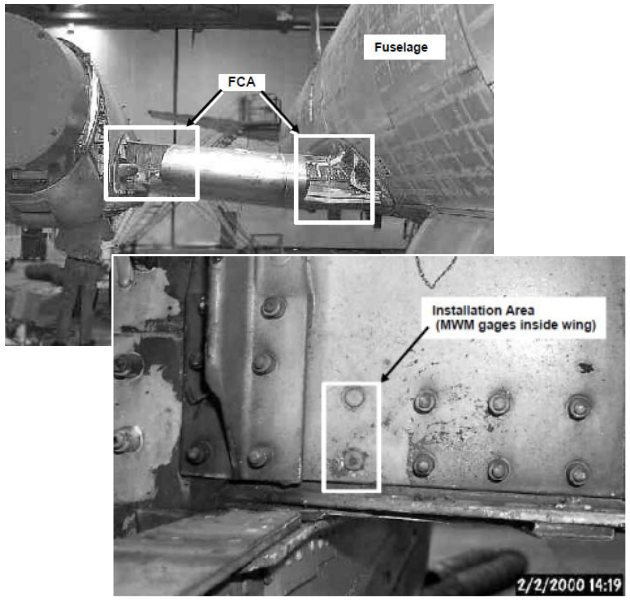
[4]John M. Papazian, et al, "Sensors for Monitoring Early Stage Fatigue Cracking," International Journal of Fatigue 29 (2007) 1668-1680.

Full-Scale Tests & Flight Tests

2000-2002 → *2006-2007* → *2013 - 2014*

Lockheed Martin

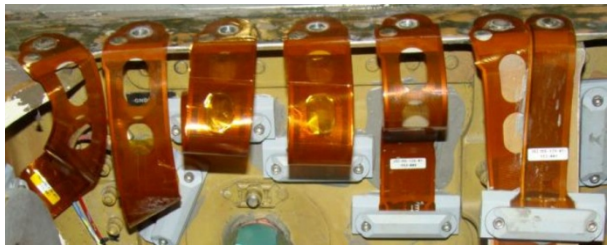
P-3 Fatigue Critical Areas[1]

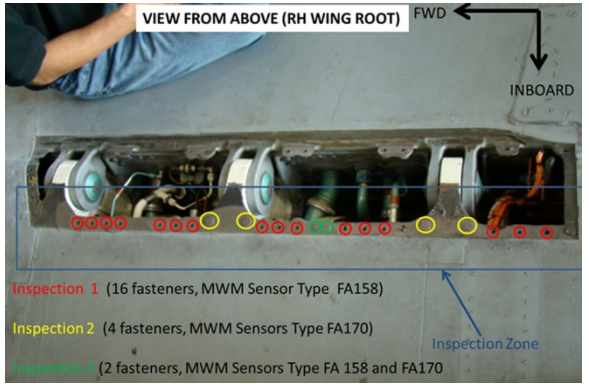


Northrop Grumman

Full-Scale Testing of EA-6B
Outer Wing Panels[2]

US Navy Fighter Aircraft





Why after hundreds of <u>successful</u> coupon tests and multiple full-scale tests has the technology not transitioned to DoD and commercial fleets?

Sources:

[1]Neil J. Goldfine, et al, "Surface Mounted Periodic Field Current Sensors for Structural Health Monitoring," SPIE Conference: Smart Structures and Materials NDE for Health Monitoring and Diagnostics, Newport Beach, California; March 2001

[2]http://adt.larc.nasa.gov/files/2013/01/ADT_Sept2012_NorthGrum.pptx

Outline

- Obstacles to Permanently Installed Foil-Type Eddy Current Sensor Implementation
- Permanently Installed Linear MWM-Array & MWM-Rosettes for Crack Detection
- POD Curve Generation
- Durability & Environmental Testing
- Ongoing flight test
- Generational Hardware Development

Obstacles to Implementation of Local (vs Global) Sensors

- **POD** *(Probability of Detection)* validation standard practice did not exist
  - JENTEK developed a method for local sensors (AF Phase II)
  - Global sensors must be validated for all sensor/defect positions
- **Durability** must be proven, including in harsh environments
- **Costs** for sensors, cables and data loggers must be low enough

Local sensors will typically outperform global sensors in local detection performance

Obstacles to Transition of Eddy Current "Foil" Type Fatigue Gauges

- Cost per sensing node
- Acceptance of POD and false indication performance
- Calibration and recalibration (after shut down and restarting of embedded or portable data loggers)
- Electronics performance
  - Drift
  - Signal-to-Noise ratio
  - Low frequency (deep penetration) capability for buried cracks

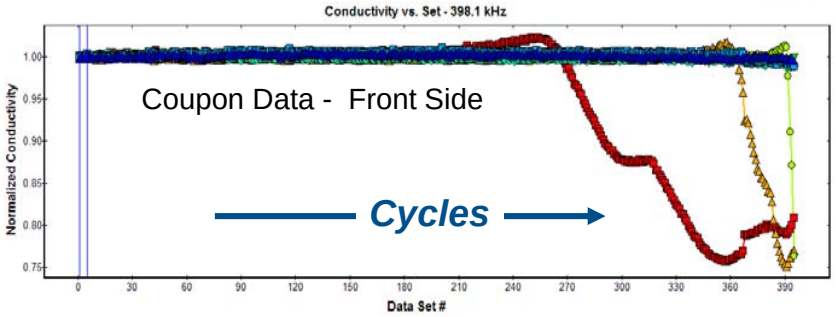
These obstacles have delayed the implementation of eddy current foil gauges for over a decade

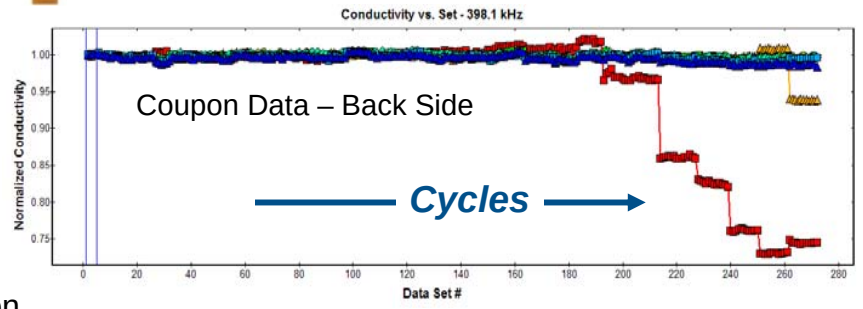
Continuous Monitoring vs. Scheduled Inspections

