Hand-Held, Wireless (or Ethernet) Eddy Current Array System for Rapid Inspection

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JENTEK MWM sensors and MWM-Arrays covered by issued and pending patents, including, but not limited to: 8,768,657, 8,494,810, 8,237,433, 8,234,433, 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

Technology Summary / Overview

Hand-Held Analytical Instrument

Applications for

- NDT (defects, quality)
- SHM (damage, stress, temperature)
- General Purpose Impedance Inst.

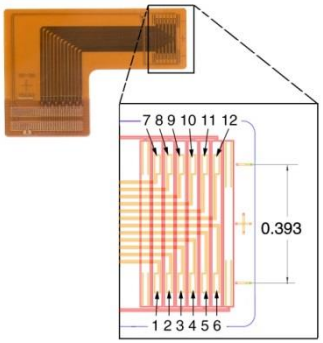
Features

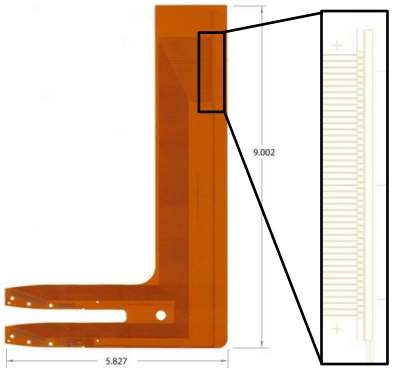
- 7-Channel Impedance Instrument
- 3 frequencies
  - > simultaneous real and imaginary parts, or magnitude and phase
  - > 7 inductive sensing elements, 1 drive
  - > 200 Hz – 20MHz
- Sensor Tips for varied applications
- GridStation Software for Model-Based Inverse Methods

MWM-Array Technology

1. Sensors: MR-MWM®-Arrays

- **Paradigm shift** in sensor design (first priority is predictable response based on physics-based modeling)



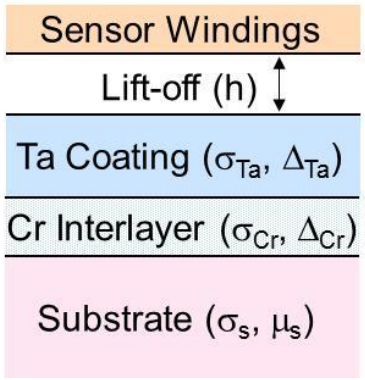


2. Next Generation® 8200α+ and jET™α Electronics

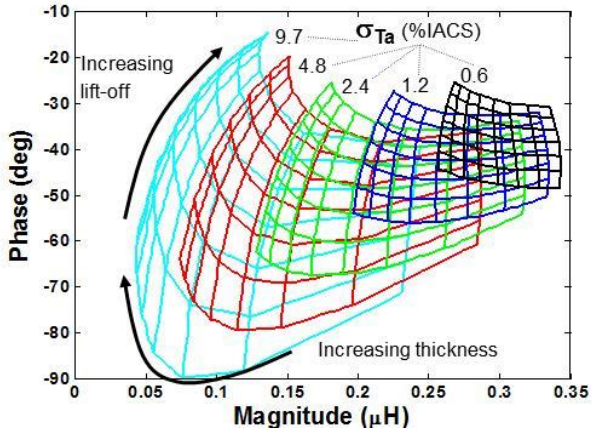
- **10x signal-to-noise improvement**
- **Very low frequencies (deep penetration)**
- **Crack detection through up to 0.5 inches of material**
- **Reduced drift**

3. GridStation® Software using Hyperlattices™

- **Rapid, autonomous data analysis**
  Performs multivariate inverse method (MIM) using precomputed databases
  - Defect & Property Images
  - Performance Diagnostics
  - Noise Suppression



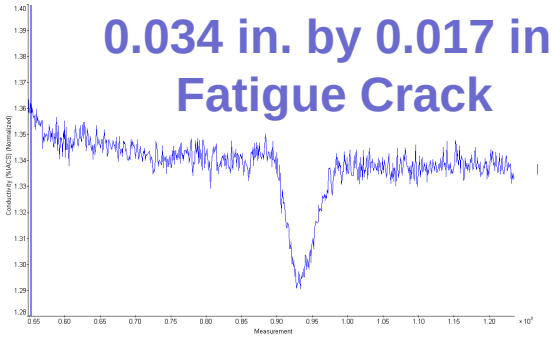
Solve Multiple Unknown Problems



Old vs New Instrumentation Performance

GS-IN7000β

- 10 kHz – 10 MHz operating frequency
- Used for all past MWM-Array engine component transitions
- Not available after 2014



IN7000 taken at 100 Hz data rate

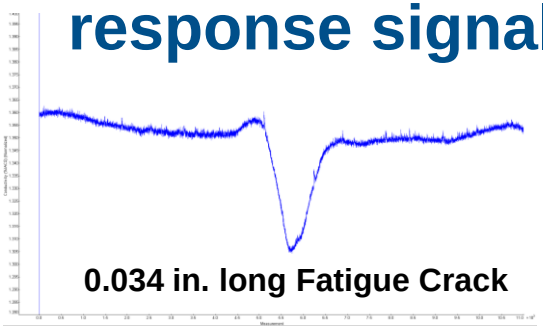
GS-8200α+

jETα

Next

- 2.5 Hz – 20 MHz operating frequency
- 100× faster data rate than IN7000
- 10× Improved signal-to-noise
- Now available

Substantially improved crack response signal-to-noise

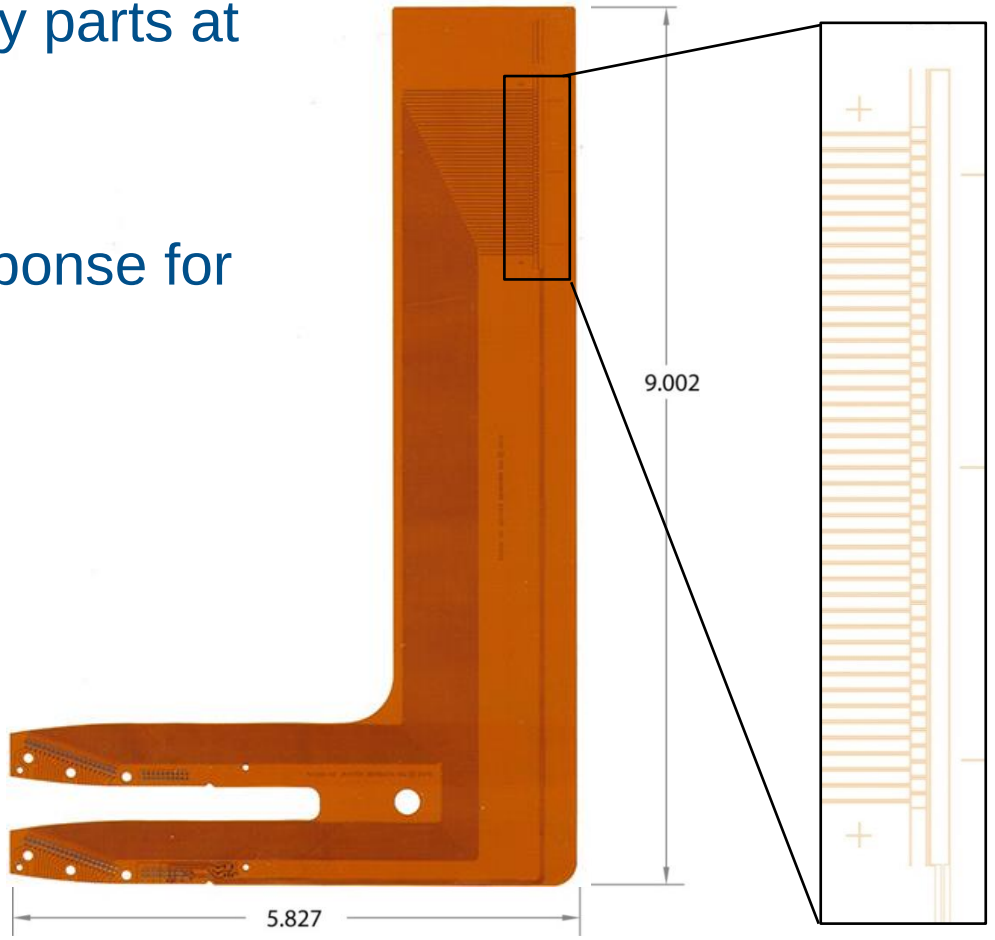


8200 taken at 1.3 kHz data rate

For complex parts

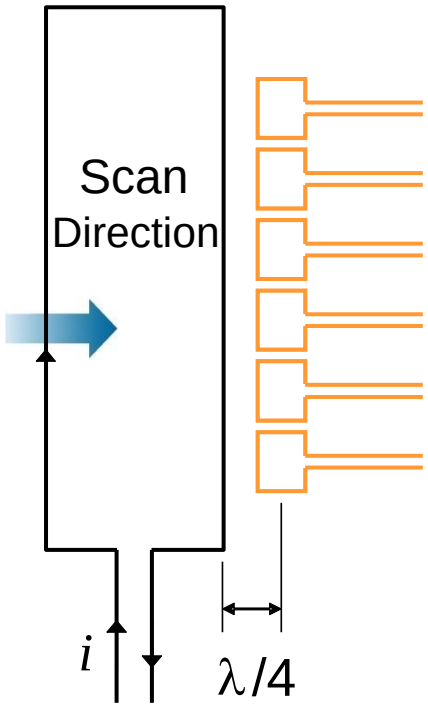
Advanced ET with Flexible Arrays: MWM-Array

- Substantially **reduced** instrument noise
- **Simultaneous measurement** of complex impedance real and imaginary parts at three frequencies
- Flexible arrays to limit lift-off
- Proper rescaling of crack response for varied lift-off



MWM-Array Sensor Selection

- Decay rate determined by skin depth at high frequency and sensor dimensions at low frequency
- Large dimensions needed for thick coatings/insulation
- Low frequencies needed to penetrate through thick materials

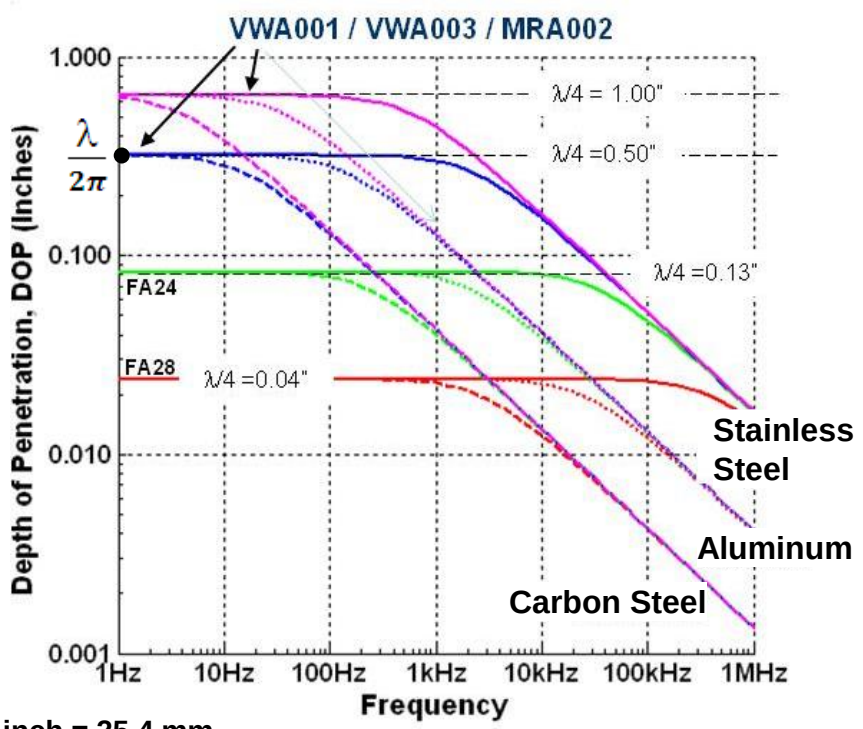


Depth of Penetration = $1/\mathrm{Re}(\Gamma_n)$

Low Frequency Limit = $\frac{\lambda}{2\pi}$

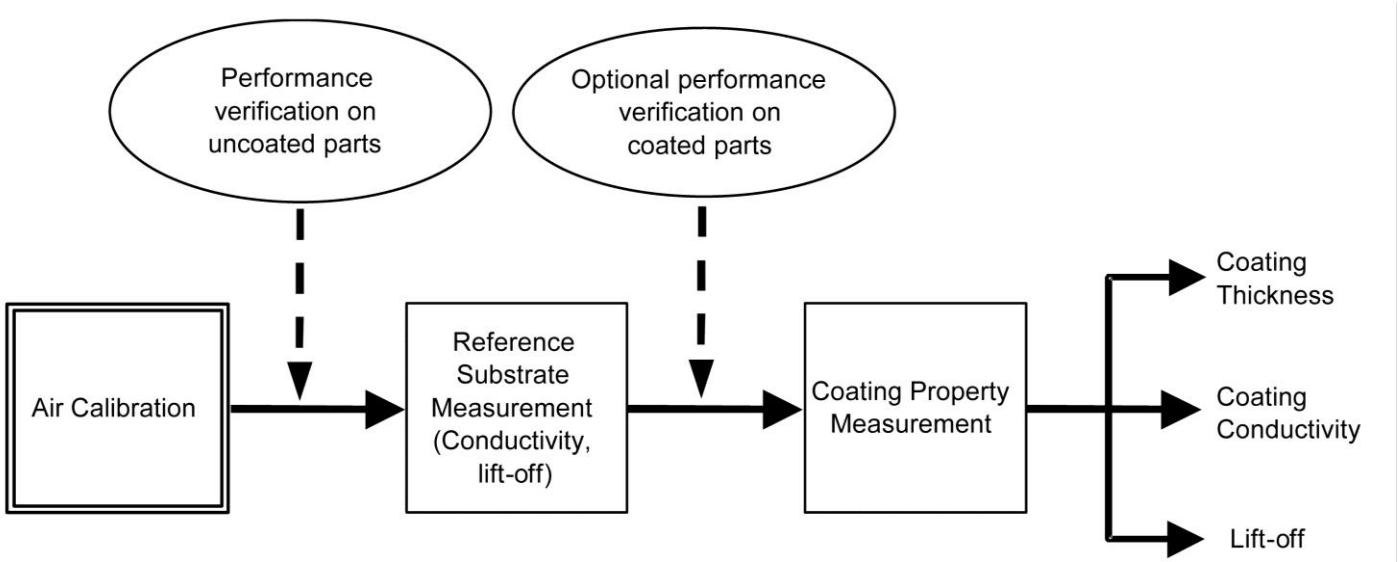
$$\Gamma_n = \sqrt{(2\pi n/\lambda)^2 + j2/\delta^2}$$

Skin depth: $\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}$



1 inch = 25.4 mm

ASTM Standard E2338-11



Designation: E 2338 – 06

Standard Practice for Characterization of Coatings Using Conformable Eddy-Current Sensors without Coating Reference Standards[1]

This standard is issued under the fixed designation E 2338; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

ASTM Standard E2884-13

Designation: E2884 – 13

Standard Guide for Eddy Current Testing of Electrically Conducting Materials Using Conformable Sensor Arrays[1]

This standard is issued under the fixed designation E2884; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the use of conformable eddy current sensor arrays for nondestructive examination of electrically conducting materials for discontinuities and material quality. The discontinuities include surface breaking and subsurface cracks and pitting as well as near-surface and hidden-surface material loss. The material quality includes coating thickness, electrical conductivity, magnetic permeability, surface roughness and other properties that vary with the electrical conductivity or magnetic permeability.

