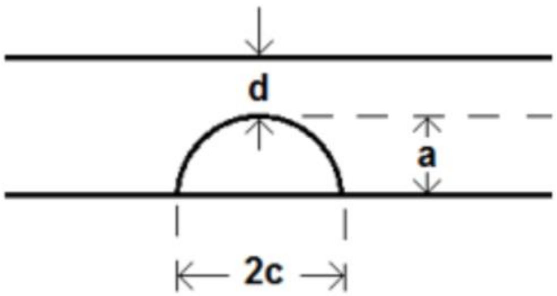
Buried Crack Detection Using Eddy Current Arrays



ASIP

November 2018

Neil Goldfine, Todd Dunford, Andrew Washabaugh, Mark Windoloski, Stuart Chaplan, Zachary Thomas

JENTEK Sensors, Inc.
121 Bartlett Street,
Marlborough, MA 01752-3025
Tel: 781-373-9700; Email: jentek@jenteksensors.com

jenteksensors.com

> 25 yrs
MWM-Array
development
NEW jET system
< 1 pound
(without laptop)

Presentation Outline

- ❑ Subsurface Crack Detection Problem
- ❑ Subsurface Crack Detection Solution
- ❑ Results for Buried EDM Notches
- ❑ Technical Approach Details for Subsurface Cracks
  - ✓ jET handheld system
  - ✓ Flexible ET arrays for curved surfaces
  - ✓ Model-based Multivariate Inverse Methods (MIMs)
  - ✓ Surface crack detection and characterization
- ❑ Making Real Crack Specimens for POD Study
- ❑ Summary & Remaining Work

Problem: Detect Sub-surface Cracks in Tight Spaces

- Conventional eddy current testing (ET) and ultrasonic testing (UT) provide **inadequate Andi capability** to meet needed inspection interval for some Air Force applications
- Individual Aircraft Tracking inspection locations on some fleets **require detection of subsurface initiated cracks** before they are surface breaking
- Goal is to **avoid field inspection requirement** for inspections in tight spaces on complex parts by
  - ✓ **Detecting cracks early enough and subsurface**
  - ✓ **Use Flexible ET arrays for curved surfaces**
  - ✓ **Use handheld portable systems that are convenient and easy to operate reliably in tight spaces**

Solution: ET Array with Handheld System and MIMs

❑ jET handheld system

- ✓ Simultaneous measurement at 3 frequencies
- ✓ Simultaneous measurement at 7 sensing elements
- ✓ Extremely low noise with wide frequency range