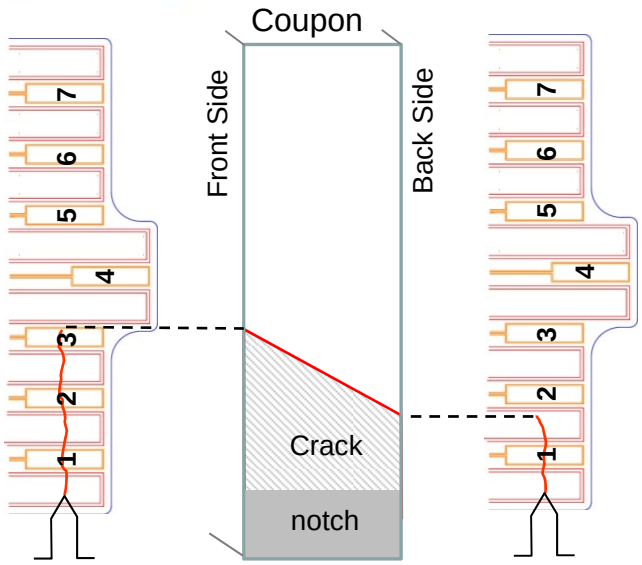
Continuous monitoring

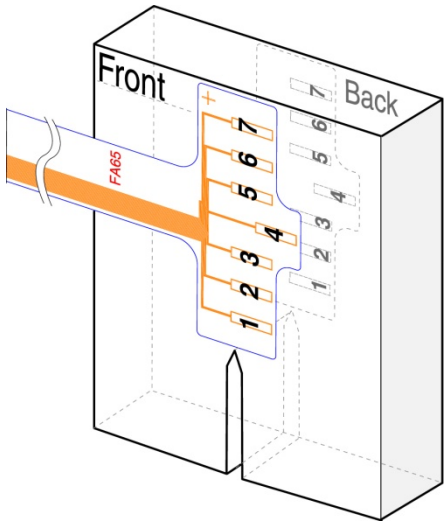
FA65 MWM-Array

Scheduled inspections to simulate on-aircraft use









This test proved that either in continuous on-board monitoring mode or when using portable data logger on the ground, surface-breaking cracks provided a large, reliable response compared to drift and other error sources

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

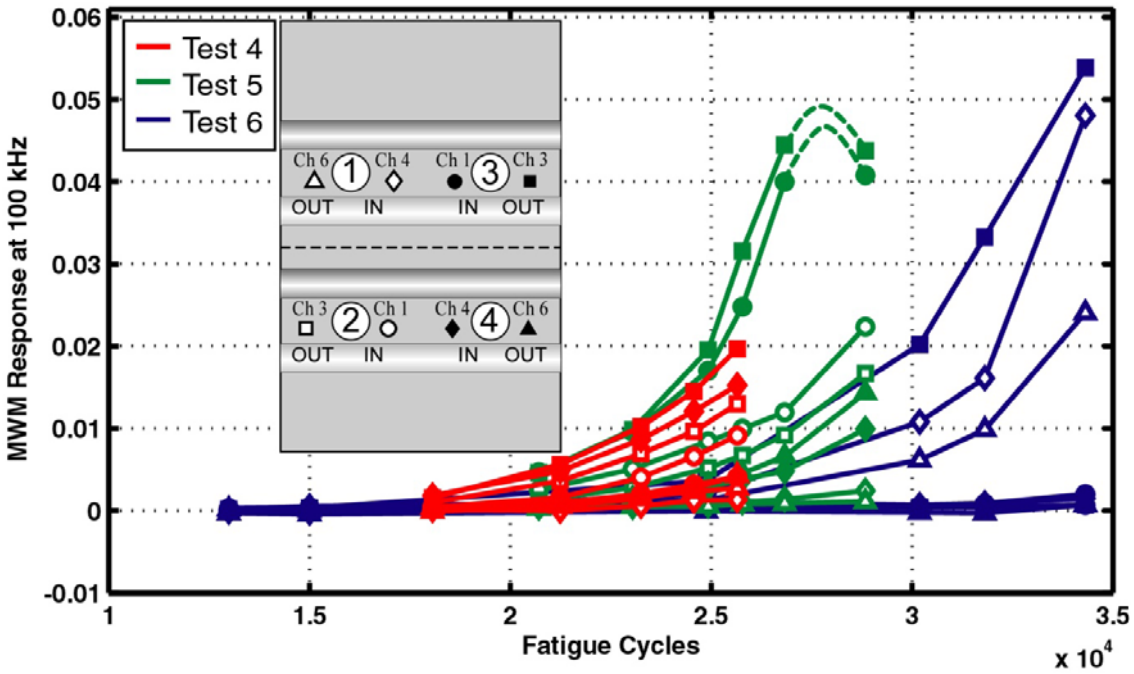
Surface Breaking vs. Buried Cracks

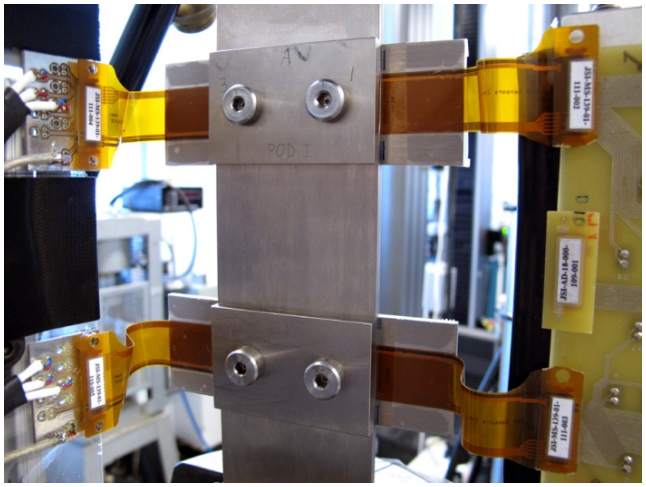
- Many practical applications require detection of second or third layer cracks
- JENTEK 7000/8000 series hardware is limited on the low frequency end to 6 kHz and is not suitable for cracks beyond the first layer
- Early tests showed that buried cracks in the far side of the first layer could be detected but performance was limited by instrument drift and signal-to-noise ratio

