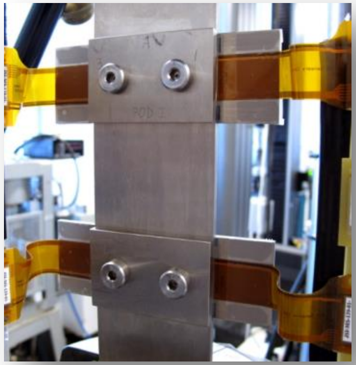
SHM Reliability Workshop, MIT, Cambridge, MA
April 14-15, 2015

SHM on Aircraft

In the Lab



Performance Studies for Permanently Installed Eddy Current Sensor Crack Detection

Neil Goldfine, Ph.D.[1], Floyd Spencer, Ph.D.[2], and David Grundy[1]

[1]JENTEK Sensors, Inc. 110-1 Clematis Avenue, Waltham, MA
[2]Sfhire, 13812 Haines Avenue, NE, Albuquerque, NM

MWM sensors and MWM-Arrays are covered by several issued and pending patents, including, but not limited to: 8,928,316, 8,803,515, 8,768,657, 8,494,810, 8,237,433, 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).

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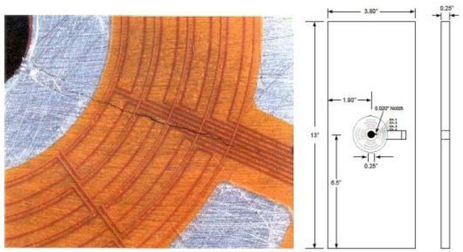
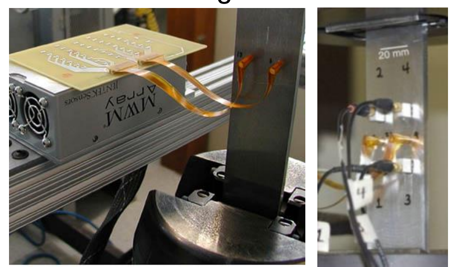
Historical MWM-Array Coupon Tests

Foil-Type Installed Eddy Current Sensors

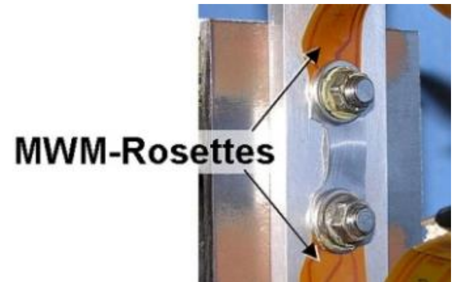
2001
Lockheed Martin Coupon Fatigue Tests[2,3]



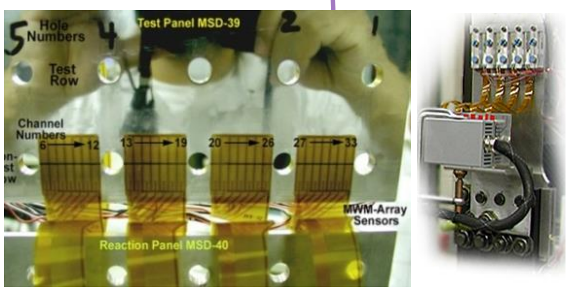
2004 - 2005
Northrop Grumman SIPS Program[1,4]



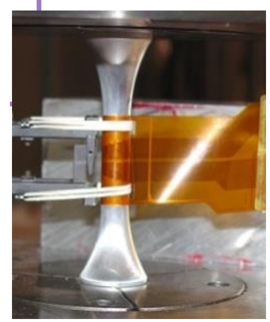
2006
U.S. Navy Phase II



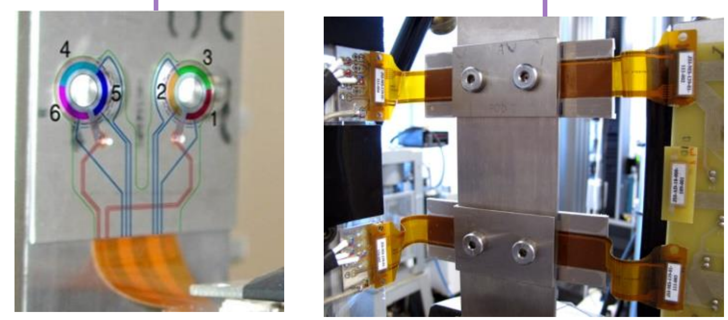
2001 → ***2013***



2004
Lockheed Martin MSD Coupon Fatigue Tests[1]



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



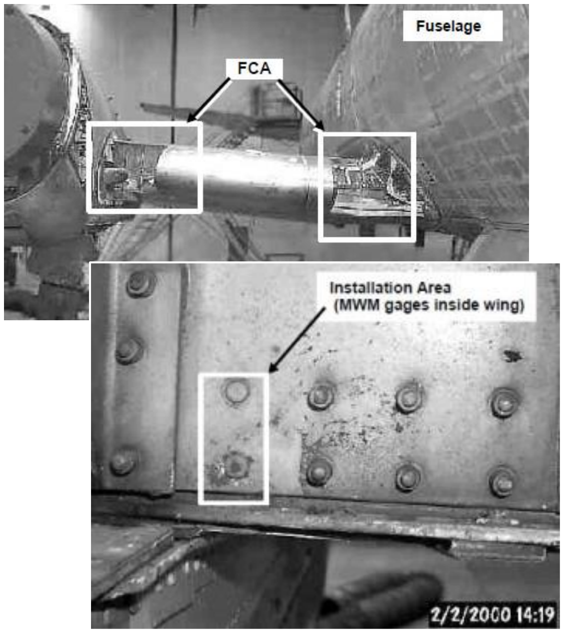
2009 - Phase I; 2012 - Phase II
U.S. Air Force

Sources:
[1]Goldfine, N., et al, "Fatigue and Stress Monitoring with Magnetic Sensor Arrays," Annual Society for Experimental Mechanics (SEM) Conference, St. Louis, Missouri; June 2006.
[2]Goldfine, N., 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]Papazian, J., et al, "Sensors for Monitoring Early Stage Fatigue Cracking," International Journal of Fatigue 29 (2007) 1668-1680.