1.2 This guide is intended for use on nonmagnetic and magnetic metals as well as composite materials with an electrically conducting component, such as reinforced carbon-carbon composite or polymer matrix composites with carbon fibers.

1.3 This guide applies to planar as well as non-planar materials with and without insulating coating layers.

1.4 *Units*—The values stated in SI units are to be regarded as standard. The values given in parentheses are mathematical conversions to inch-pound units that are provided for information only and are not considered standard.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

E2238 Guide for Evacuation Route Diagrams

2.2 *ASNT Documents:*[3]

SNT-TC-1A Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing

ANSI/ASNT-CP-189 Standard for Qualification and Certification of NDT Personnel

2.3 *AIA Standard:*

NAS 410 Certification and Qualification of Nondestructive Testing Personnel[4]

2.4 *Department of Defense Handbook:*

MIL-HDBK–1823A Nondestructive Evaluation System Reliability Assessment

3. Terminology

3.1 *Definitions*—For definitions of terms relating to this guide refer to Terminology E1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *B-Scan*—a method of data presentation utilizing a horizontal base line that indicates distance along the surface of a material and a vertical deflection that represents a measurement response for the material being examined.

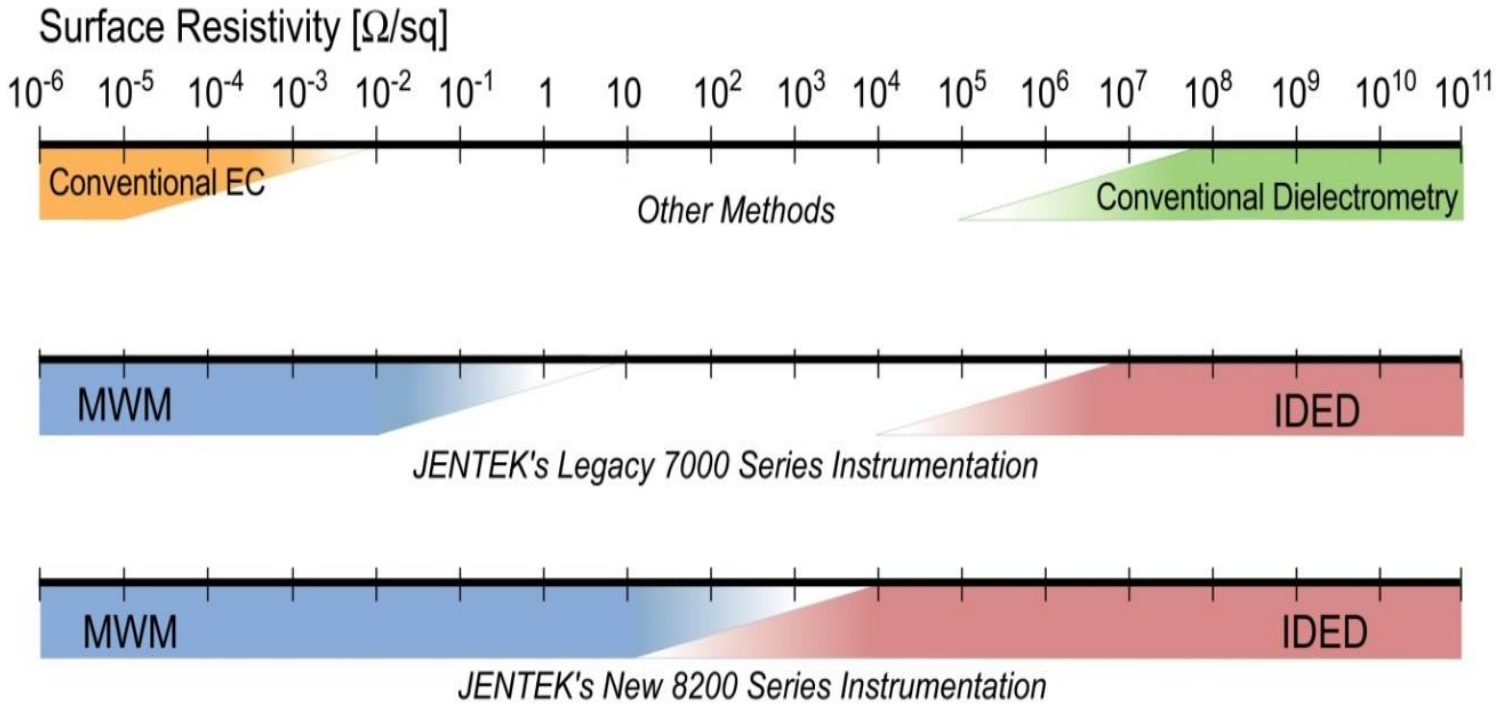
3.2.2 *C-Scan*—a method of data presentation which provides measurement responses for the material being examined in two-dimensions over the surface of the material.

3.2.3 *conformable*—refers to an ability of sensors or sensor arrays to conform to non-planar surfaces without significant

JENTEK Hand-Held Impedance Instrument

Leap in Sensitivity

Leap in sensitivity made possible by dramatically improved phase measurement resolution

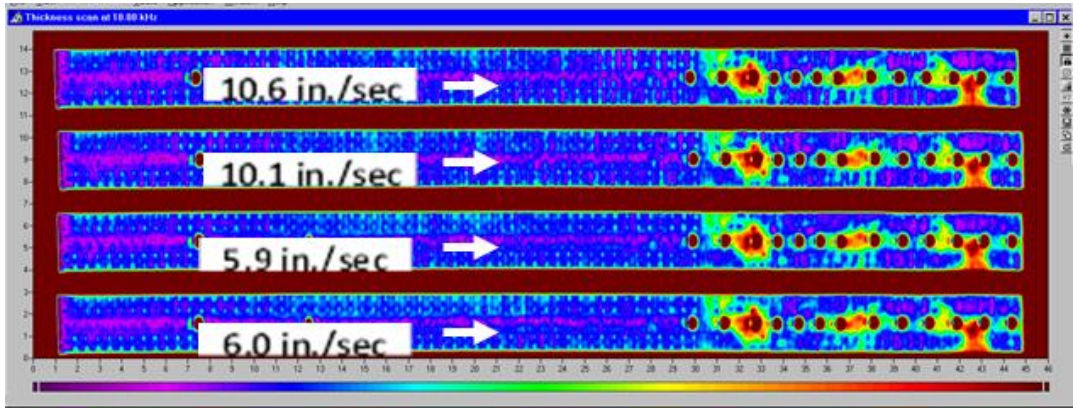


The hand-held and 8200 series systems bridge the gap between insulating and conducting materials to enable inspection of all materials

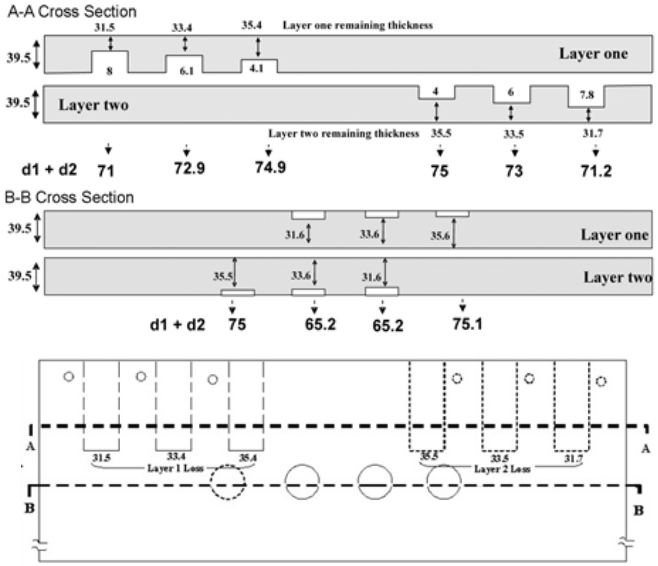
Example Applications

- Corrosion Imaging
  - Lap joints
- Crack Detection
  - Engines
- Stress & Torque
- Burnishing/Shotpeening QA
- Fatigue Testing
- Coatings Characterization
- Composites

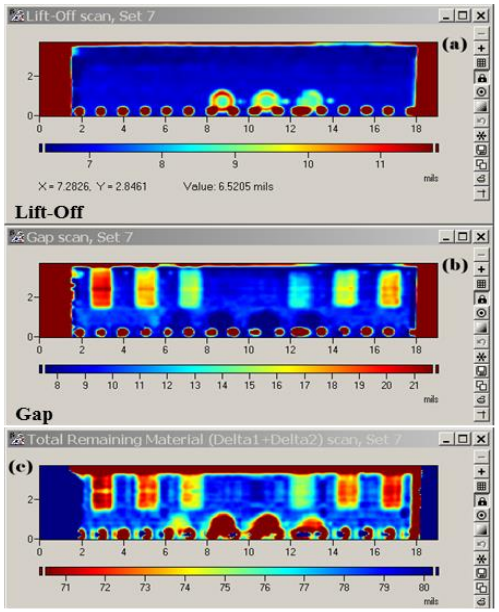
Detection of Surface and Buried Cracks and Surface and Buried Corrosion in Lap Joints

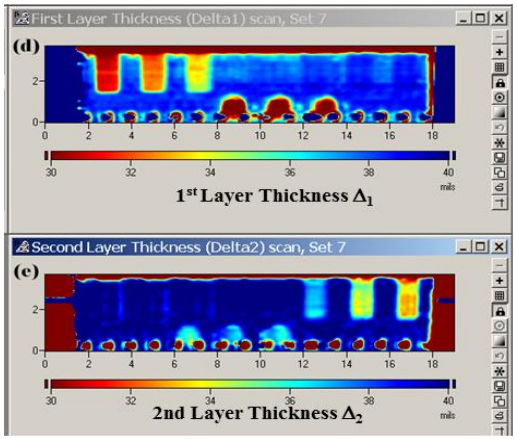


Results for a military aircraft lap joint using a two unknown, single frequency method to image corrosion



Air Force material loss calibration standards as configured for previous MWM-Array demonstrations; dimensions in mils (1 mil = 0.001 in.).



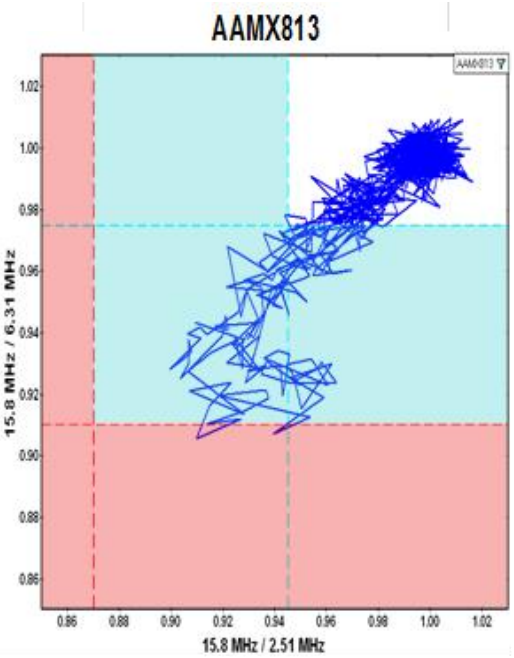


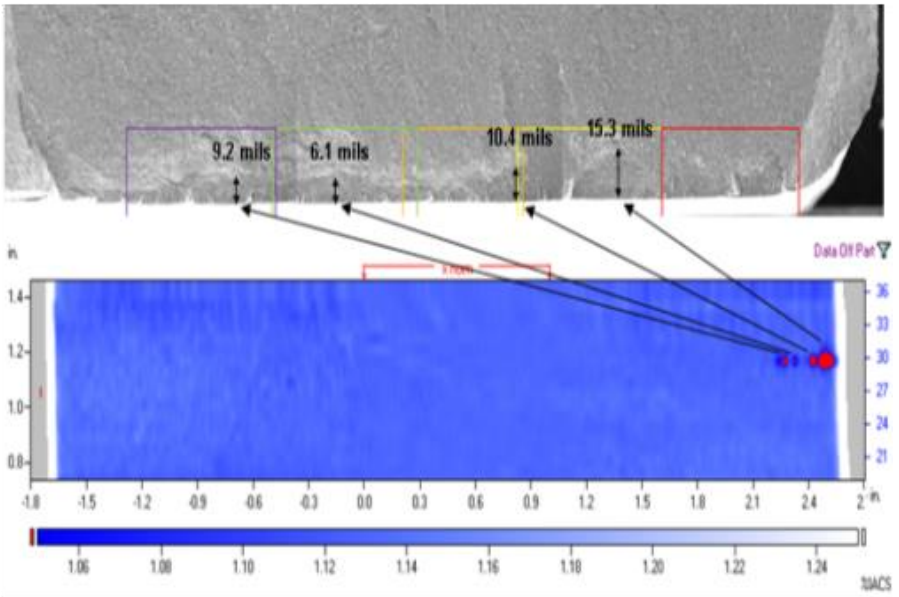
NOTE: 1st and 2nd layer metal loss and gap are all measured during the same scan, accurately and independently, using a six frequency MWM-Array method at a 0.5 in./sec. scan speed with a 3.7 in. wide scan path. This capability is not offered by any other system.