This low-frequency limitation has delayed implementation for many applications

Buried Crack Detection Demonstration

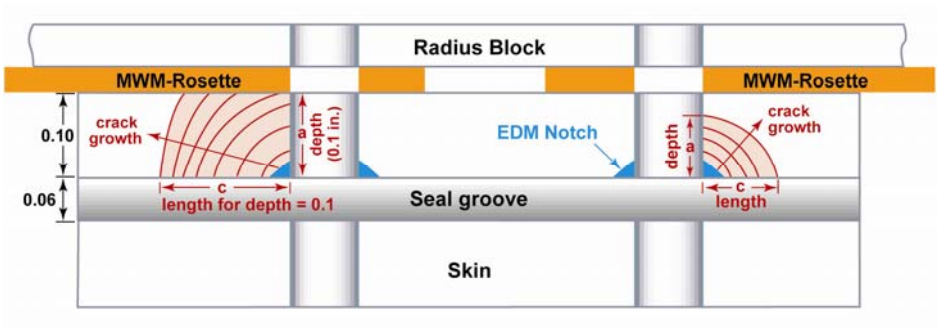
*from Three Tests vs Fatigue Cycles





Note that on the same coupon with holes machined in the same manner, under the same load, there is still a very large scatter in the time to crack initiation.

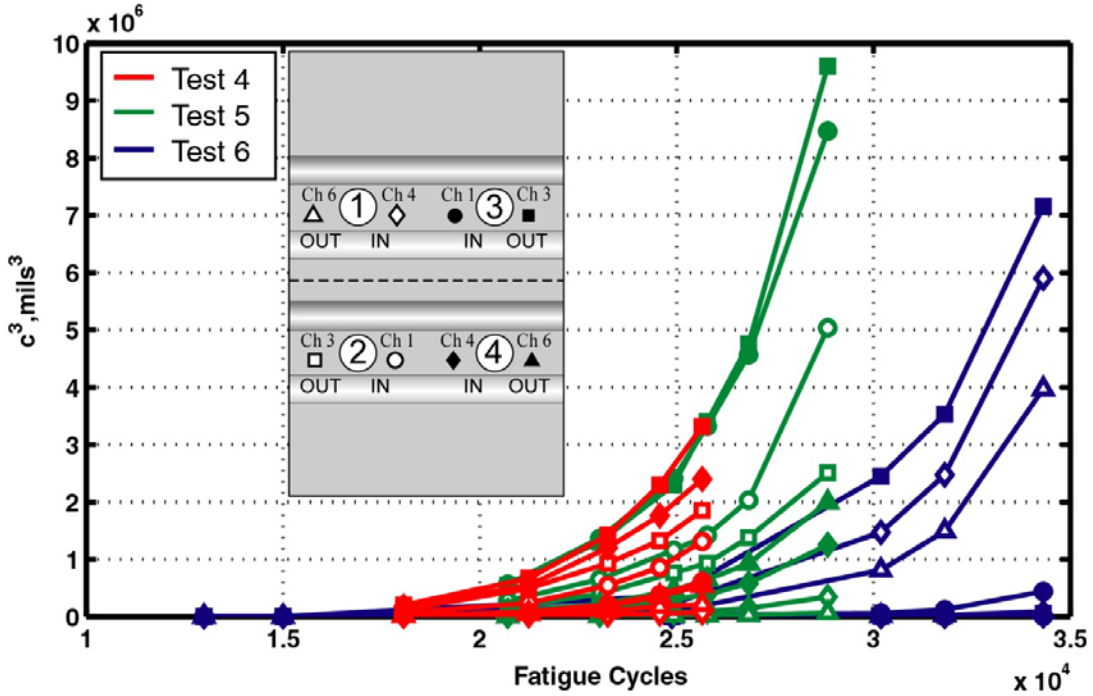
This validates the need for on-board installed fatigue sensors

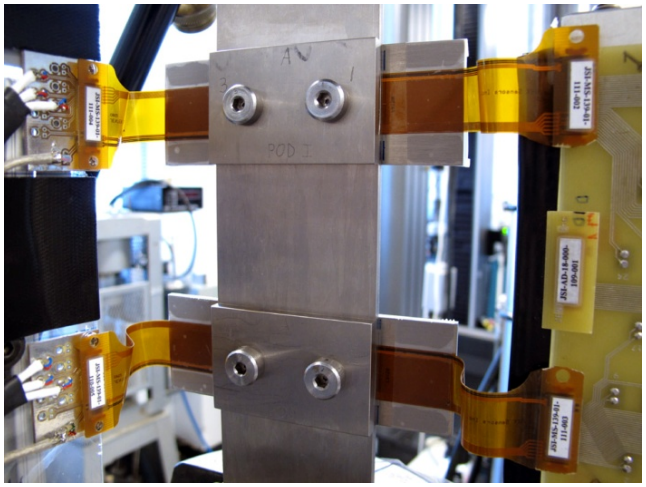


Cross-section of layers in the region of interest with the definition of crack length and depth