Example Full-Scale Tests & Flight Tests

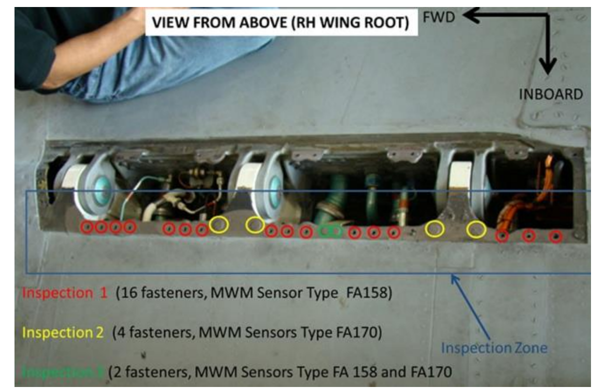
2000-2002 → **2006-2007** → **2013 - 2014**

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?

[1]**Source, left image:** Neil J. Goldfine, et al, "Surface Mounted Periodic Field Current Sensors for Structural Health Monitoring," SPIE Conf.; Smart Structures and Materials NDE for Health Monitoring and Diagnostics, Newport Beach, California; March 2001
[2]**Source, Middle image:** http://adt.larc.nasa.gov/files/2013/01/ADT_Sept2012_NorthGrum.pptx [Public released, Approved for Public Release, Distribution Unlimited : Northrop Grumman Aerospace Systems Case 12-1952]

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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

Local sensors will typically outperform global sensors in local detection performance

But coverage is inherently limited for local sensors

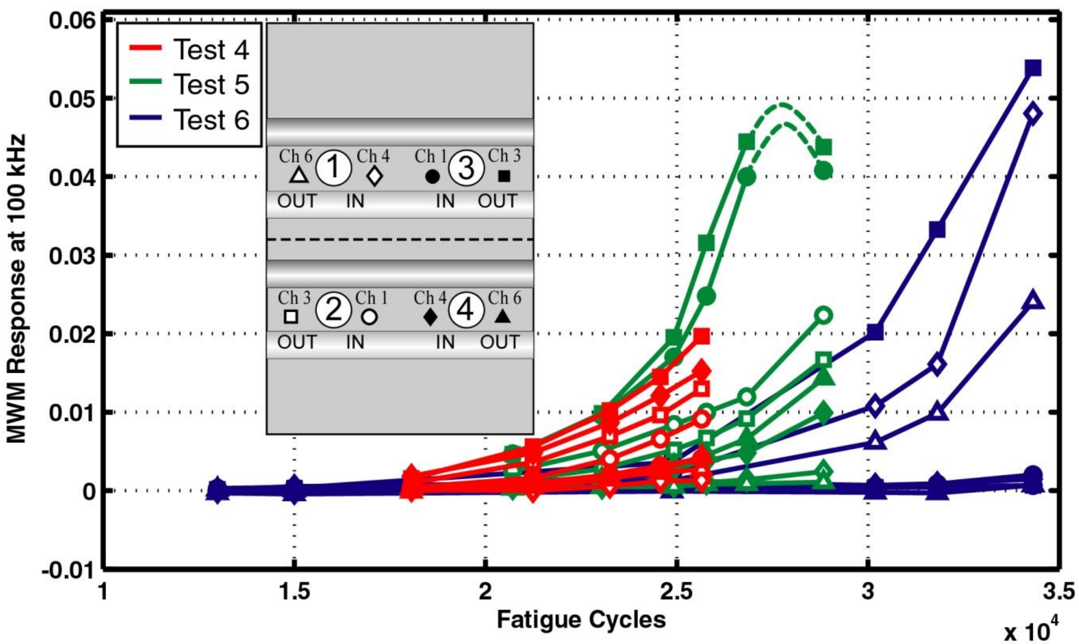
Obstacles to Transition of Eddy Current "Foil"-Type Fatigue Gauges

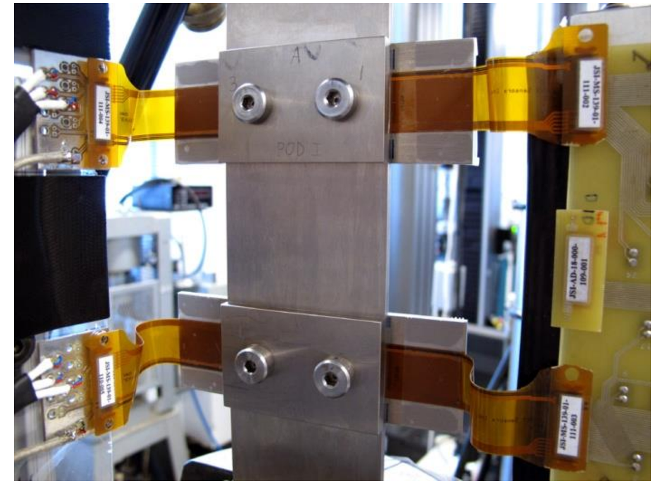
- Acceptance of POD and false indication performance
- Calibration and recalibration (after shut down and restarting of embedded or portable data loggers)
- Electronics performance
  - Drift
  - Signal-to-Noise ratio
  - Low frequency (deep penetration) capability for buried cracks
- **Durability** must be proven, including in harsh environments
- **Costs** for sensors, cables and data loggers must be low enough