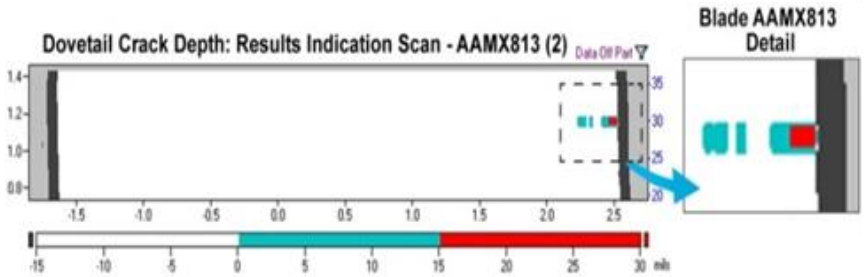
The rectangular milled-out regions show up in the correct layers (1st or 2nd), the circular regions also show up in the correct layers.

Crack Detection and Depth Estimation (Titanium Alloy Blade Dovetail)

Earlier results for crack detection and depth estimation for an engine blade dovetail on a military engine component



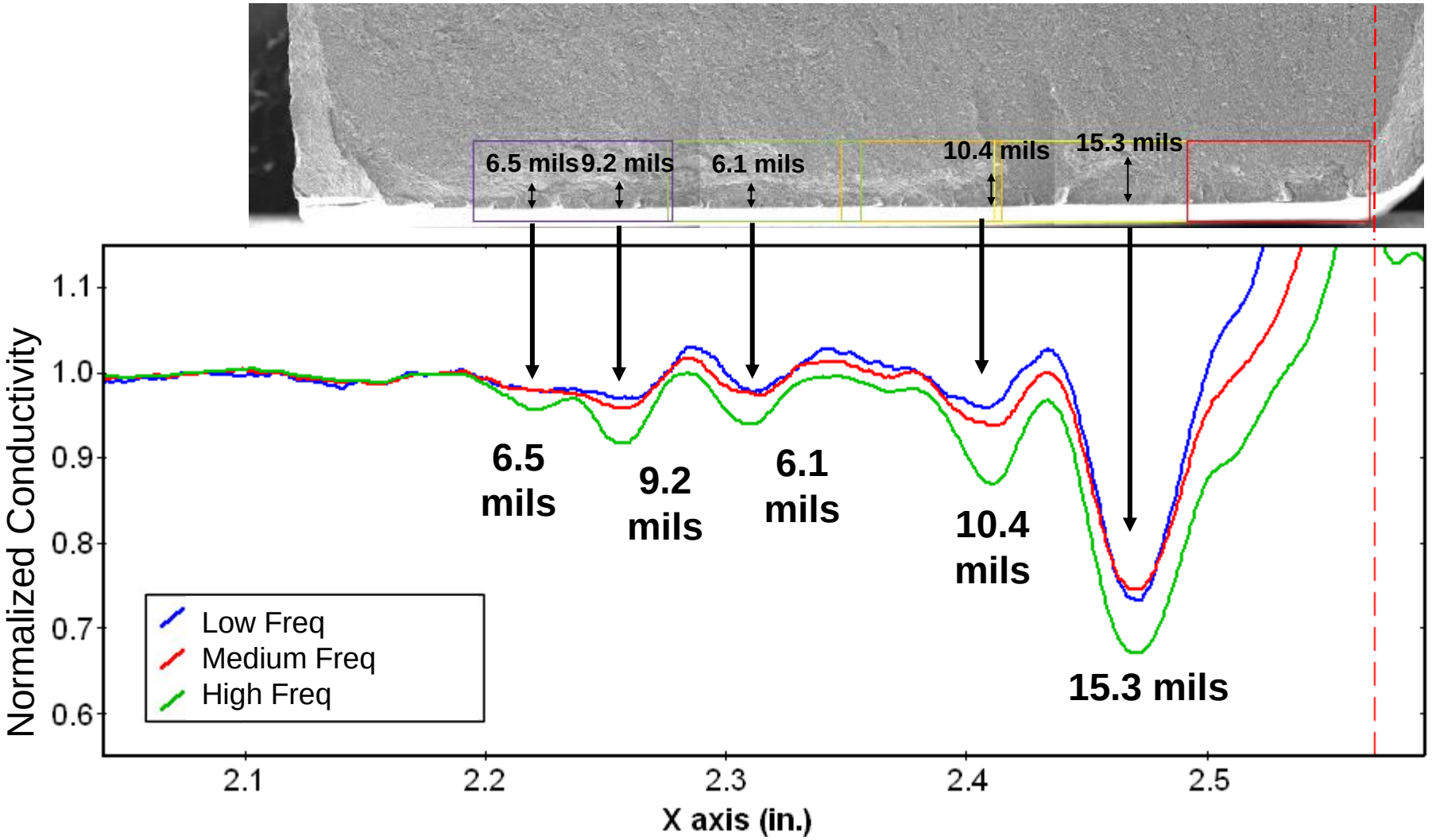




Crack Depth Image

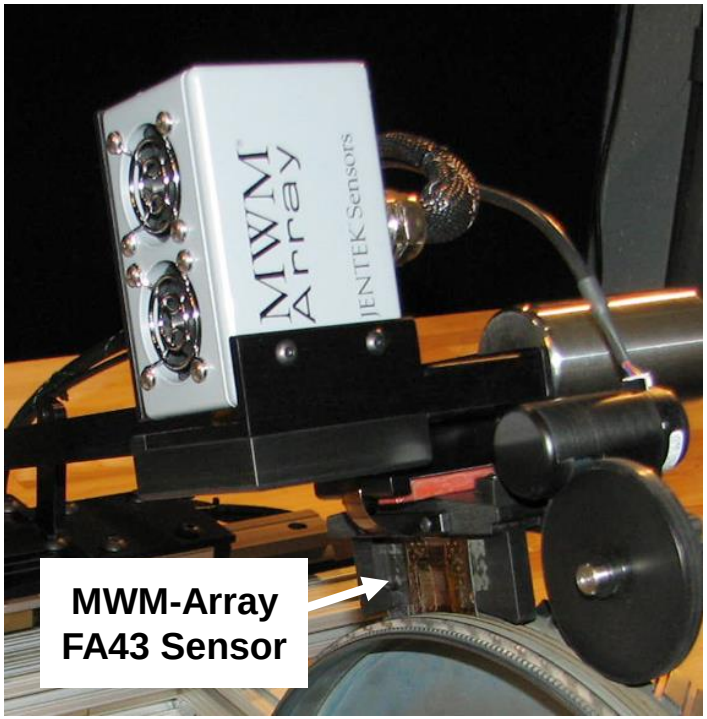
Crack Detection and Depth Estimation (Titanium Alloy Blade Dovetail)

Blade #13



Commercial Engine Knife Seal Inspection

- "Technical aspects of the method are FAA approved" (See Service Bulletin)
- Engine OEM implemented this inspection
- Multiple systems in use world-wide since 2011
- AE family engine knife seal Inspection on several stages for cracks
- Thousands of engine stages inspected per year
- Inspection performed with blades in place (minimal disassembly saves substantial dollars)



AE SERIES PROPULSION SYSTEM
Service Bulletin Index

Rolls-Royce

LIST OF AE 3007A SERIES SERVICE BULLETINS

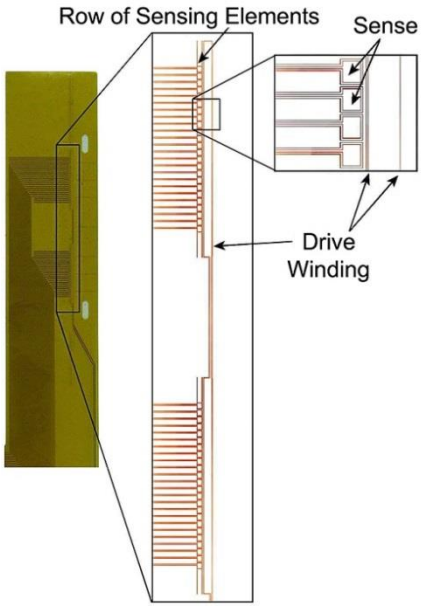
SB No.	Rev No.	Title	Compliance Category	Date	Models Affected	Module or ATA Locator
AE 3007A-72-386		See AE 3007A-A-72-386				
AE 3007A-72-388	1	Engine - 6th- thru 13th-Stage Compressor Wheel Knife Edge Seals - Jentek Eddy Current Inspection	8	09-May-11	7A, 7A1/1, 7A1/3, 7A1, 7A1E, 7A1P, 7A2, 7A3	72-37-00

MWM-Array FA43 Sensor adapted for knife seal inspection

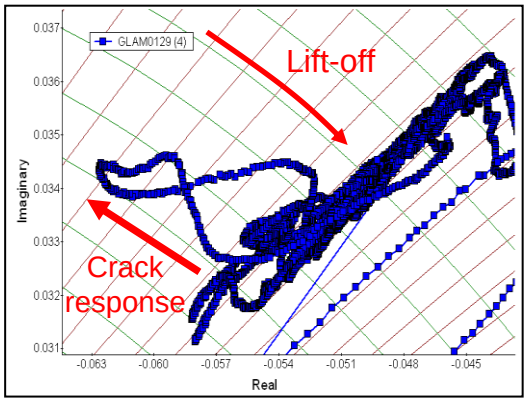
Reference: https://aeromanager.rolls-royce.com/control/publicsite/publicnoticeboard/categorylist?userAction=performDisplayDocument&selectedLevel=2&selectedLevelID=65

Military Blade Dovetail Inspection

MMW-Array Sensors

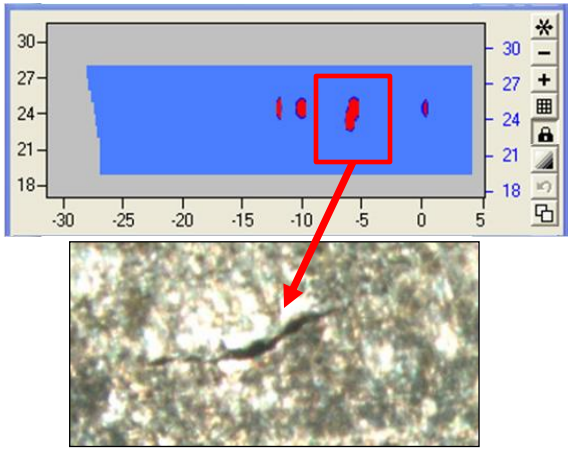


Precomputed Database (Grid)



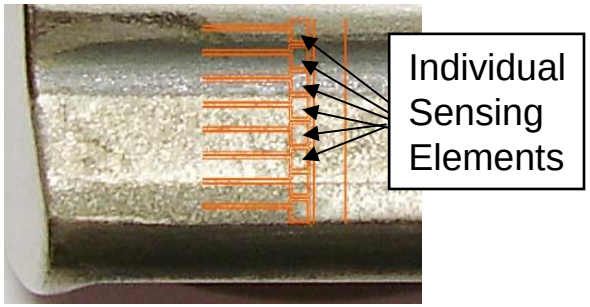
Crack response rescaled based on lift-off