❑ MWM-Array: Flexible ET array

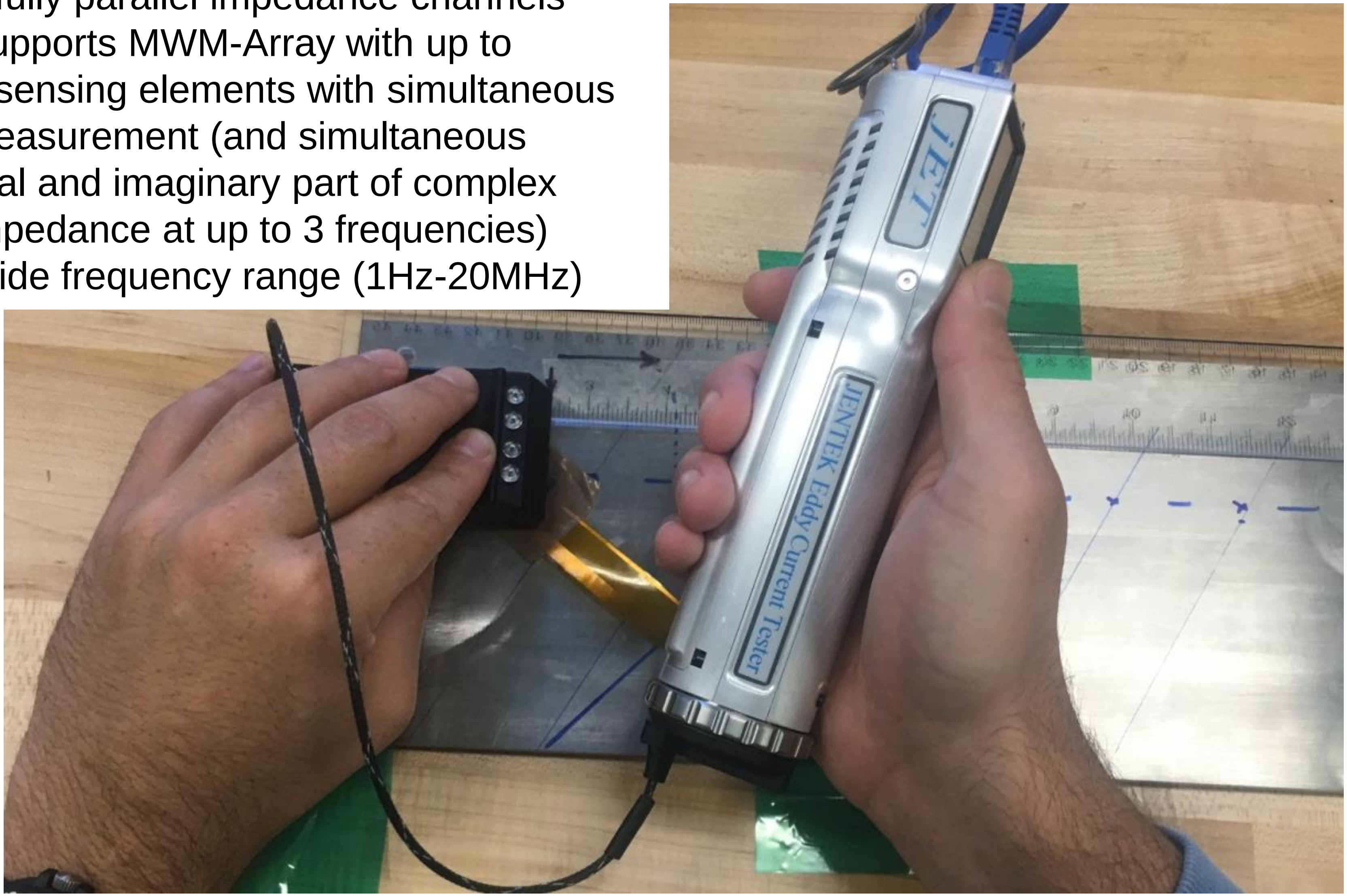
- ✓ linear drive conductor
- ✓ linear array of sensing elements

❑ Model-based Multivariate Inverse Methods (MIMs)

- ✓ Use physics models to improve reliability
- ✓ Use MIMs for rapid data analysis
- ✓ Use MIMs for crack depth estimation and "rescaling"
- ✓ performance verification to improve confidence