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

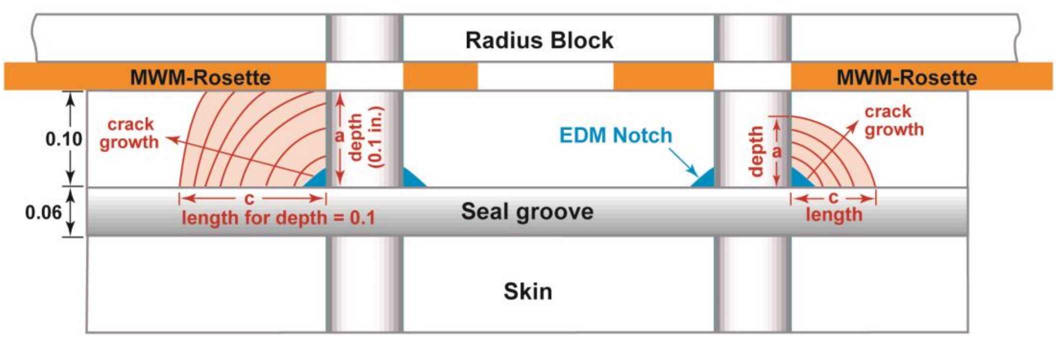
Buried Crack Detection Demonstration (7000 Series Results)

*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.

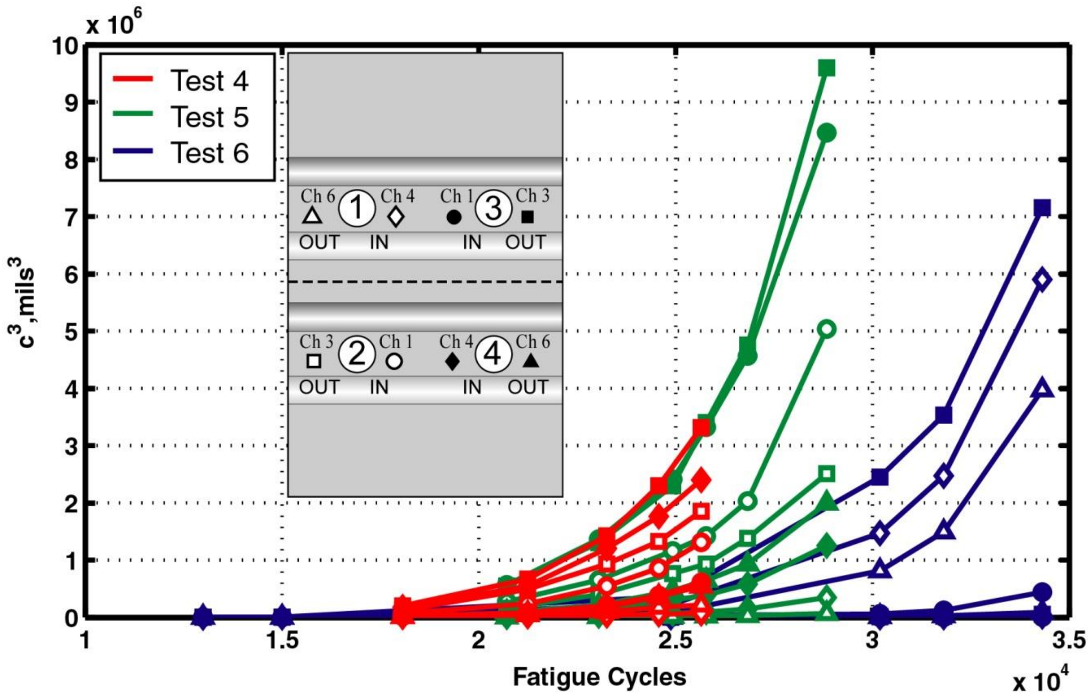


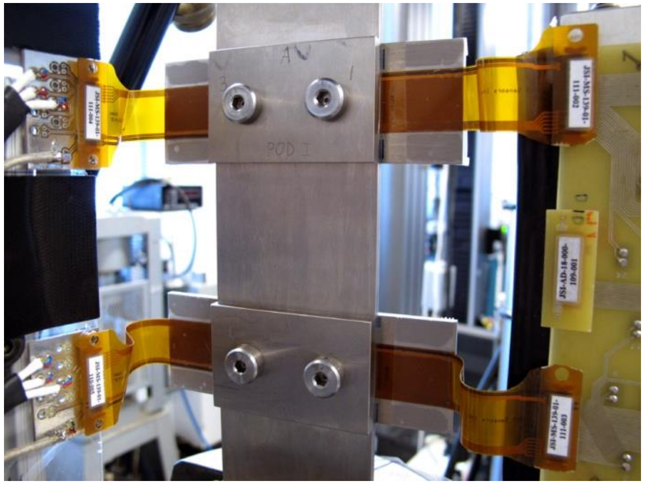
Cross-section of layers in the region of interest with the definition of crack length and depth