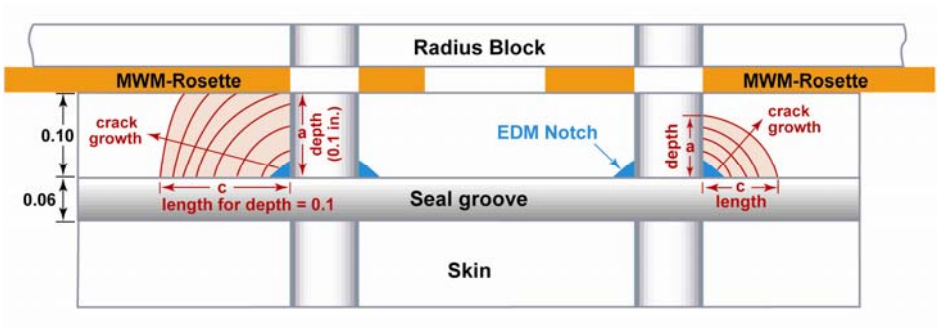
Graph of Flaw-Size Measurements from Acetate Replicas

*from Three Tests vs Fatigue Cycles



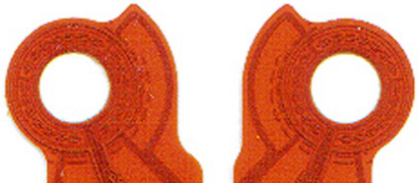


Acetate replica results were used to enable generation of POD curves

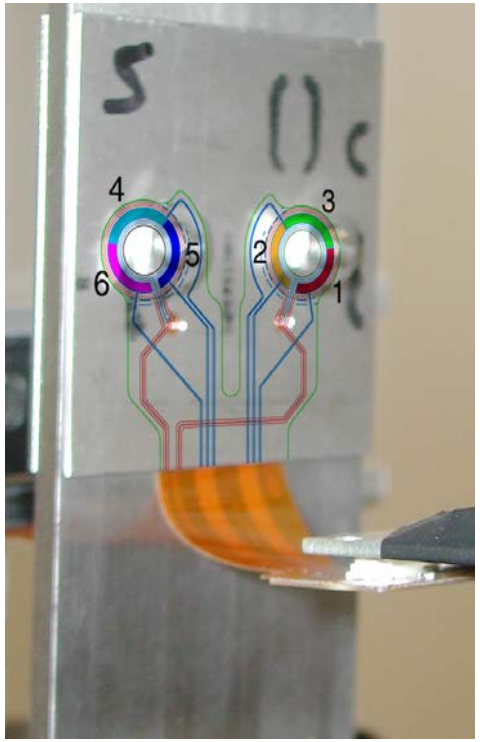


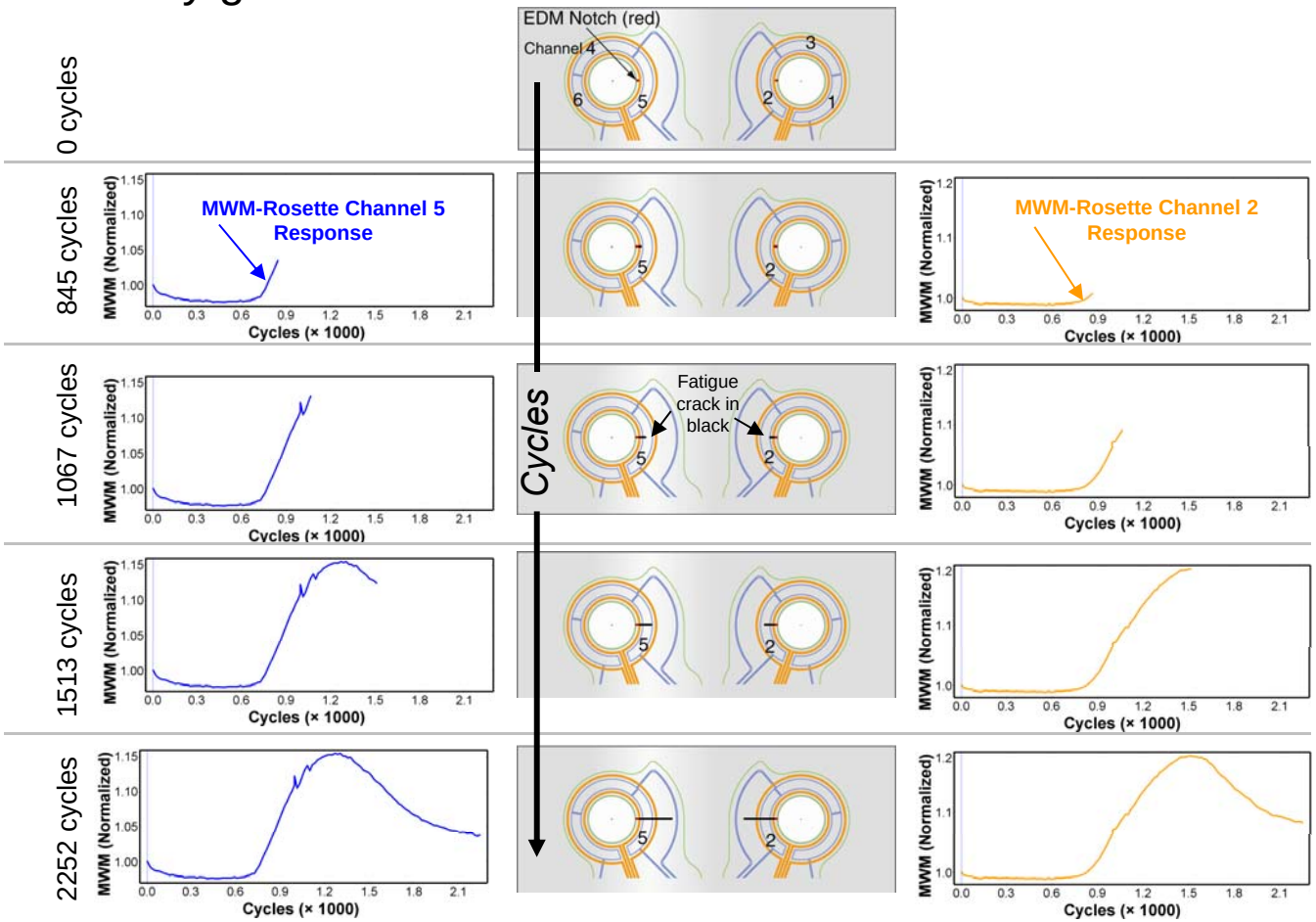
POD Data Generation for Surface Breaking Flaws