C-Scan Image

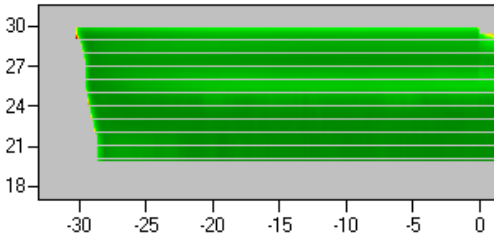


42-mil Crack

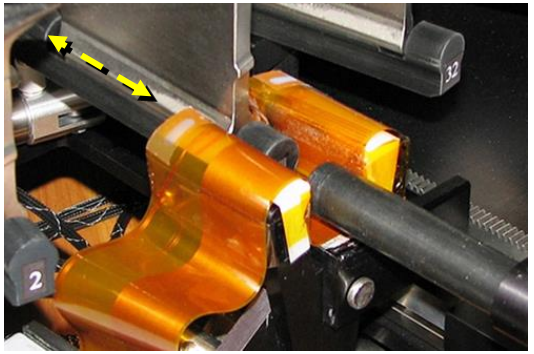
Sensor Coverage



Lift-Off Imaging

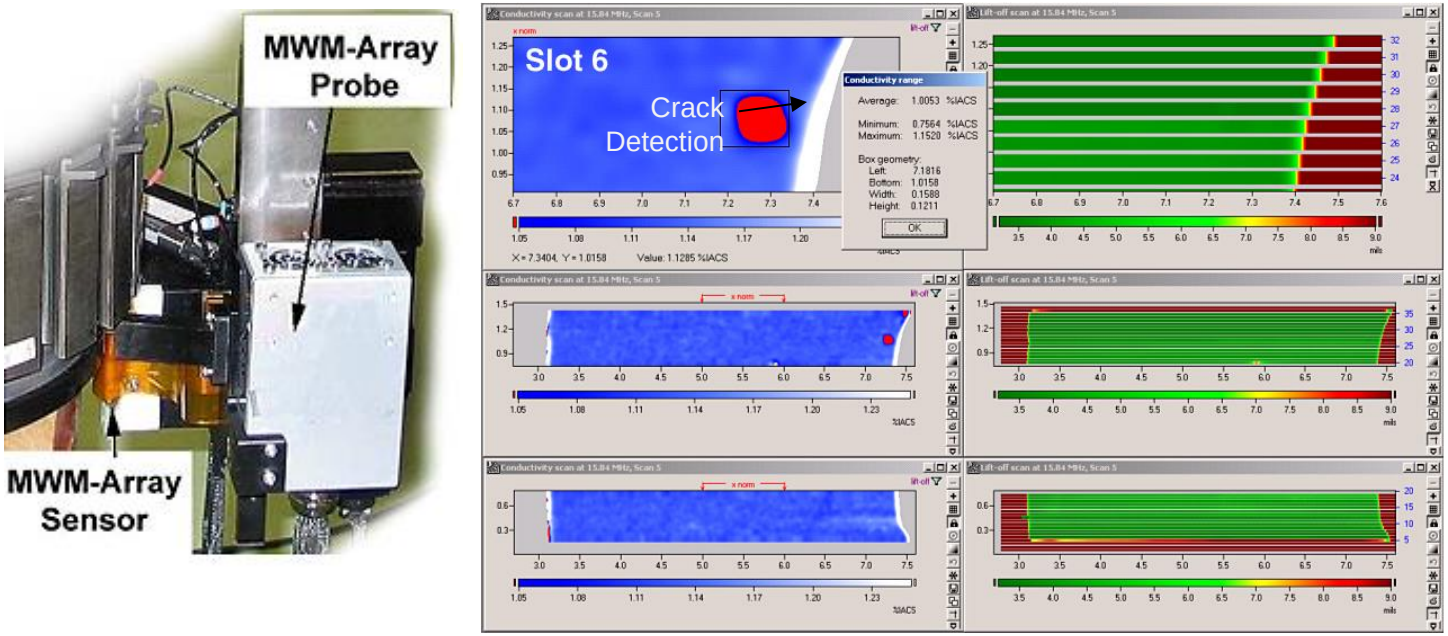


Sensor Position at Edge of Dovetail



Automated Engine Disk Inspection System

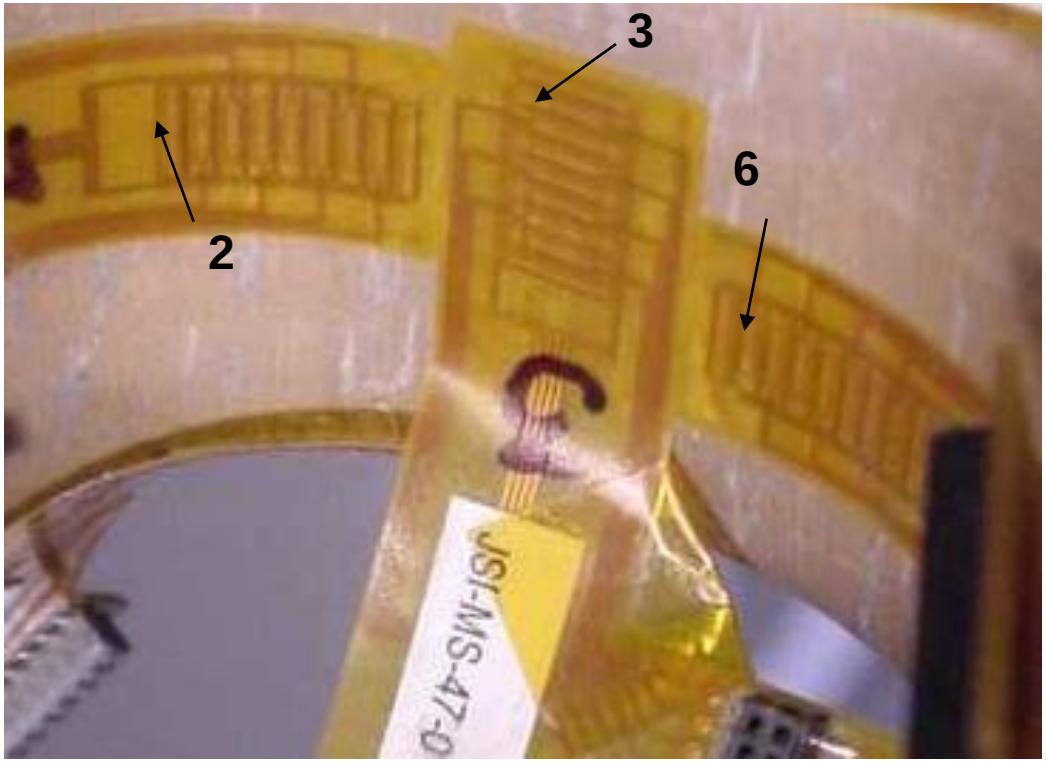
- In use at NAVAIR Depot since April 2005, **for a decade**
- Nine disks with **verified cracks detected**, several of these large and small cracks **not detected by conventional ET and LPI**
- No false indications (numerous slots inspected)



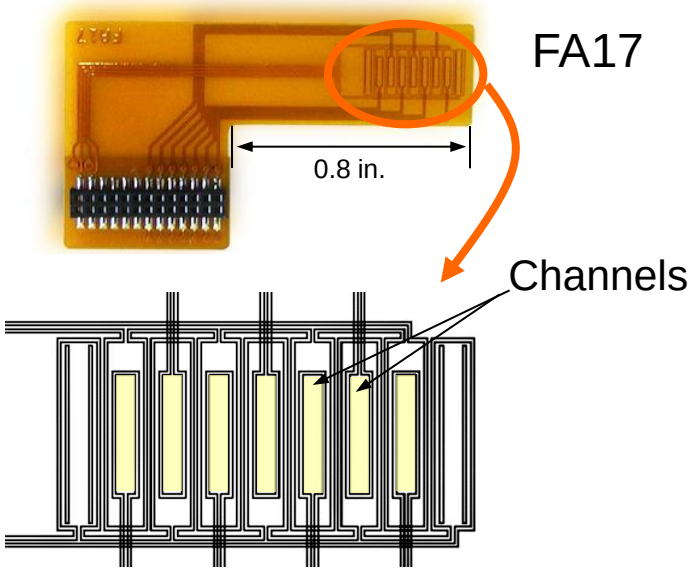
Winner, FAA-Air Transport Association 2007 "Better Way" Award for "MWM and MWM-Array Engine Component Inspection Technology"

Landing Gear Overload & Residual Stress Monitoring

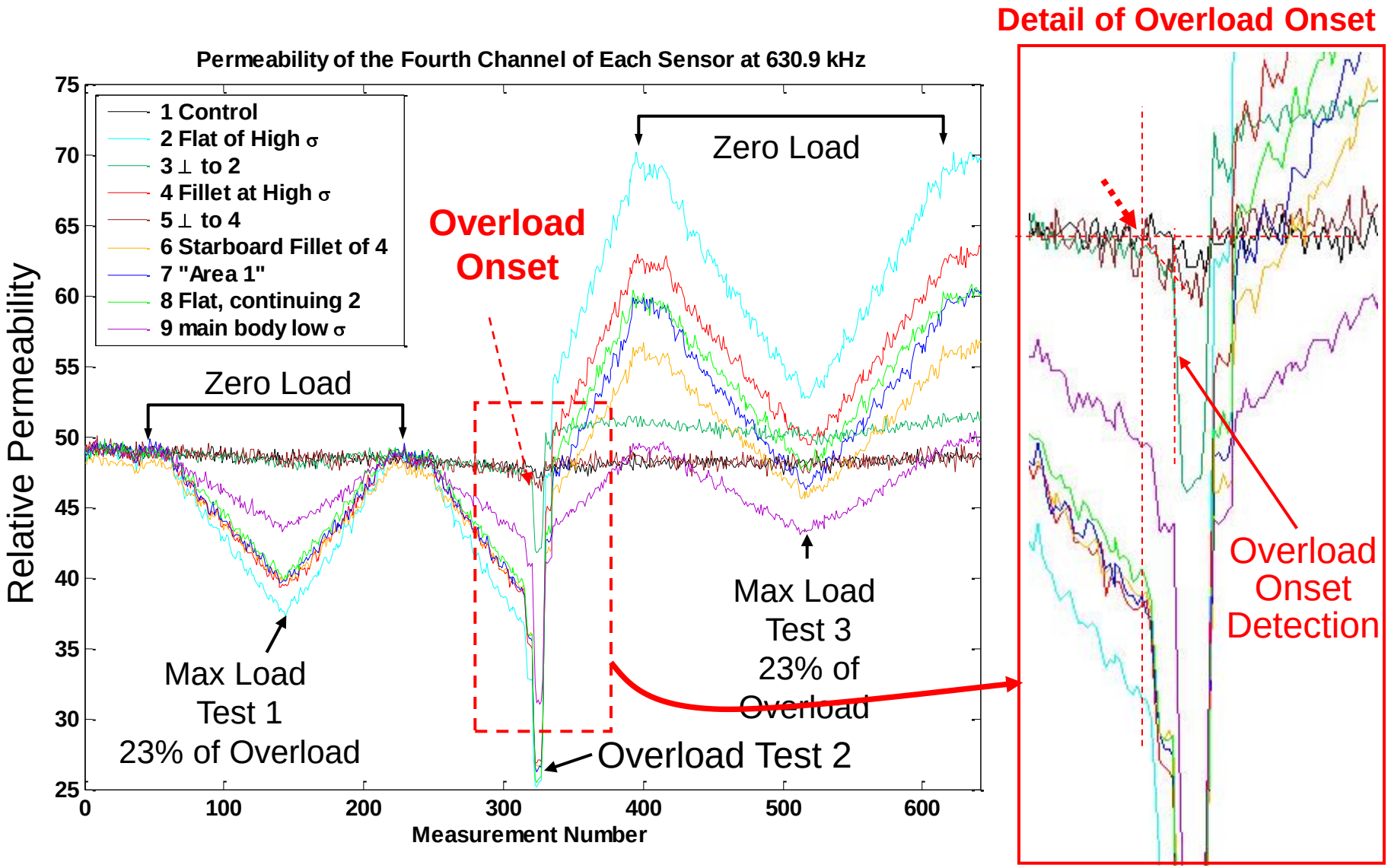
Independent Monitoring of Stress and Overload Detection during Testing and Potentially In-Service



- Bi-directional permeability
- Detect onset of overload event
- Load/stress monitoring



MWM-Array FA17 Channel 4 Permeability Response from all 9 Sensors During Strength Tests



Inspection of Cold Rolling Integrity on C-130 Propeller Blades

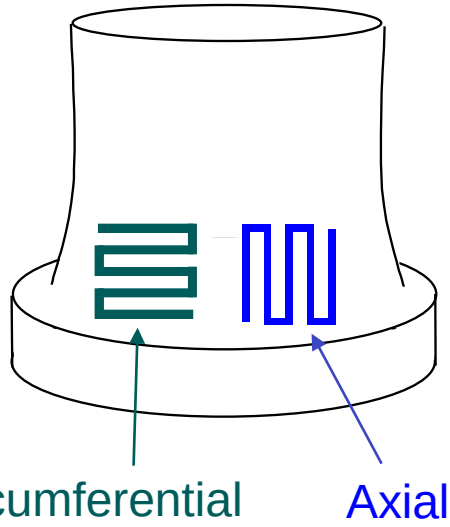
JENTEK GridStation System for C-130
Propeller Cold Rolling Inspection