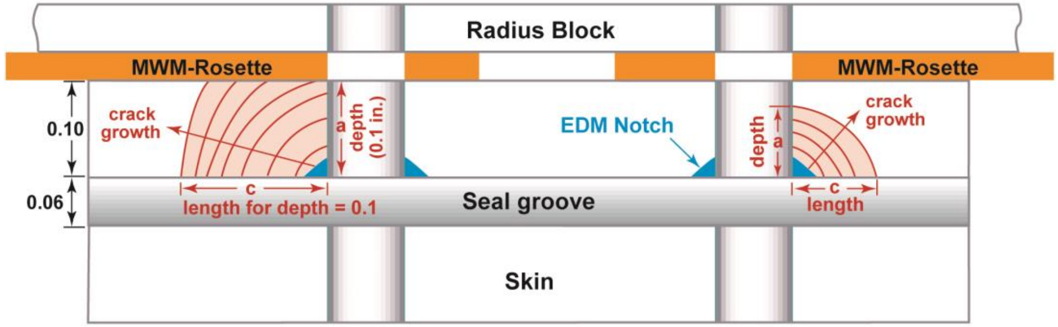
This validates the need for on-board installed fatigue sensors

Flaw-Size Measurements from Acetate Replicas

*from Three Tests vs Fatigue Cycles



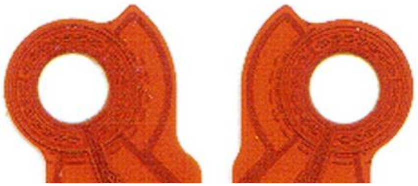




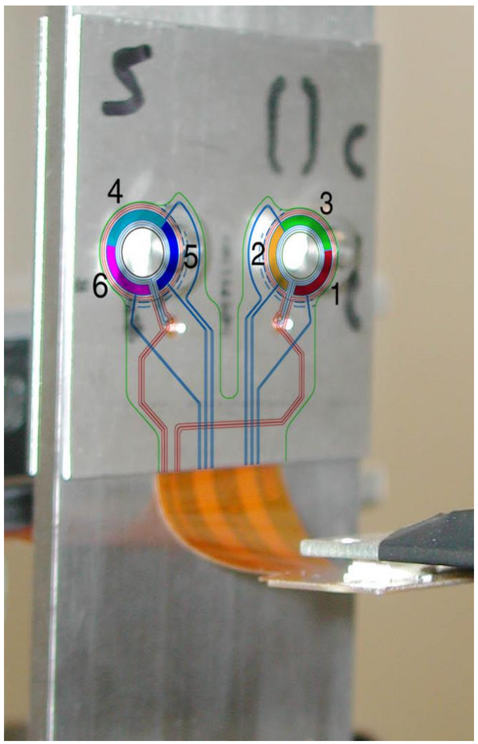
Acetate replica results were used to enable generation of POD curves

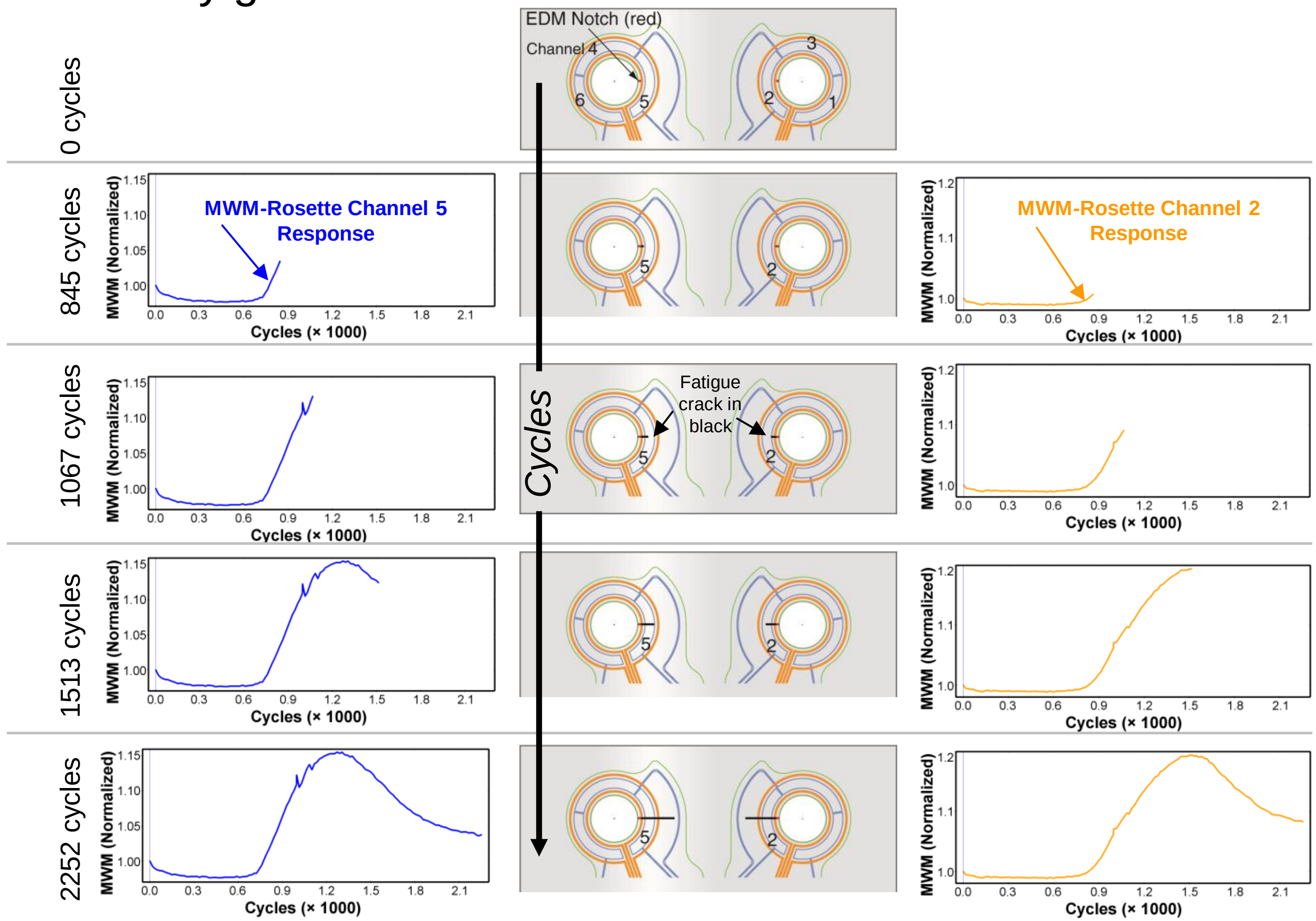
POD Data Generation for Surface Breaking Flaws