Technical Approach: jET Handheld System with mini-scanner and MWM-Array

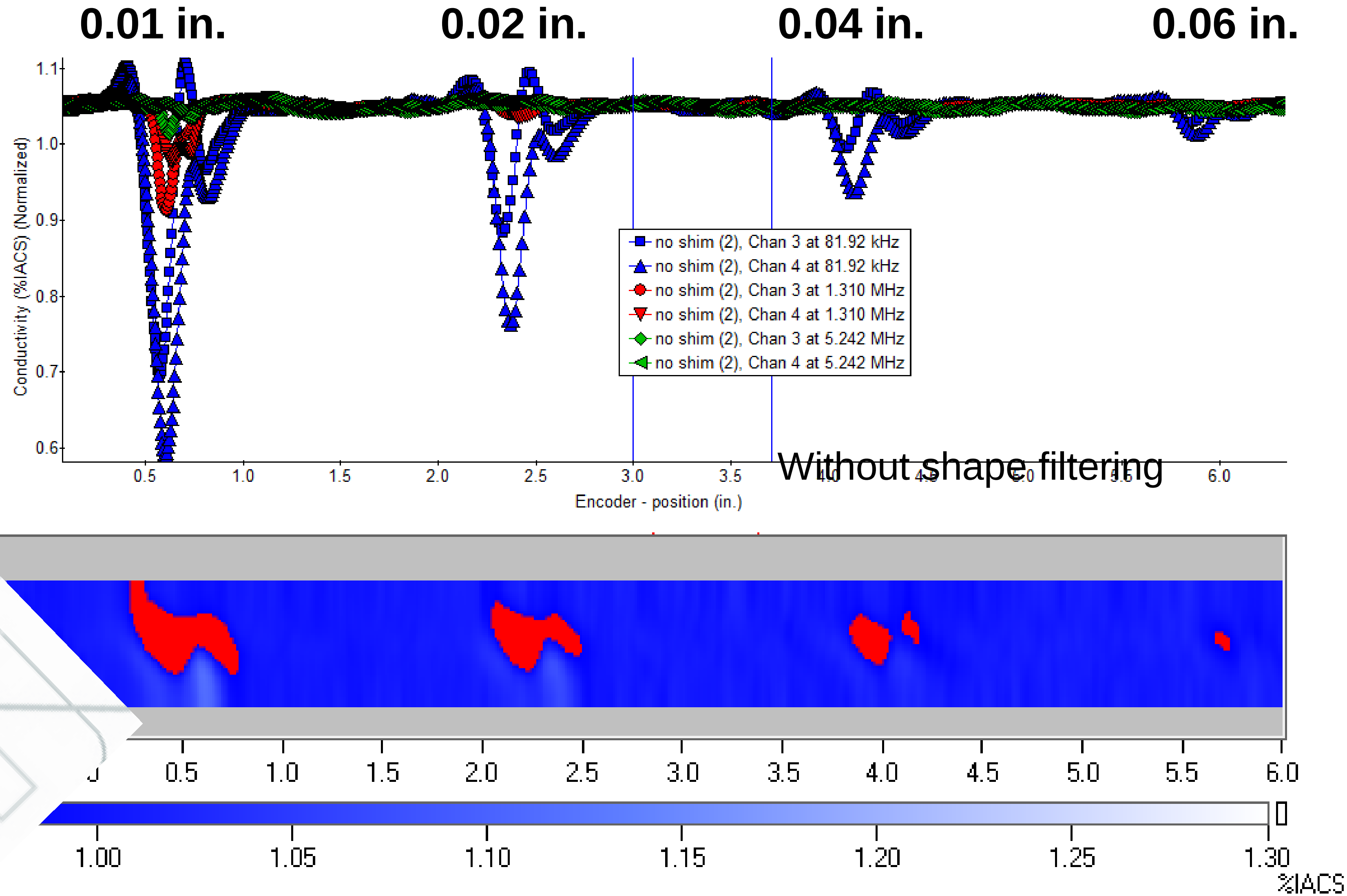
- ✓ Weight < 1 pound (without laptop)
- ✓ 7 fully parallel impedance channels
- ✓ Supports MWM-Array with up to 7 sensing elements with simultaneous measurement (and simultaneous real and imaginary part of complex impedance at up to 3 frequencies)
- ✓ Wide frequency range (1Hz-20MHz)



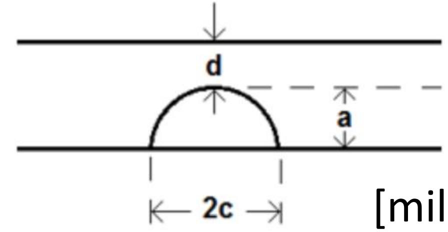
Results: Demonstrated for buried EDM notches