- No method existed for generating POD data for foil gauges
- Method was developed and validated with the statistical support of Floyd Spencer
- POD curves were successfully generated



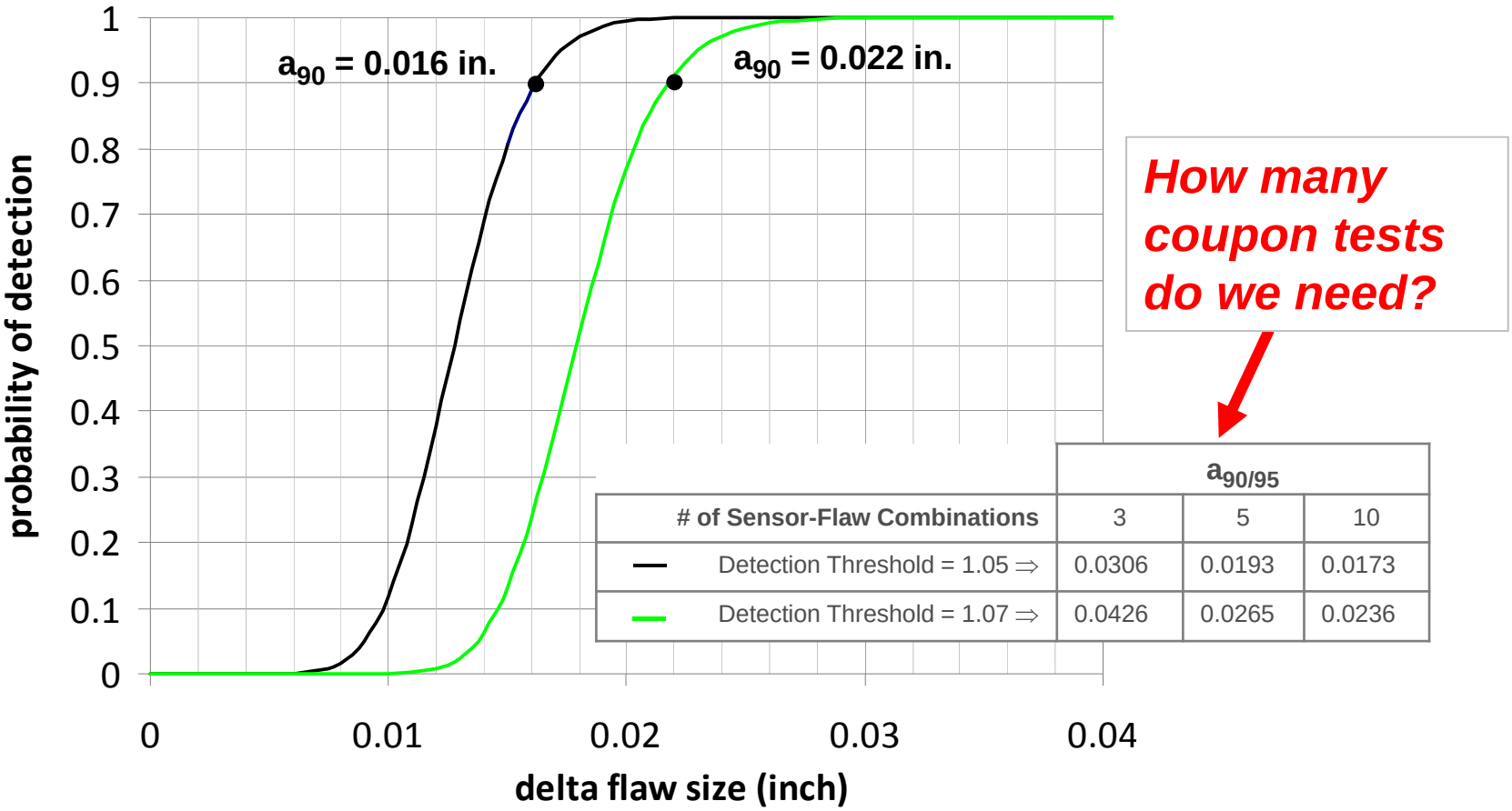
FA138 MWM-Rosette





First POD Curves for Installed Foil-Type Eddy Current Sensors – Surface Breaking Flaws