- 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



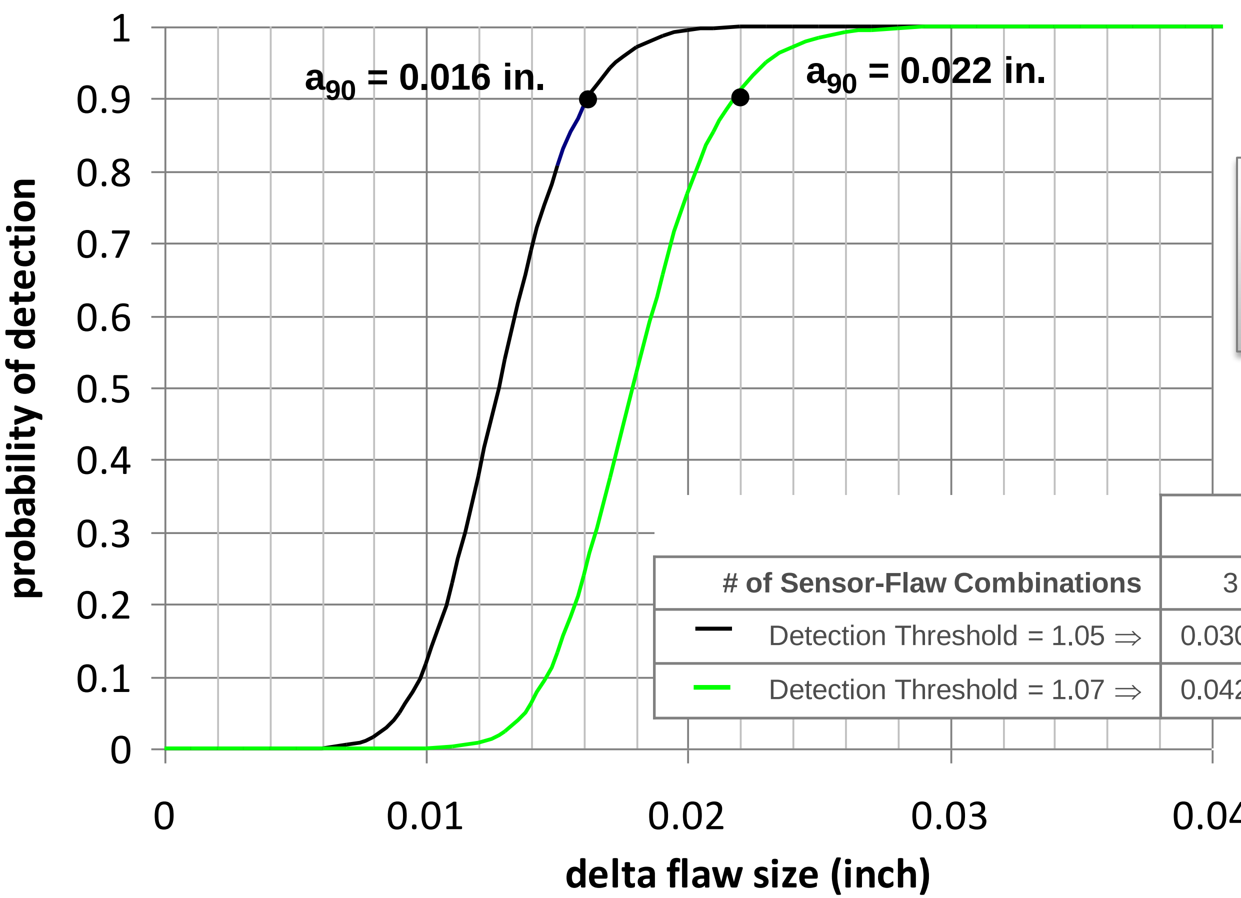
FA138 MWM-Rosette





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

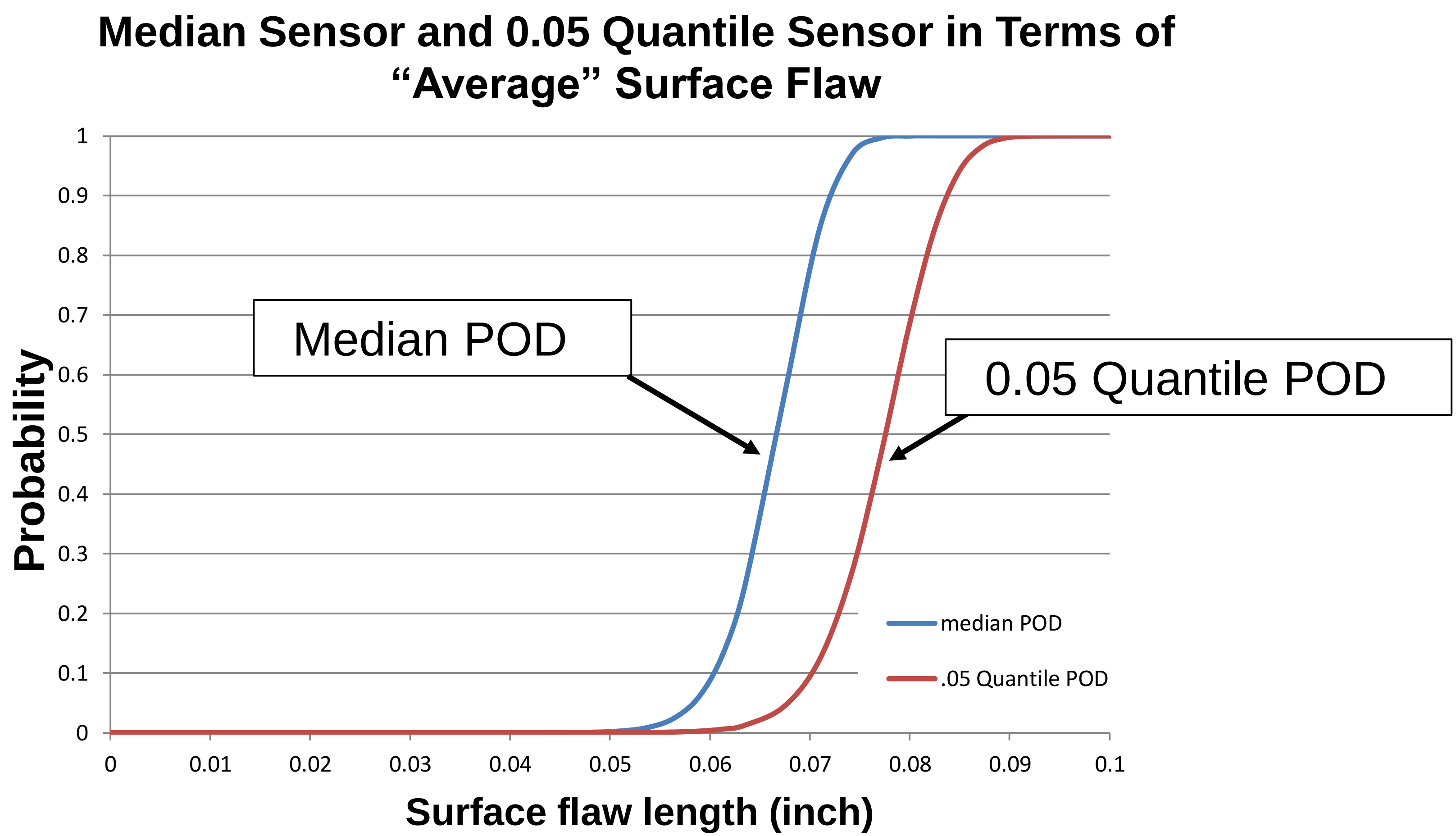
- Phase I data limited to 2 flaws
  b_0 est. = 3.920, σ_s est. = 0.400, and σ_r est. = 0.0082



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

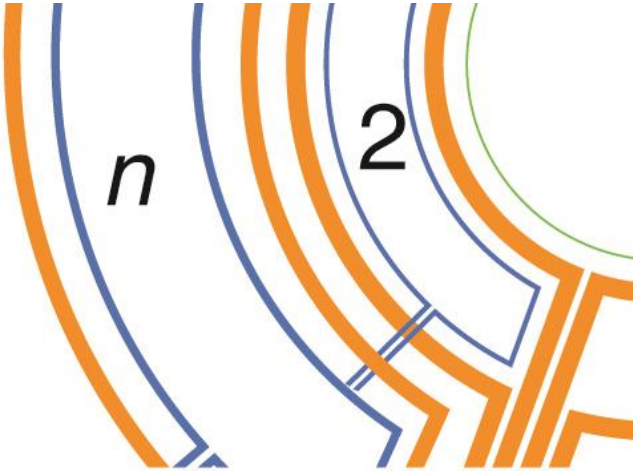
First POD Curves for Installed Foil-Type Eddy Current Sensors – Buried Flaws