Bi-Directional Conductivity Measurements and Definition of Conductivity Ratios

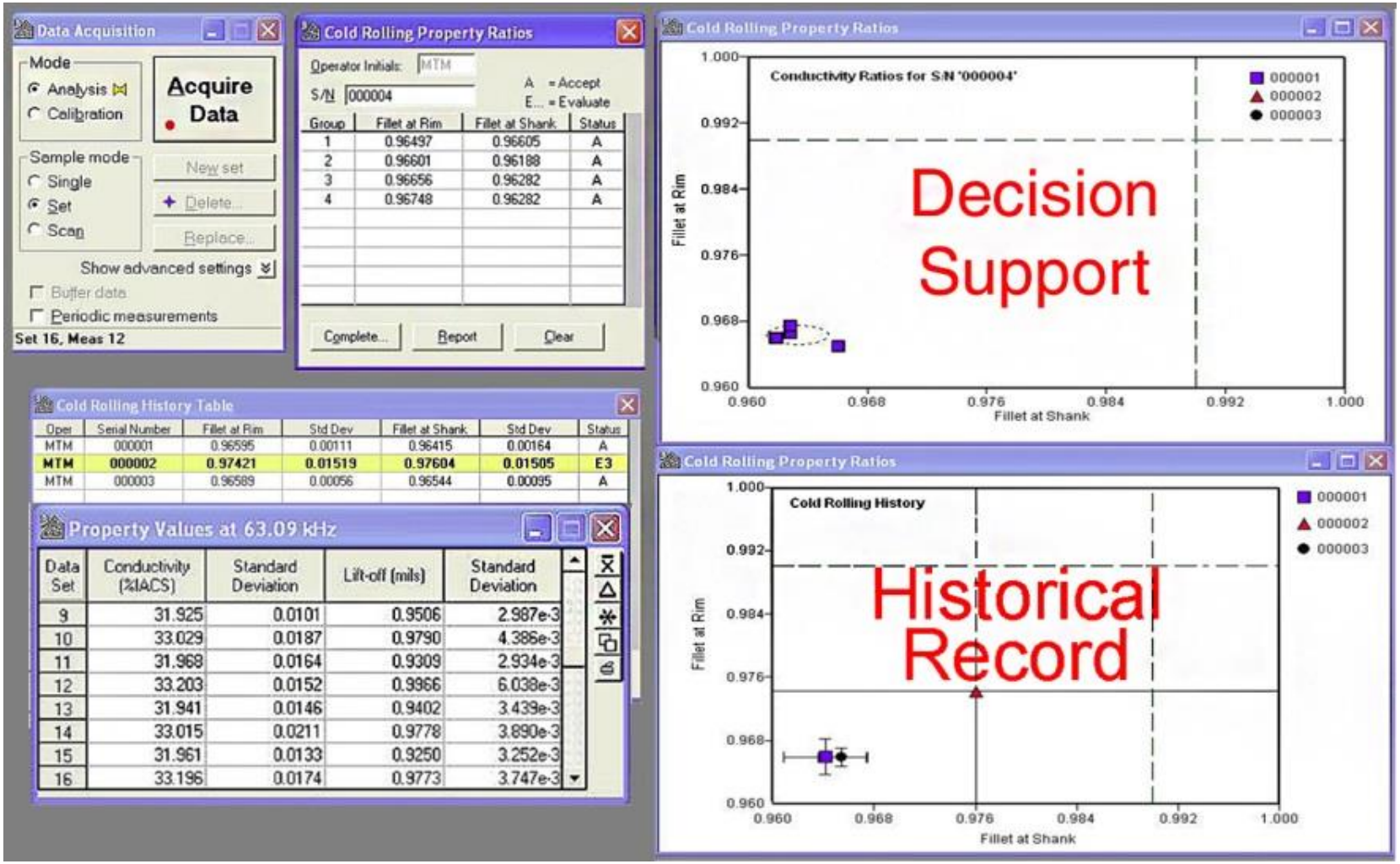
Ratio Analysis

$$\text{Fillet Ratio} = \frac{\text{Fillet Axial}}{\text{Fillet Cir.}}$$

$$\text{Shank Ratio} = \frac{\text{Shank Axial}}{\text{Shank Cir.}}$$



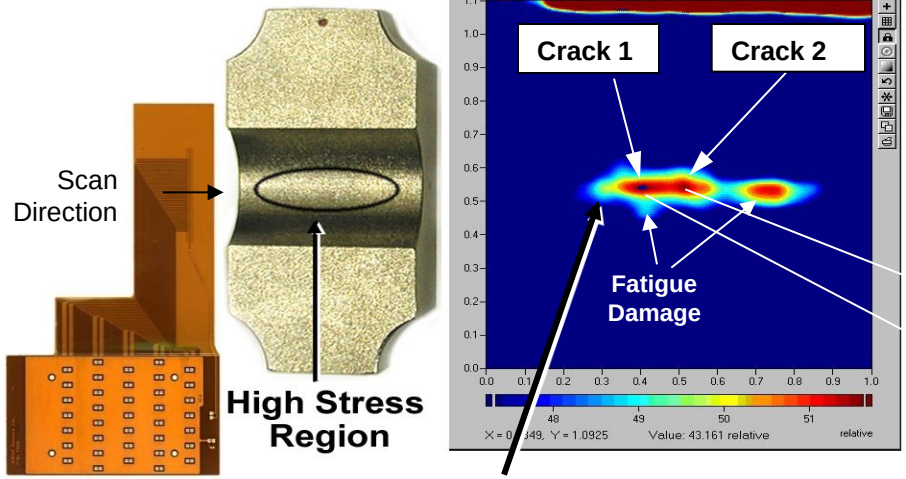
Typical Interface for Cold Work Quality Control



Shot Peened 4340M Steel Fatigue Coupon, ET vs FPI

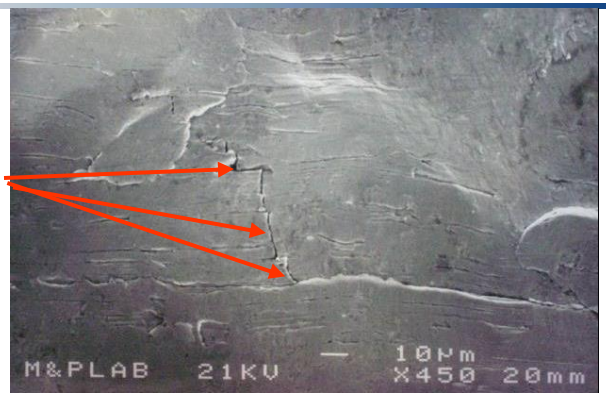
After stopping fatigue test

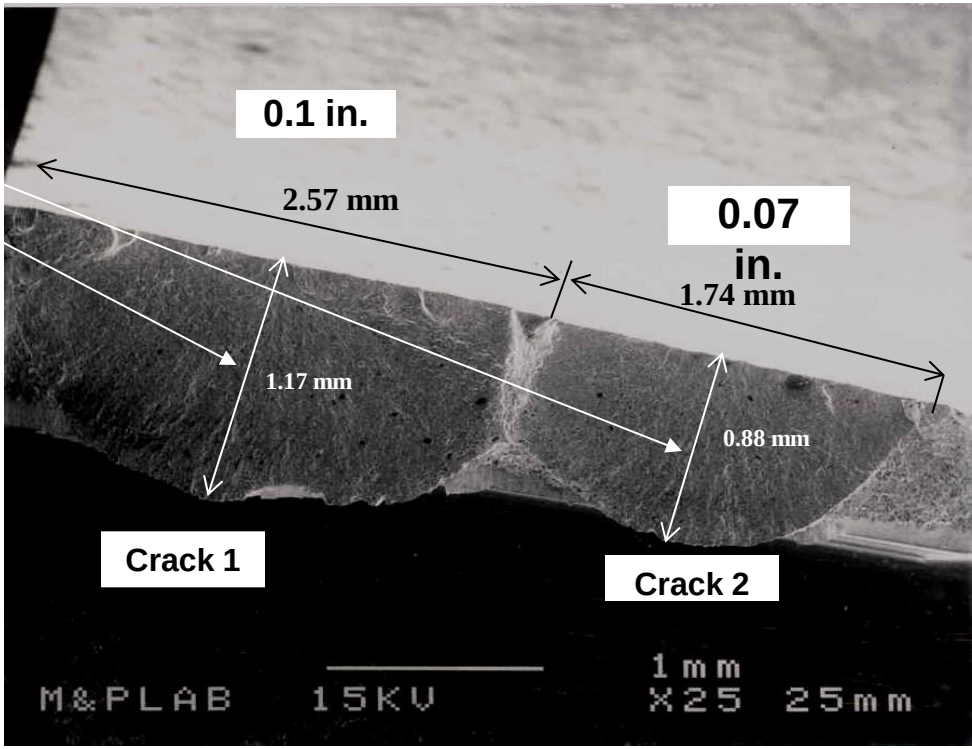
4340M Shot Peened Steel Specimen



SEM found only cracks up to 0.008-in. long

The longest crack (approx. 200 µm) detected in SEM MWM detected two cracks during and after the fatigue test of the shot peened specimen, prior to fractography

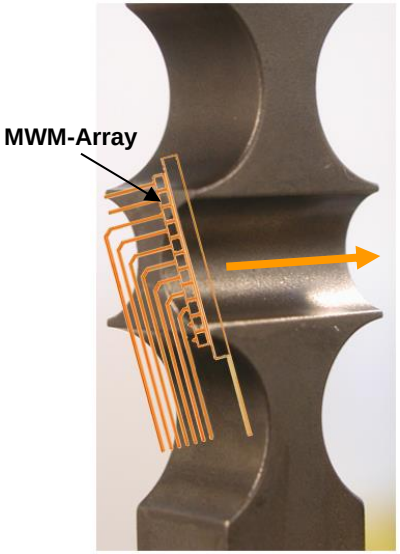


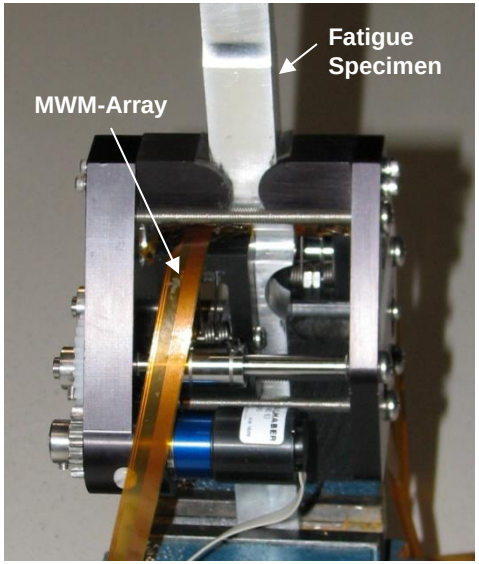


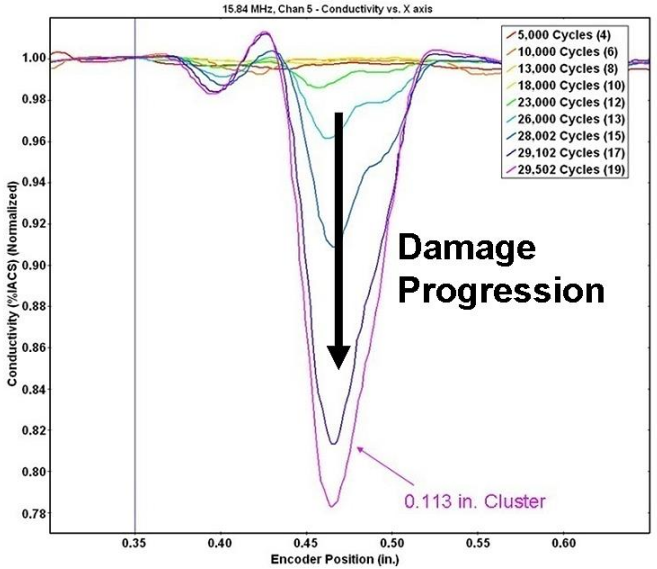
Conventional ET, UT, FPI, WFMT could not detect cracks on shot peened surface

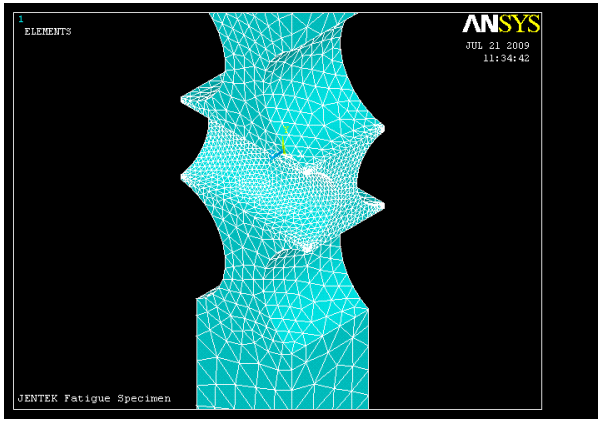
Two cracks were confirmed by destructive testing

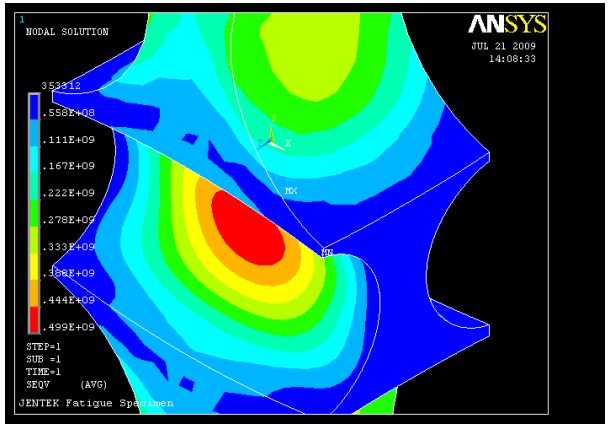
Fatigue Specimen and Sensor Scanner

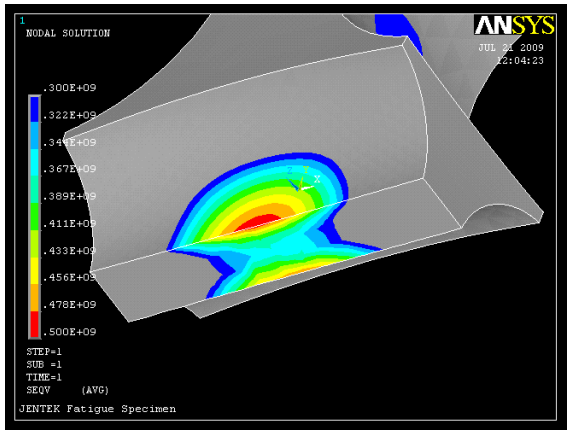










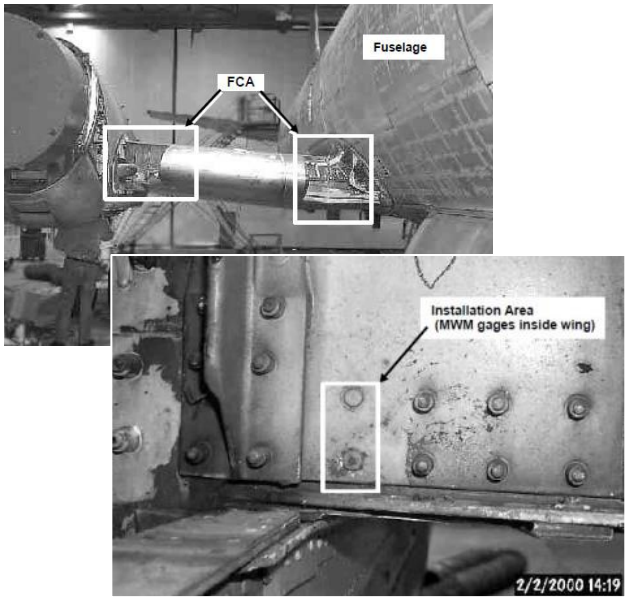


Full-Scale Tests & Flight Tests

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

Lockheed Martin

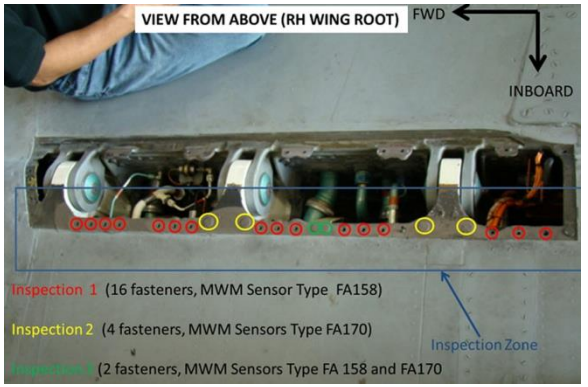
P-3 Fatigue Critical Areas[1]



Northrop Grumman

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

US Navy Fighter Aircraft



The new jET hand-held and improved cabling designs will substantially reduce implementation costs for laboratory and full-scale tests.