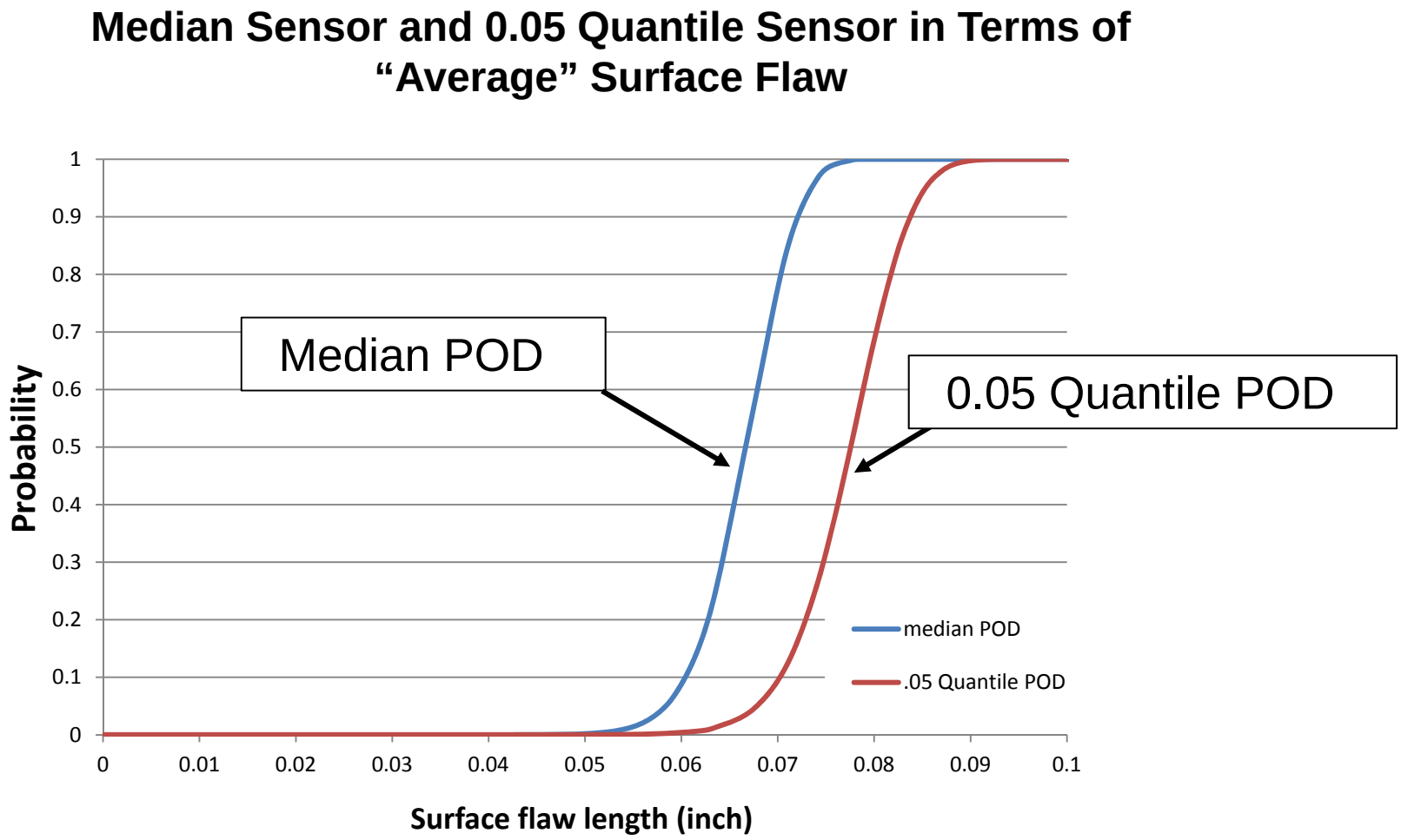
- Phase I data limited to 2 flaws
  b_0 est. = 3.920, σ_s est. = 0.400, and σ_r est. = 0.0082



	$a_{90/95}$		
# 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

How many coupon tests do we need?

First POD Curves for Installed Foil-Type Eddy Current Sensors – Buried Flaws



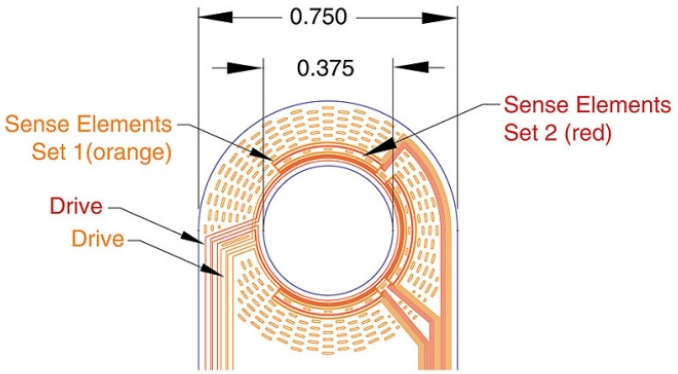
POD data can now be generated in days not weeks

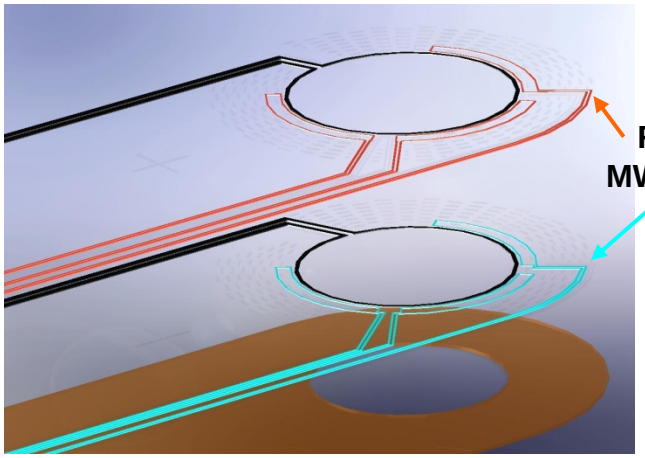
Durability and Environmental Testing

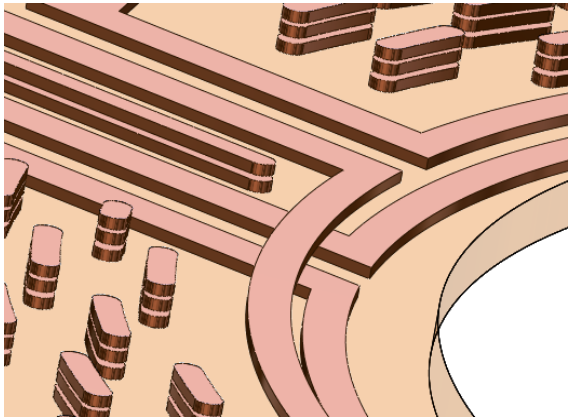
- **F-16 ASIP Program for Environmental Exposure Testing**
  - Exposure to:
    - Salt Fog
    - Fuel
    - Cleaning Fluid
    - Hydraulic Fluid
- **Durability Testing & Performance Evaluations in Fatigue Tests**
  - Linear MWM-Arrays at faying surface embedded in lap joint
  - MWM-Rosettes at fastener holes, under washer
  - Numerous coupon tests and full-scale tests
- **Phase II Air Force SBIR: "Embedded Sensors for Monitoring Fatigue Damage in Harsh Environments"**
  - Develop **MWM-Rosettes** for target applications
  - Develop low-cost **POD curve generation** method for embedded sensors
    - Use coupons monitored with embedded sensors to generate $\hat{a}$ vs a data
    - Generate POD curves using a process similar to that of MIL-HDBK-1823
  - Perform **environmental and durability testing** for target applications