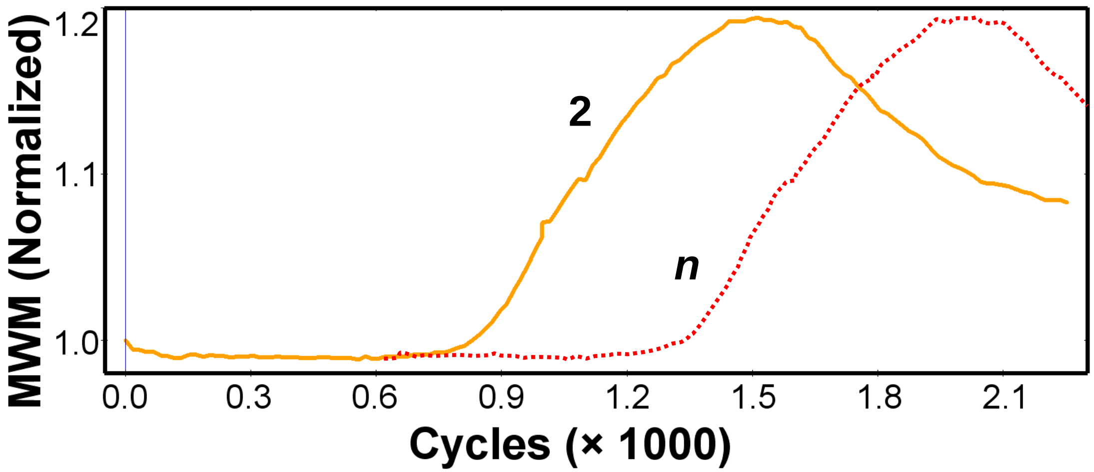


POD data can now be generated in days not weeks

To Improve POD Curve Estimation

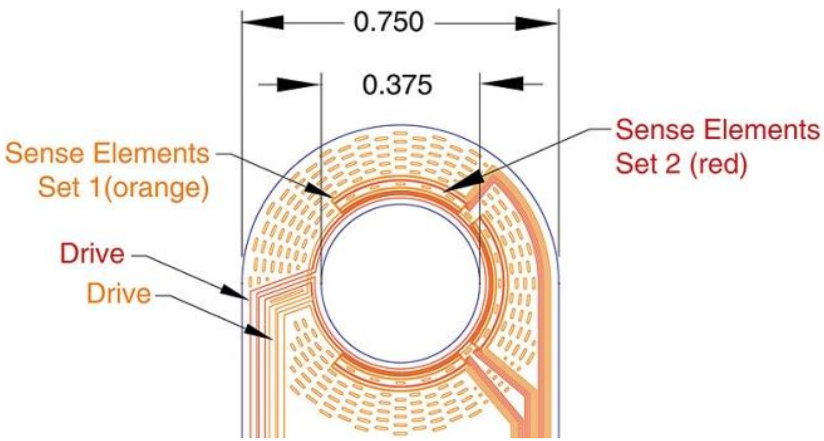
- **We can add another channel to expand linear range**



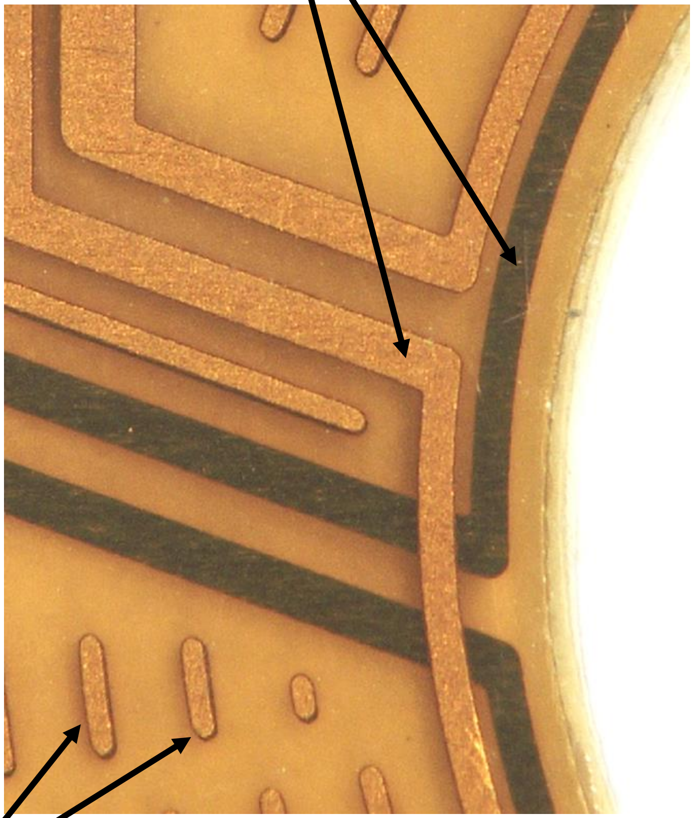


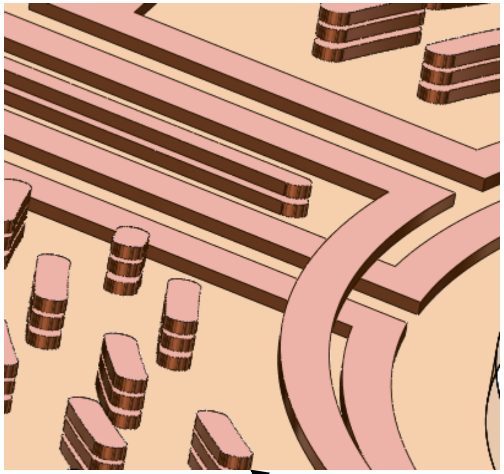
Redundant Drives & Durability Enhancing Pillars

FA158 MWM-Rosette



Redundant Drives





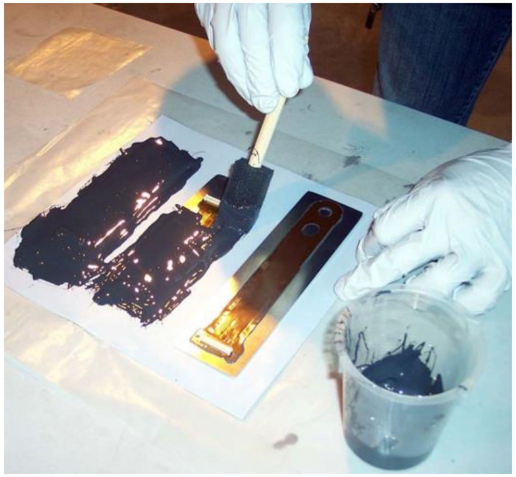
Durability Pillars

Sensor Environmental Testing

- Program targets monitoring of fatigue in military aircraft 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