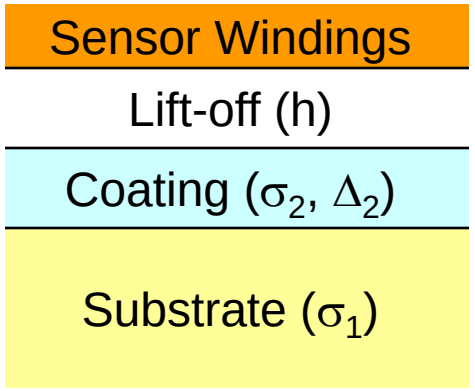
Sources:

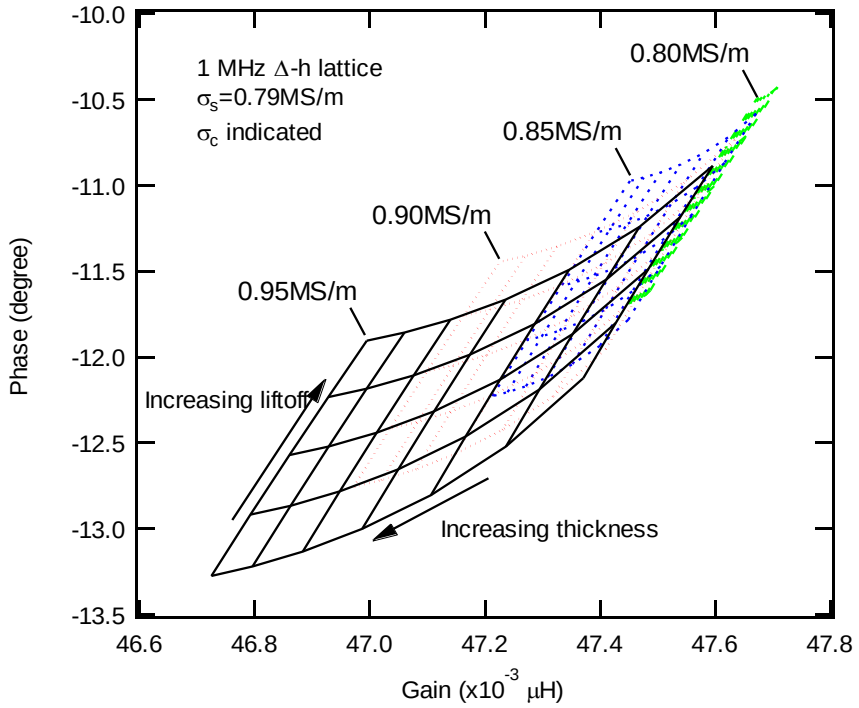
[1]Neil J. Goldfine, et al, "Surface Mounted Periodic Field Current Sensors for Structural Health Monitoring," SPIE Conference: Smart Structures and Materials NDE for Health Monitoring and Diagnostics, Newport Beach, California; March 2001

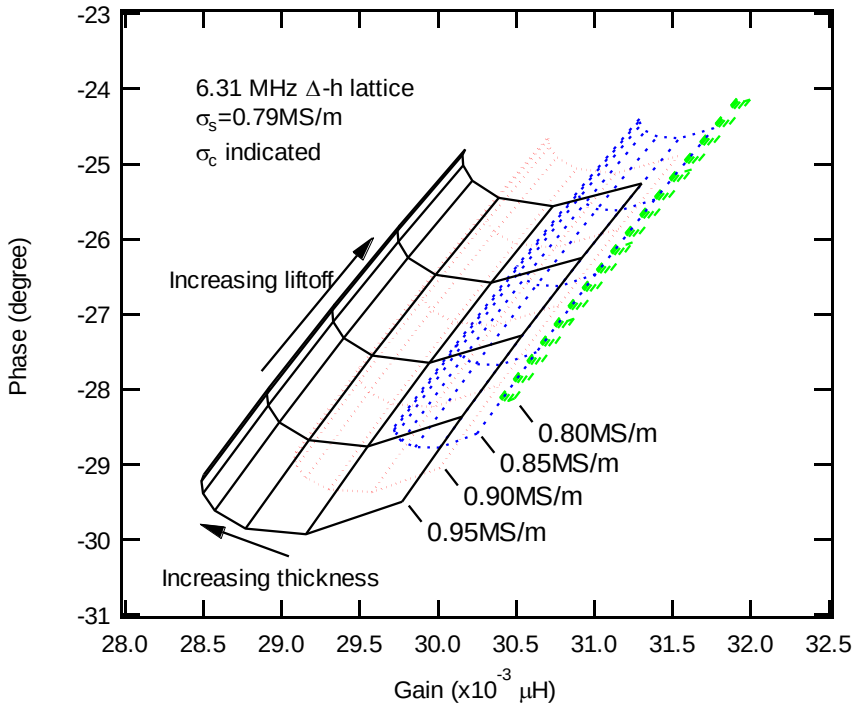
[2]http://adt.larc.nasa.gov/files/2013/01/ADT_Sept2012_NorthGrum.pptx

Measurement Grid Lattice Algorithm

- Collections of 2-D grids
  - coating conductivity, coating thickness, lift-off
- Approach:
  - conductivity/lift-off to determine coating presence
  - use lattices to find properties that are independent of frequency



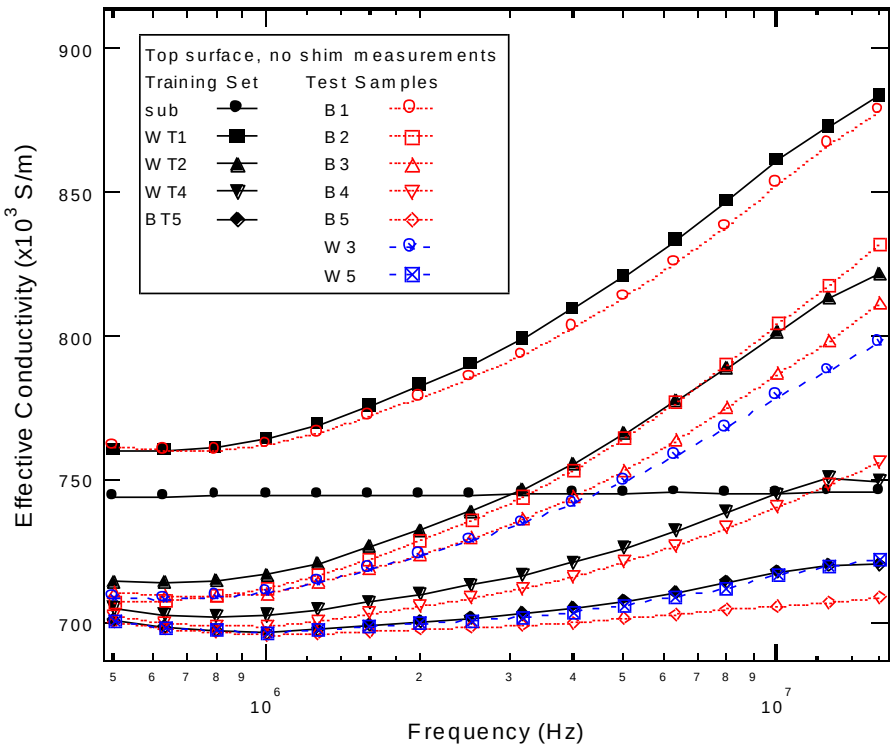


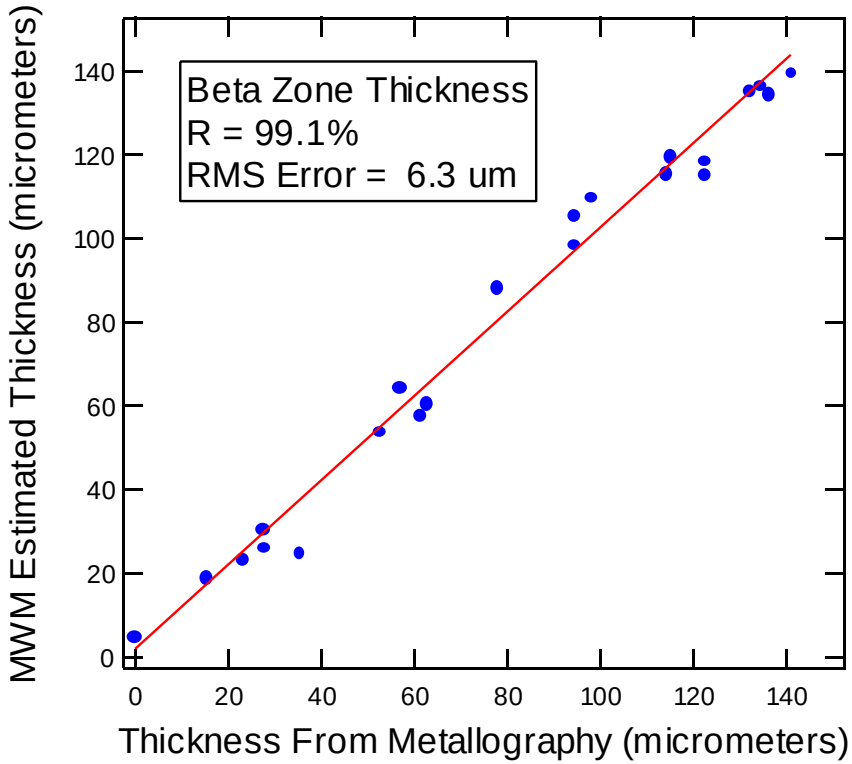


Thermal Spray Coating: Thermal Aging

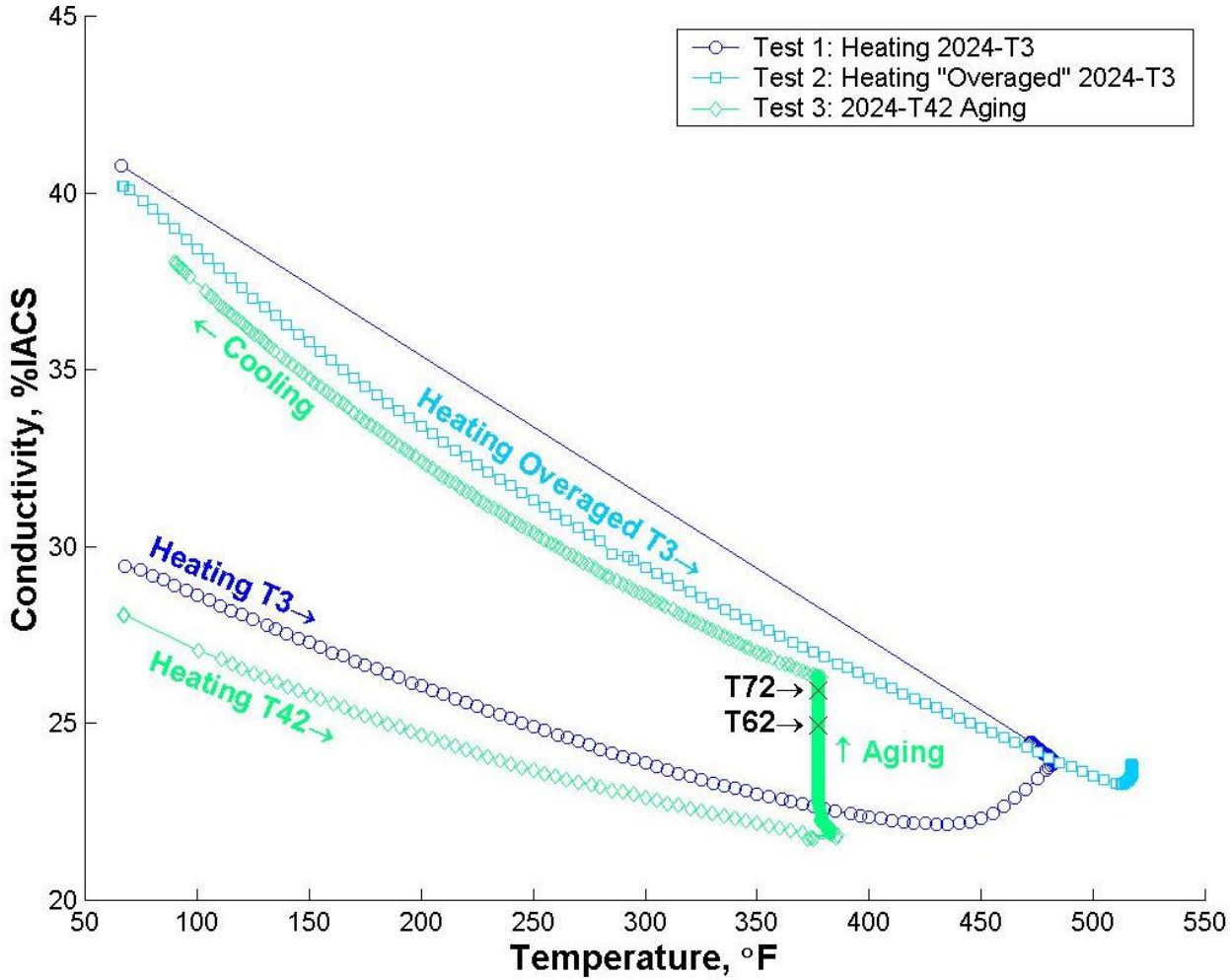
Left: **Comparison of the MWM multifrequency effective conductivity measurements for training set and blind test samples;**