Real crack results expected in 2019

Depth below surface

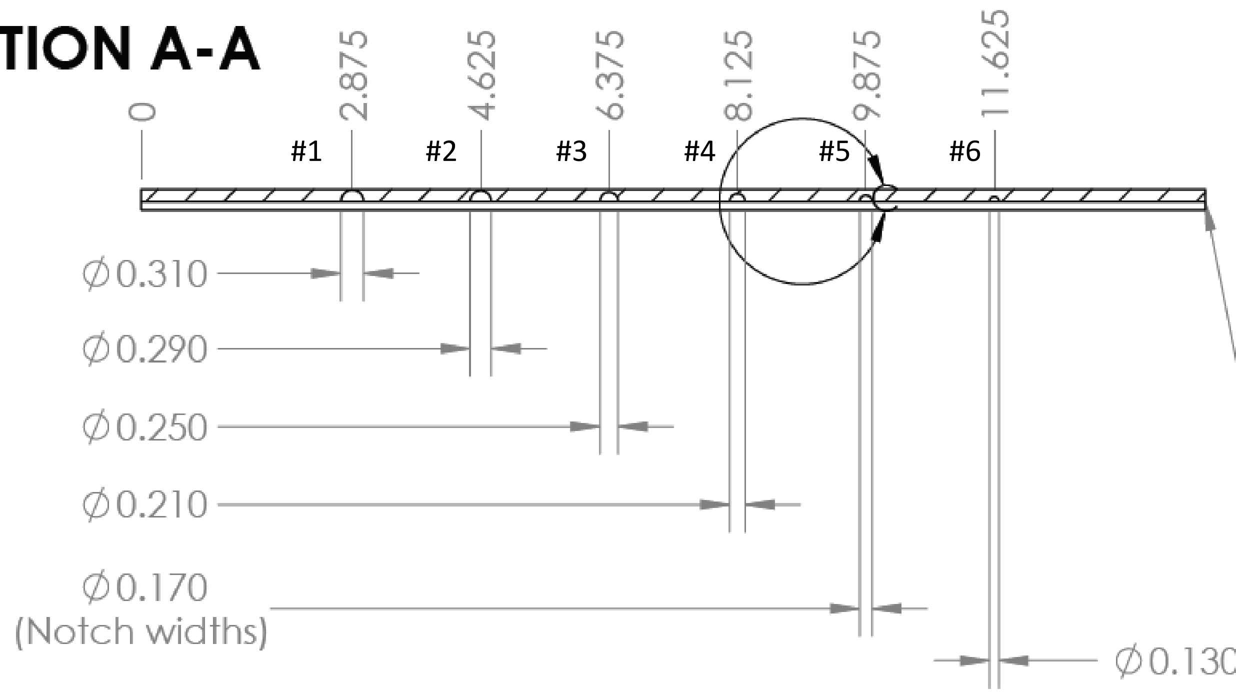


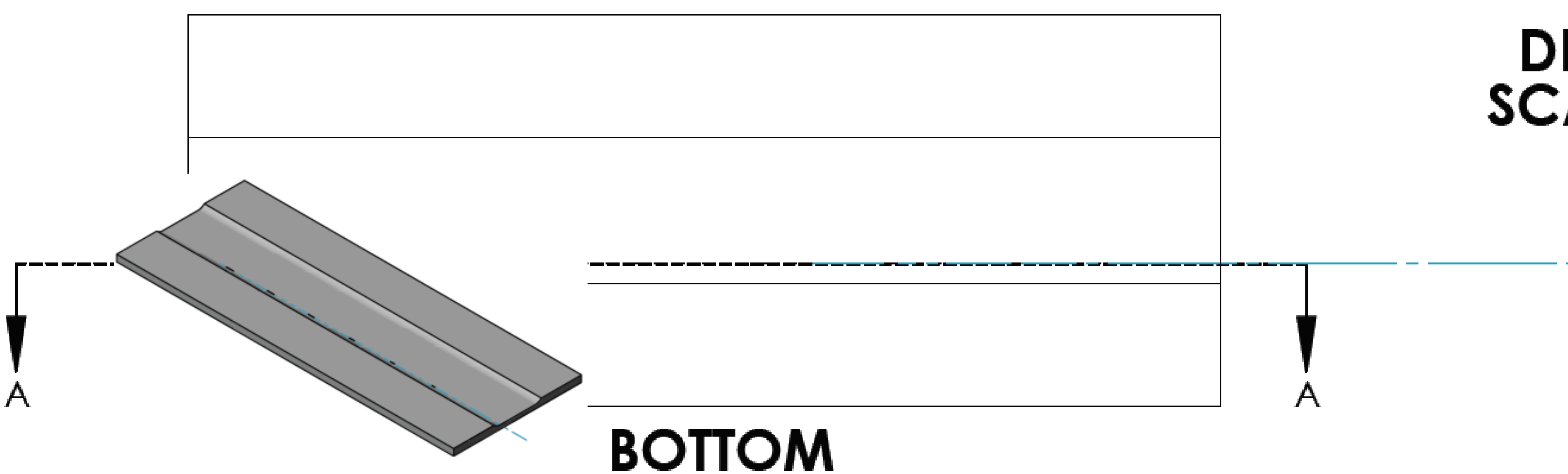
Subsurface Crack Specimen



JENTEK Sensors

Notch #	[mils] Length (2c)	Depth (a)	Distance From Surface (d)
1	310	155	10
2	290	145	20
3	250	125	40
4	210	105	60
5	170	85	80
6	130	65	100