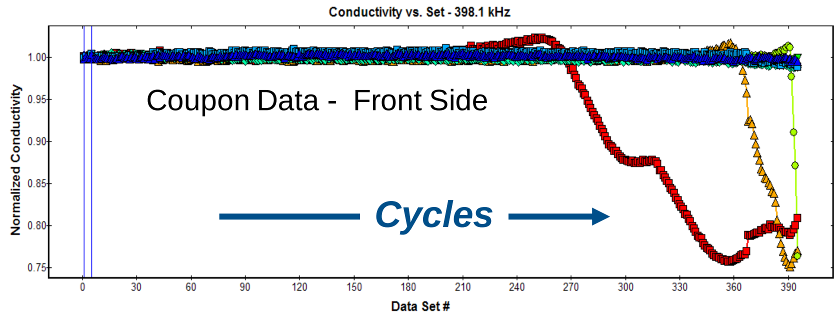
Environmental Test Results Summary

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**

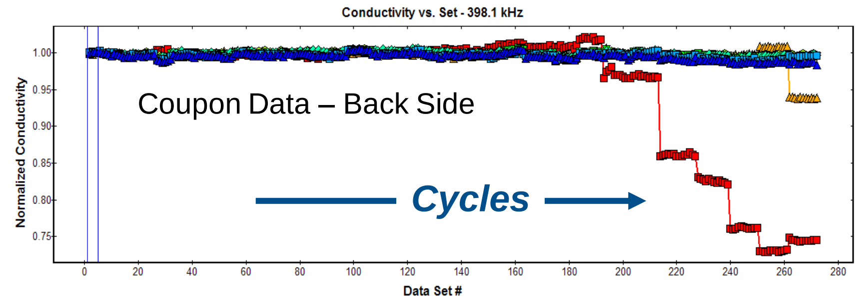
All sensors passed all environmental tests without any noticeable change in their electrical characteristics

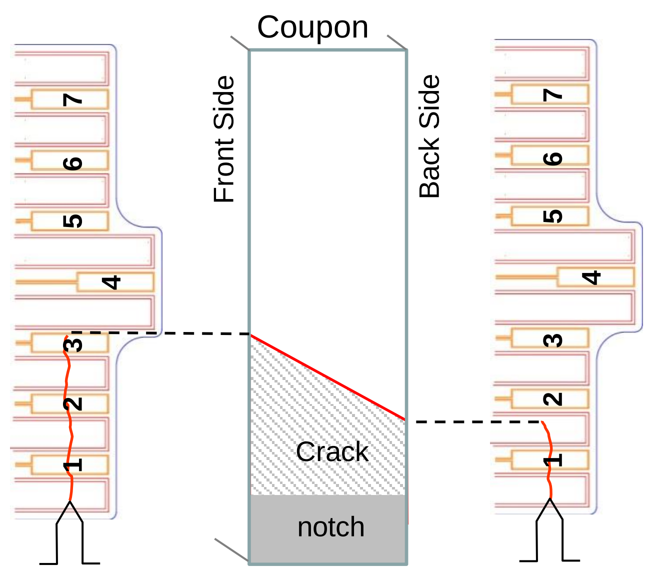
Continuous Monitoring vs. Scheduled Inspections

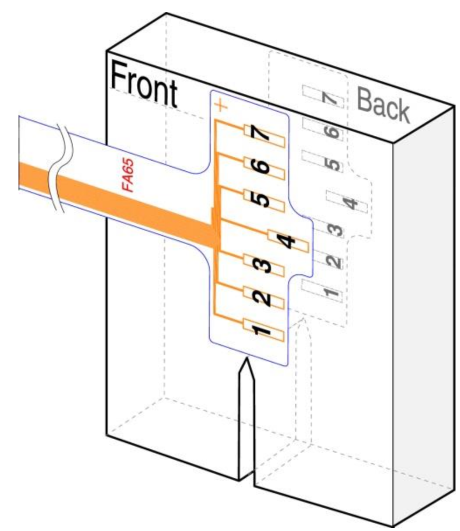
Continuous monitoring



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

- New 8200 systems provide the needed deep penetration, low frequency operation for buried cracks

Summary

- POD studies for local and global sensors must follow a self-consistent procedure that addresses each damage/sensor combination
- Foil-type eddy current sensors (such as MWM-Arrays) can **reliably detect surface and buried cracks**
- Instrument drift and actual in-service scenarios must be represented by reliability studies to capture actual performance
- For high-priority surface and buried crack applications, near-term implementations with portable 8200 series data loggers have addressed previous drift issues that prevented early adoption

Technical Contacts & References

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Phone: 781-373-9700 • Web: www.jenteksensors.com

Additional References

Goldfine, N., Grundy, D., Marx, J., Manning, B., Martin, C., Floyd S., Root, C., Nguyen, A., Engstrand, C., Kulowitch P., and Barrett, A., "Flight Testing of Permanently Installed Eddy Current Sensors for IVHM", AA&S 2014, Baltimore, MD, April 14-17, 2014.
NAVAIR Public Release SPR-2014-295. Distribution statement A -- approved for public release, distribution is unlimited.

Goldfine, N. and Spencer, F., "Calibration vs Calibration Verification for POD Studies & "Reliability" 2012 ASNT Fall Conference, Orlando, FL, October 29-November 1, 2012.

Goldfine, N., Sheiretov, Y., Grundy, D., Jablonski, D., Spencer, F., Keene, D., LeMasters, T., "POD Studies for Embedded Eddy Current Sensors," Aircraft Structural Integrity Program (ASIP) Conference, San Antonio, Texas, Nov. 29 - Dec. 3, 2011.

Sheiretov Y., Spencer F., Jablonski D., Grundy D., Goldfine N., Keene D., "POD Curve Generation for Permanently-Mounted ET Arrays" 2011 Aircraft Airworthiness & Sustainment (AA&S) Conference San Diego, CA; April 18-21, 2011.

Goldfine N., Sheiretov Y., Grundy D., Jablonski D., Spencer F., Keene D., "A POD Curve Generation Methodology for Embedded NDT Sensing", Integrated Systems Health Management (ISHM) Conference, Boston, MA, July 19-21, 2011.