Right: **MWM measured beta-phase layer thickness versus reported beta-phase layer thickness for blind test set.**

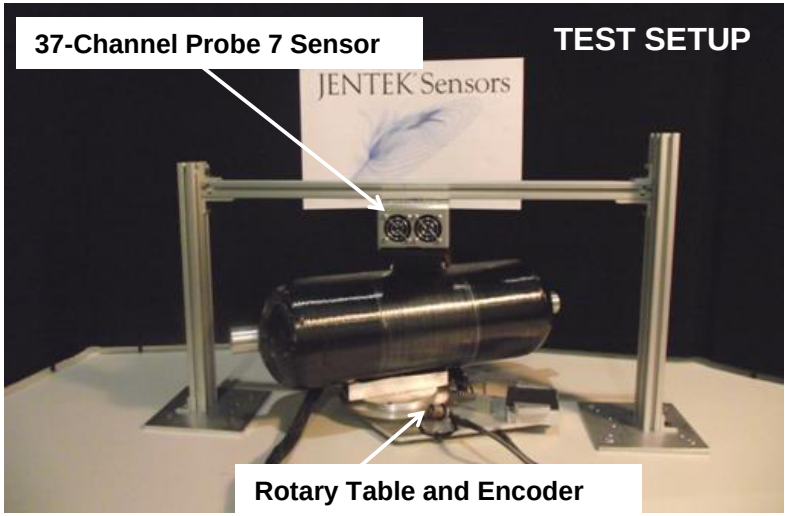


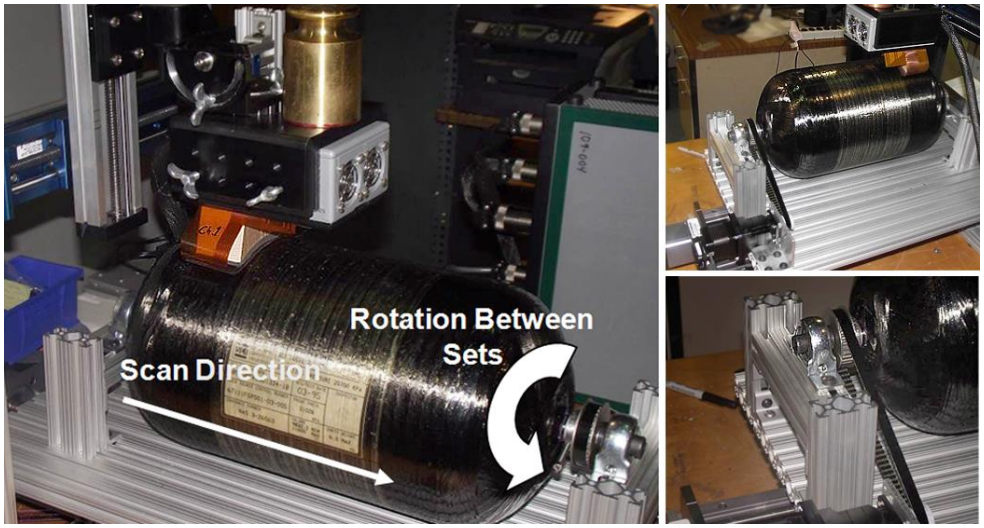


MWM Measured Conductivity Changes for Al 2024 at Temperatures up to 270ºF.



COPV Testing





See complimentary presentation:

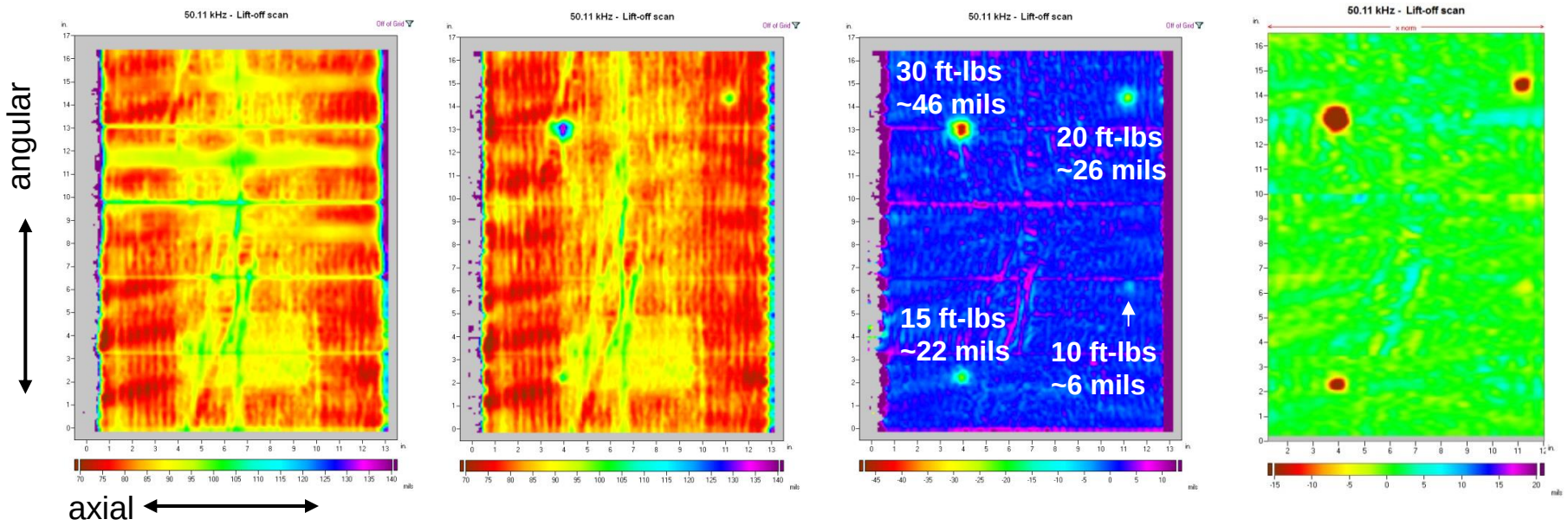
"Continued Development of Meandering Winding Magnetometer (MWM®) Eddy Current Sensors for the Health Monitoring, Modeling and Damage Detection of Composite Materials"

Session:
IVHM - Structural Health Monitoring for Damage Detection
Presentation time:
Thursday, April 05, 2012
2:30 PM

MWM-Array Low Freq. Lift-Off Scans on COPV

Lift-Off image shows liner damage; freq. 50.11 kHz

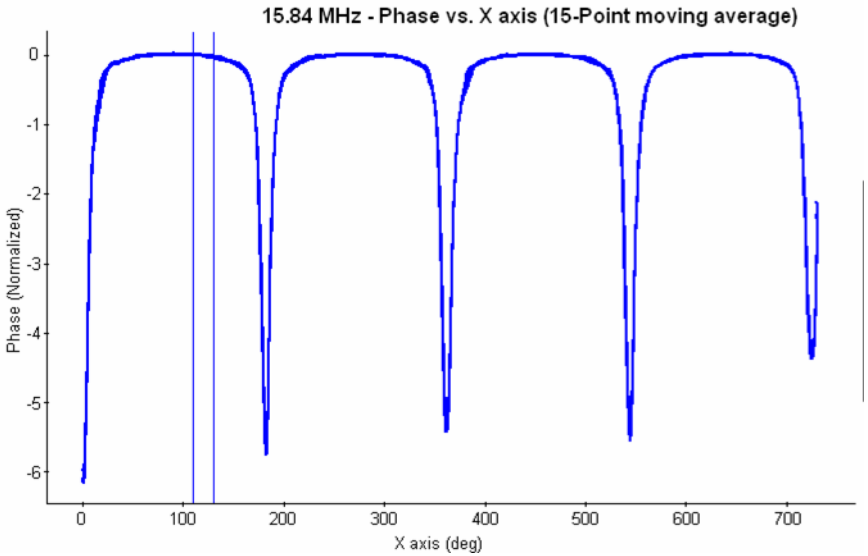
Before Impact Damage | **After Impact Damage** | **Baseline Subtracted** | **Preliminary Filtering**



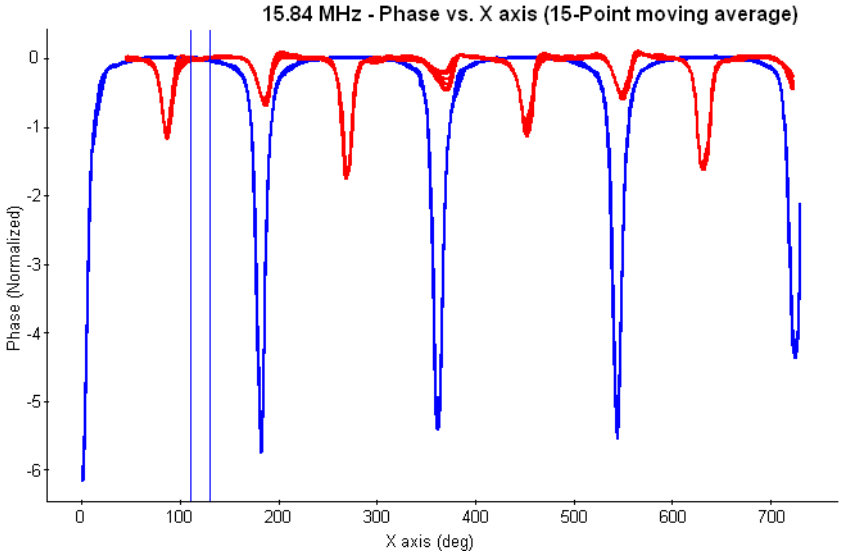
- Sample AC5250-030; 90˚ Sensor drive orientation
- Higher impact energy results in larger dents in the aluminum liner
- Sensor: MWM-Array FA24

MWM-Array Rotational Scans of Two Parts

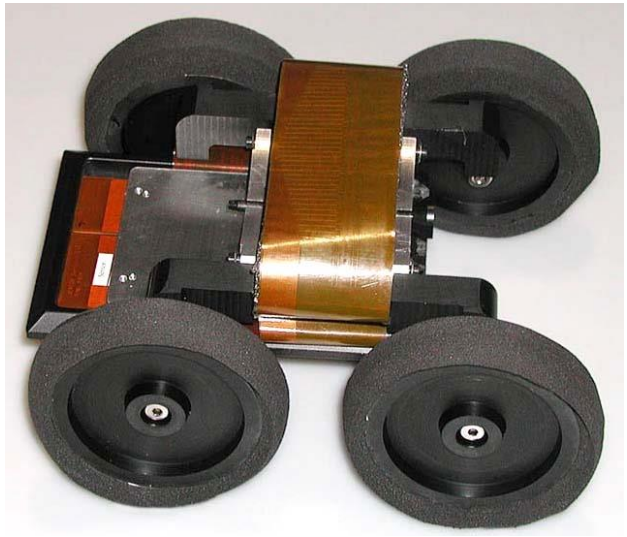
Rot. scan of just the uni-axial fiber part

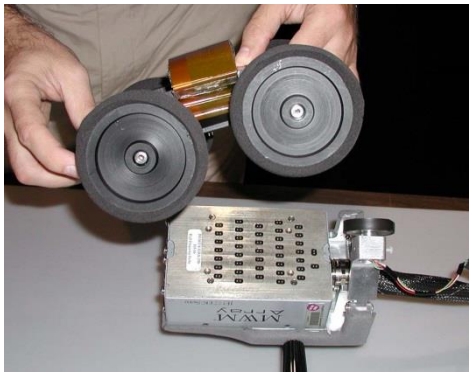


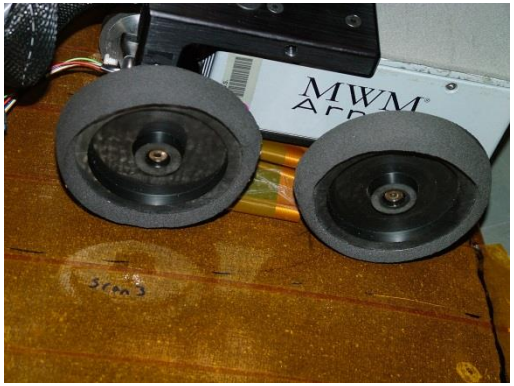
Add rot. scan of fine weave (±45°)