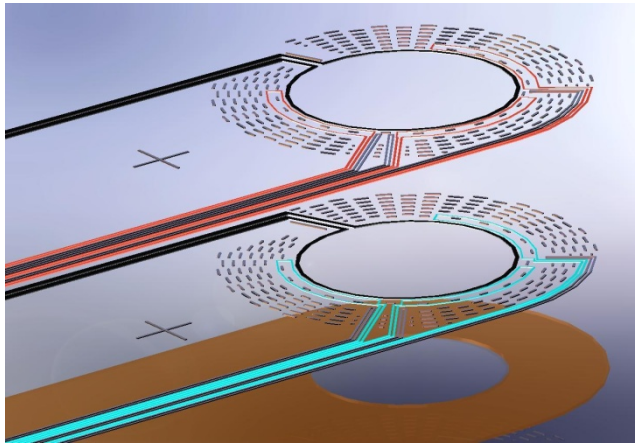
Redundant Drives & Durability Enhancing Pillars

FA158 MWM-Rosette









Sensor Environmental Testing

- Program targets monitoring of fatigue in F-16 components using embedded eddy current sensors
- The focus of this funded program was sensor adaptation and environmental testing

Mount

Seal

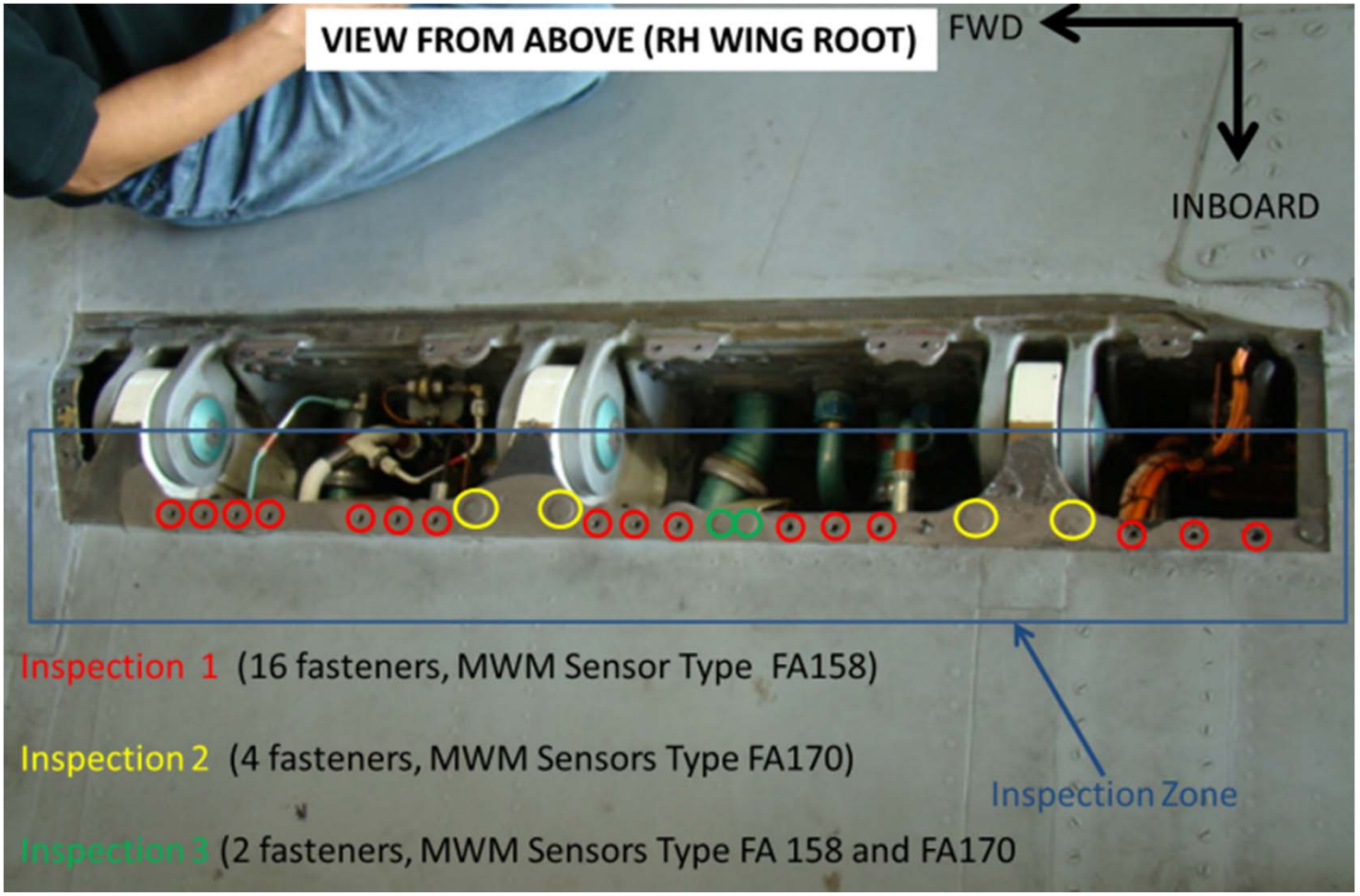
Sealant removal for data acquisition

Environmental Test Results Summary

Test	Format	Duration	Survive?
JP-5 Fuel Immersion	Sealed with Cable	17.5 days	**Yes**
	Sealed	35 days	**Yes**
	Other sleeving materials	35 days	**Yes**
Salt Fog Exposure	Sealed	200, 300, 400, 500 hrs	**Yes**
	Sealed with Cable	500 hrs	**Yes**
	Bare leads	200 hrs	**Yes**
	Bare Connector	100 hrs	**Yes**
Cleaning Fluid	Bare, MEK	½ day	**Yes**
	Bare, DS-108	½ day	**Yes**
Hydraulic Fluid	Bare, Royco 782	7 days	**Yes**

All sensors passed all environmental tests without any noticeable change in their electrical characteristics