DETAIL C
SCALE 1 : 1

Old vs New JENTEK Instrumentation Performance

ensors

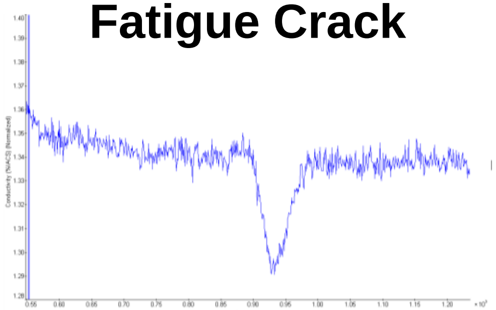
GS-IN7000β

GS-8200α+

NEW < 1 pound

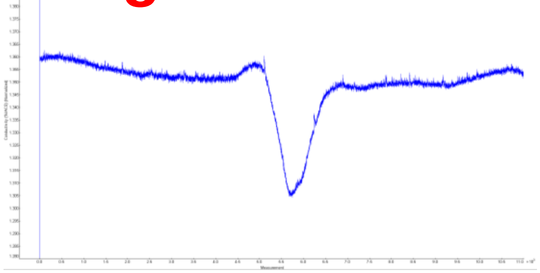
jET platform

0.034 in. by 0.017 in.
Fatigue Crack



Old IN7000 taken at
100 samples per second

Improved crack response signal-to-noise



Same crack

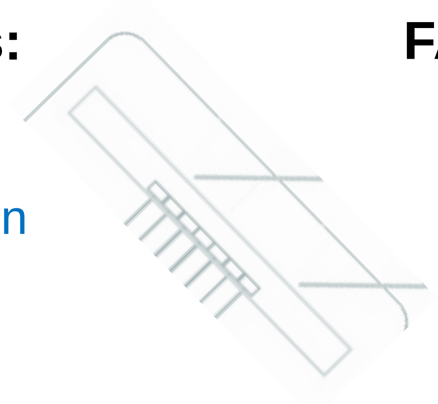
New GS8200
taken at 1,300 samples per second

Technical approach: MWM-Array eddy current testing (ET)

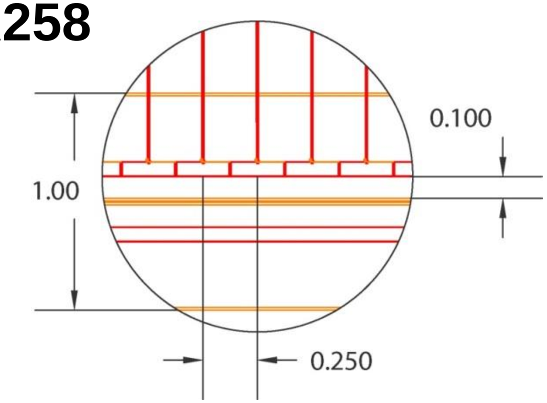
Paradigm shift in sensor design.
First priority is predictable response based on physics-based modeling.

Features for subsurface cracks:

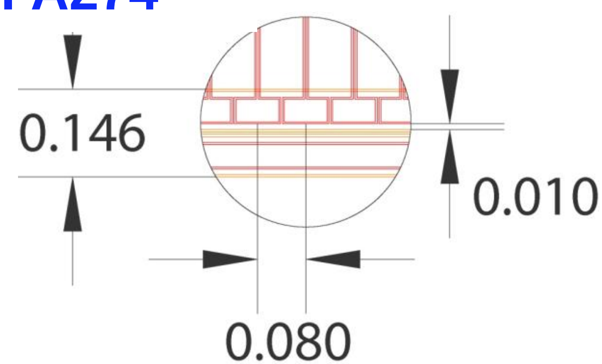
- ✓ Linear central drive conductor for
  - ✓ increase eddy current density
  - ✓ consistent eddy current pattern across array
  - ✓ No gaps in sensitivity
  - ✓ Dual rectangle for more predictable response
- ✓ Linear sensing element array with
  - ✓ Fixed drive-sense gap
  - ✓ Abutted sensing elements
  - ✓ All elements always on when using jET parallel instrument channels for acquisition
- ✓ Flexible for curved parts
- ✓ Long leads for convenient scanning