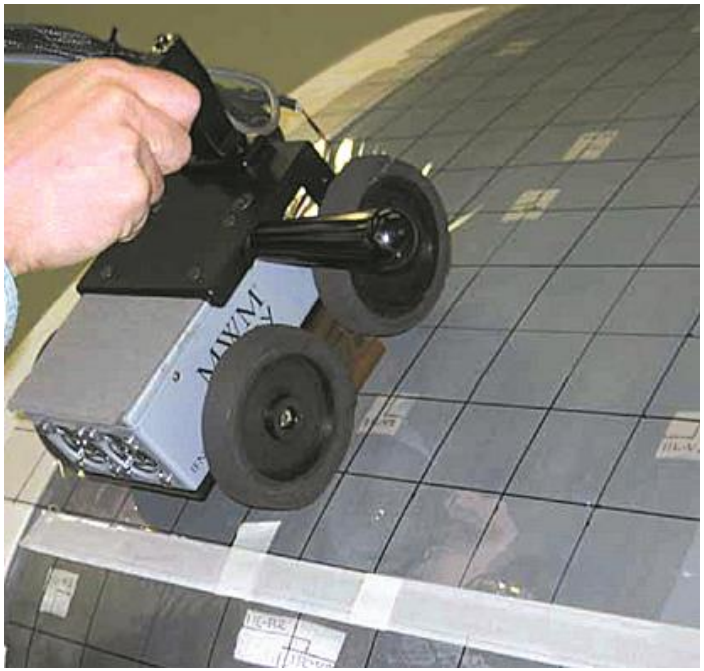


MWM-Array for Inspecting Complex Composite Surfaces (Implemented at NASA KSC on Space Shuttle Leading Edge)





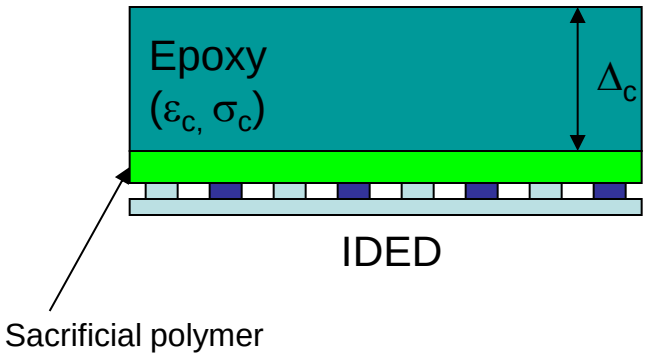


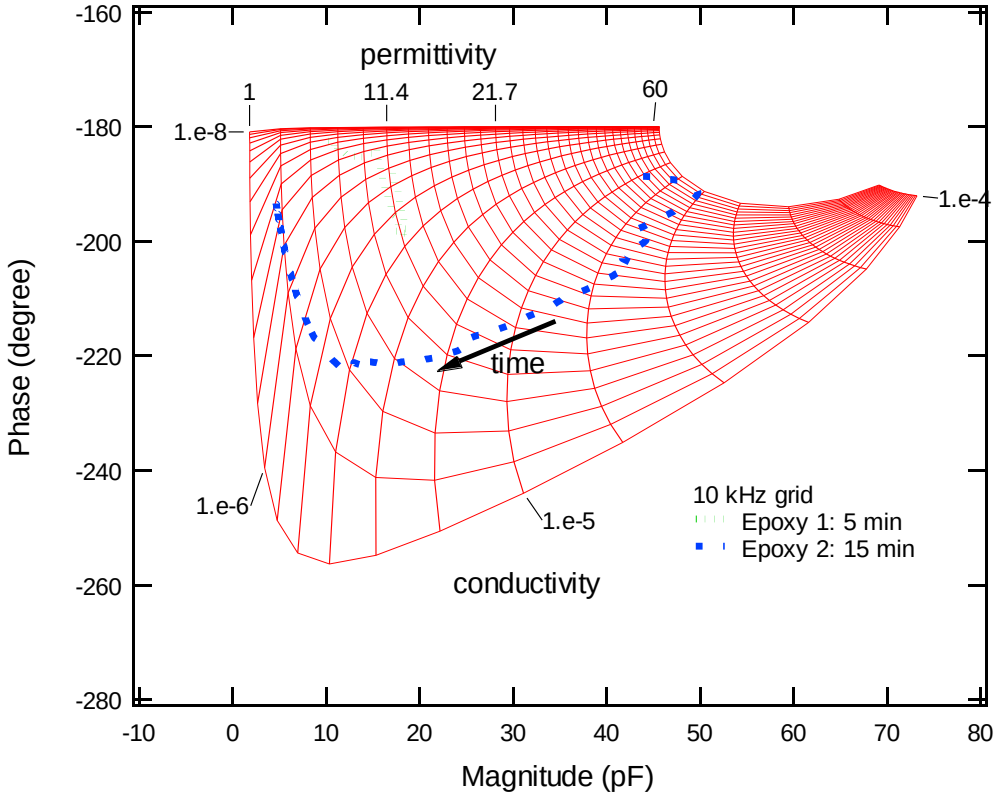


- Foam wheels protect surface
- Manual scanning for complex surfaces
- C-Scan images of wide areas built from multiple passes
- Adapts automatically to varied curvatures

Epoxy Cure Measurements (1)

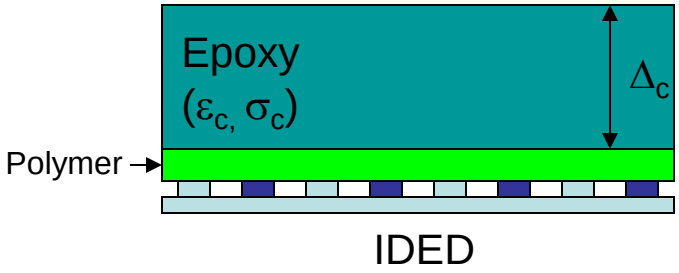
- Epoxy types:
  - Epoxy 1: 5 minute fast drying
  - Epoxy 2: 15 minute plastic welder epoxy
- σ_c - ε_c grids used

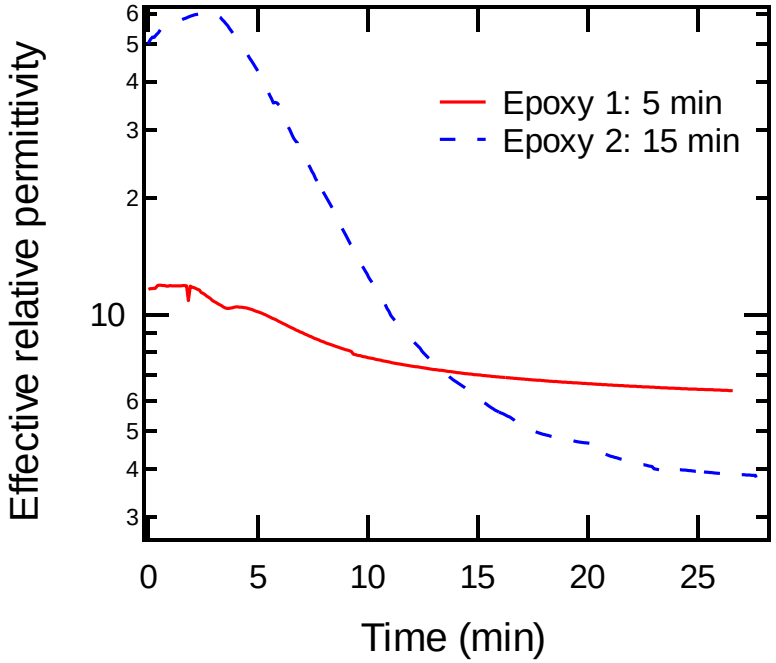


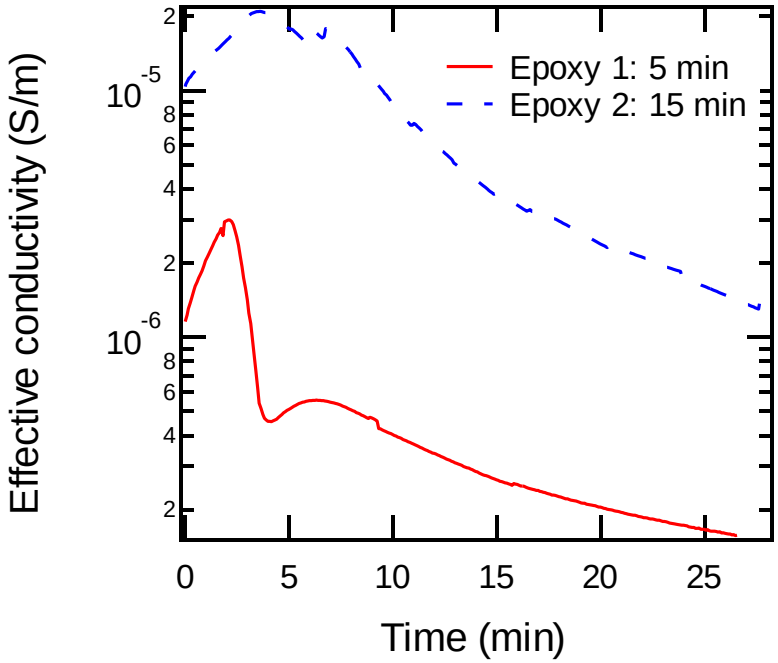


Epoxy Cure Measurements (2)

- Grids used to convert to dielectric properties
- Real-time inversion
  - preprocess to generate grids

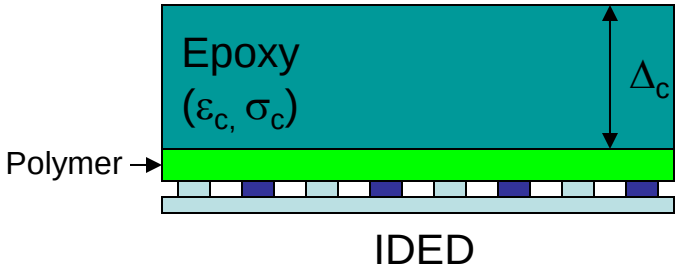


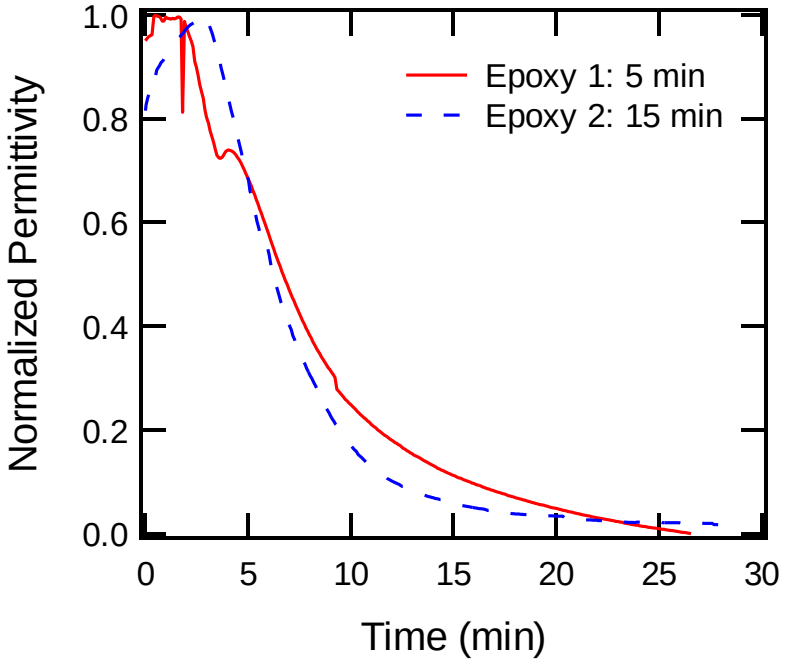


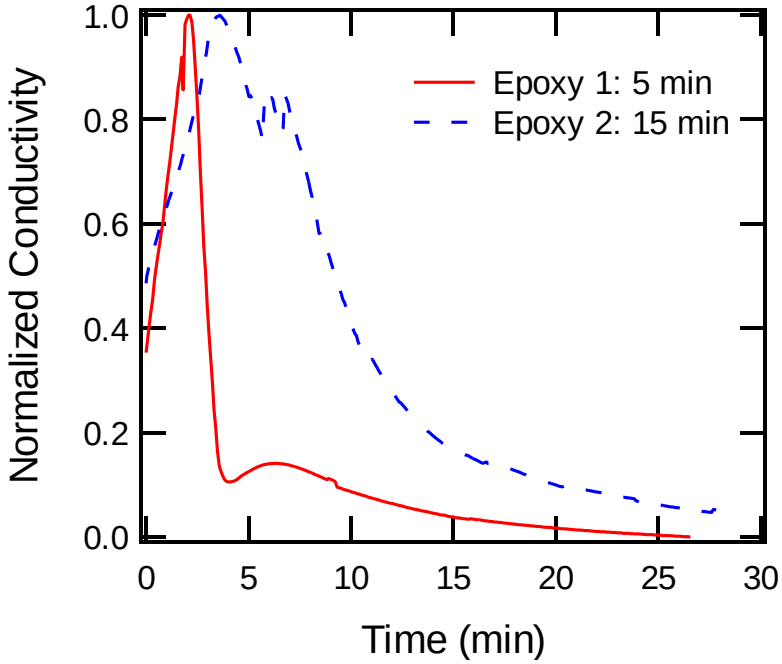


Epoxy Cure Measurements (3)

- Dielectric properties from grids
- Real-time inversion
  - preprocess to generate grids
- Normalized conductivity correlates to nominal cure time







Summary

- Hand Held jET, 7-Channel Alpha-Test prototype system is now available.
- First applications: Coating characterization, surface and buried crack detection, and some corrosion imaging.
- Wide range of additional applications to be addressed under ongoing funded programs and related efforts.