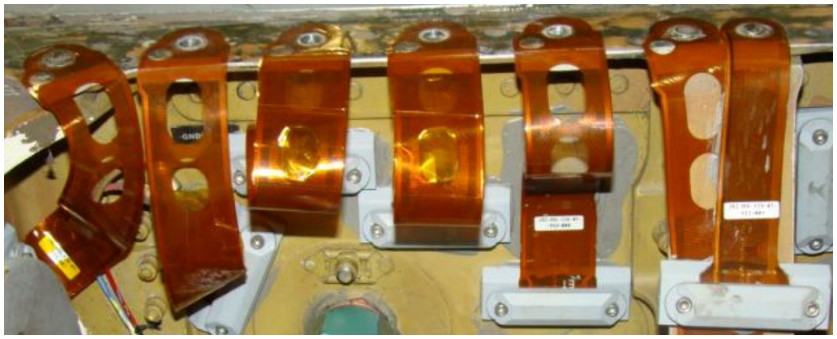
U.S. Navy Flight Test Installation Locations

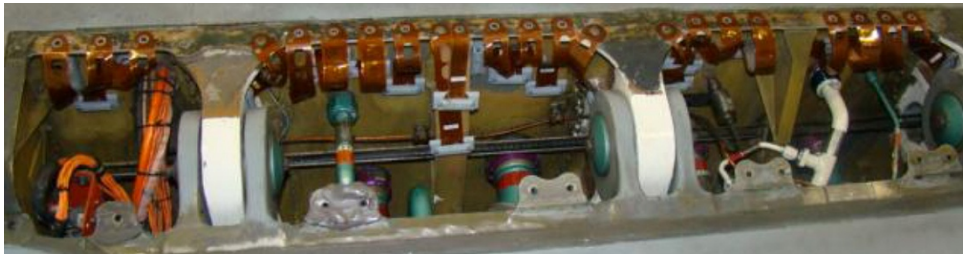


GridStation® System

Used for U.S. Navy Flight Test MWM Installation

U.S. Navy Flight Test Installation





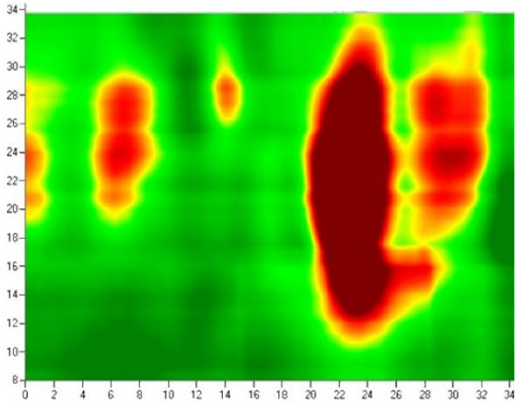
- 23 MWM-Array sensors installed
- Now in flight testing
- U.S. Navy personnel trained to take data with JENTEK GridStation

Hardware Improvements Address Remaining Obstacles: Drift/Signal-to-Noise and Cost

- **7000/8000 Hardware**
  - Too costly
  - Drift and related error sources that limit performance
  - Limited to first layer crack detection

- **8200 Hardware**
  - Solves drift and related error issues
  - Very low frequency capability
  - Dramatically improved signal-to-noise

Now Capable of *Internal Corrosion Characterization* through Metallic Weather Jacket and Insulation



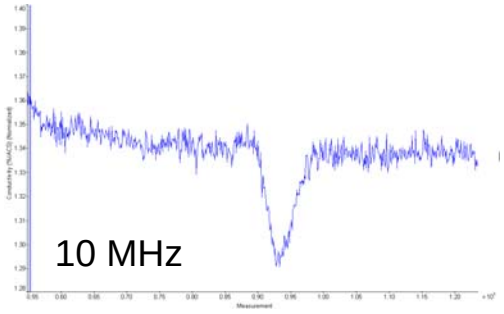
- **Lower cost**
- **Lighter weight**
- **More Practical**

- **Future Generation Hardware**
  - Targeted for specific need
  - Lower-cost components
  - Simplified cabling or wireless communication

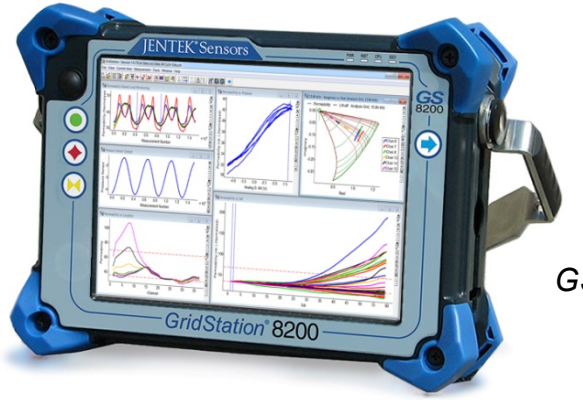
Noise Improvement

GS-IN7000β / GS-8000β

- 10 kHz – 10 MHz operating frequency
- Not for sale after May 2014

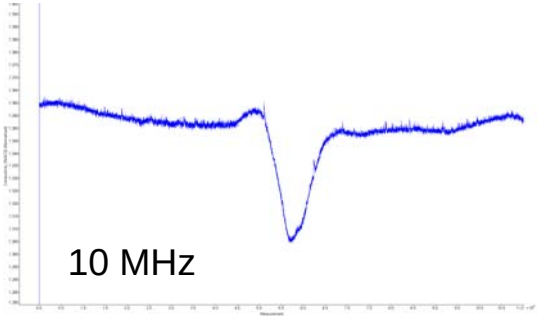


IN7000 taken at 100 Hz data rate



GS-8200

- 5 Hz – 20 MHz operating frequency
- 100× faster data rate than IN7000
- 10× Improved signal-to-noise
- 2014 product launch
- MR-MWM-Arrays can now inspect through ½ inch of steel (or aluminum)



8200 taken at 1.3 kHz data rate

Summary

- Foil-type eddy current sensors (such as MWM-Arrays) can **reliably detect surface and buried cracks**
- BUT, cost issues have not been addressed for embedded solutions
- For high-priority surface and buried crack applications, near-term implementations with portable 8200 series data loggers are practical
- Next generation systems must be lighter weight, lower cost, and more practical (e.g. modular, wireless, etc.)