FA258



FA274



Subsurface crack modeling option

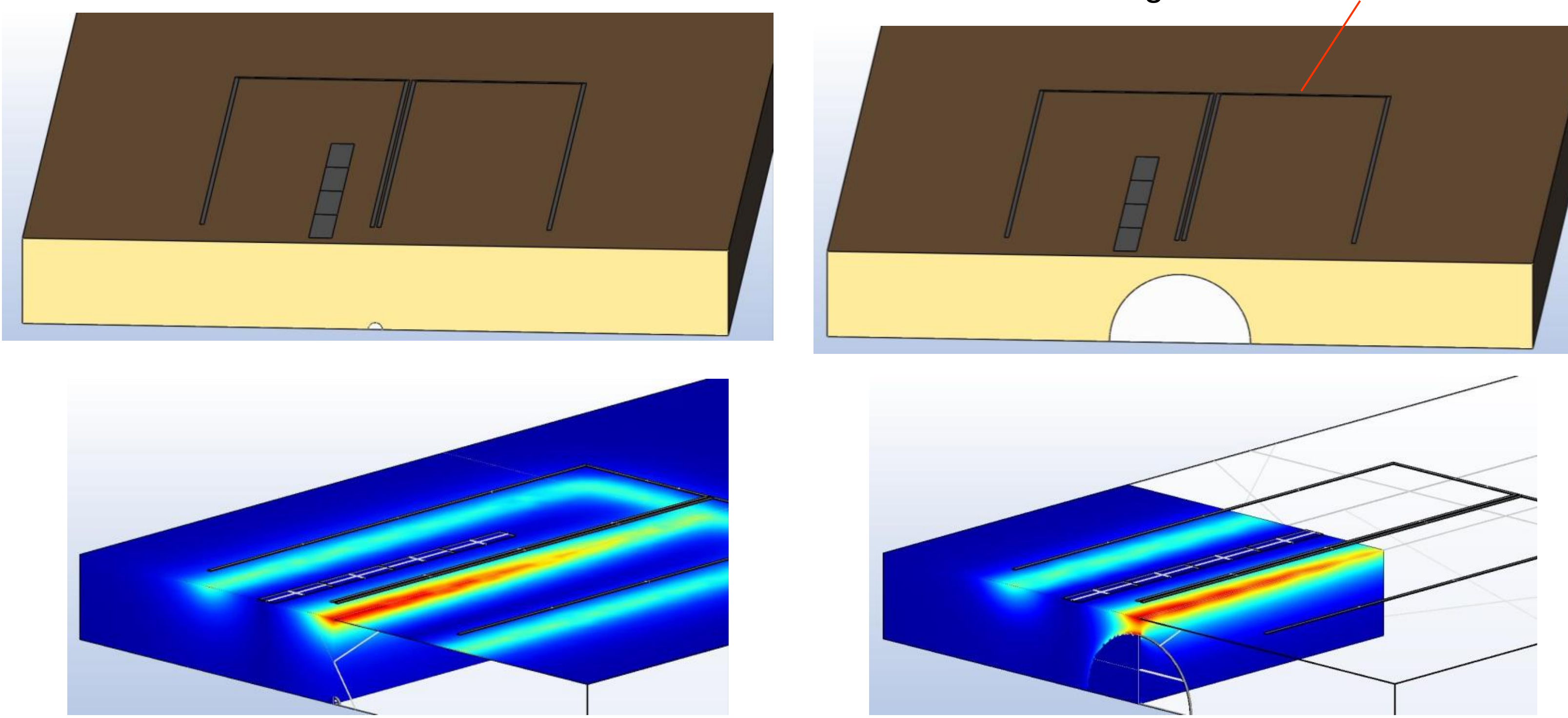
3D models to better understand eddy current patterns

- FA258 over a 0.25 in. plate with small and large cracks (for 1%IACS)
- Linear eddy current pattern
- Crack interferes with eddy current pattern

Smaller Flaw

Larger Flaw

½ of FA258 MWM-Array



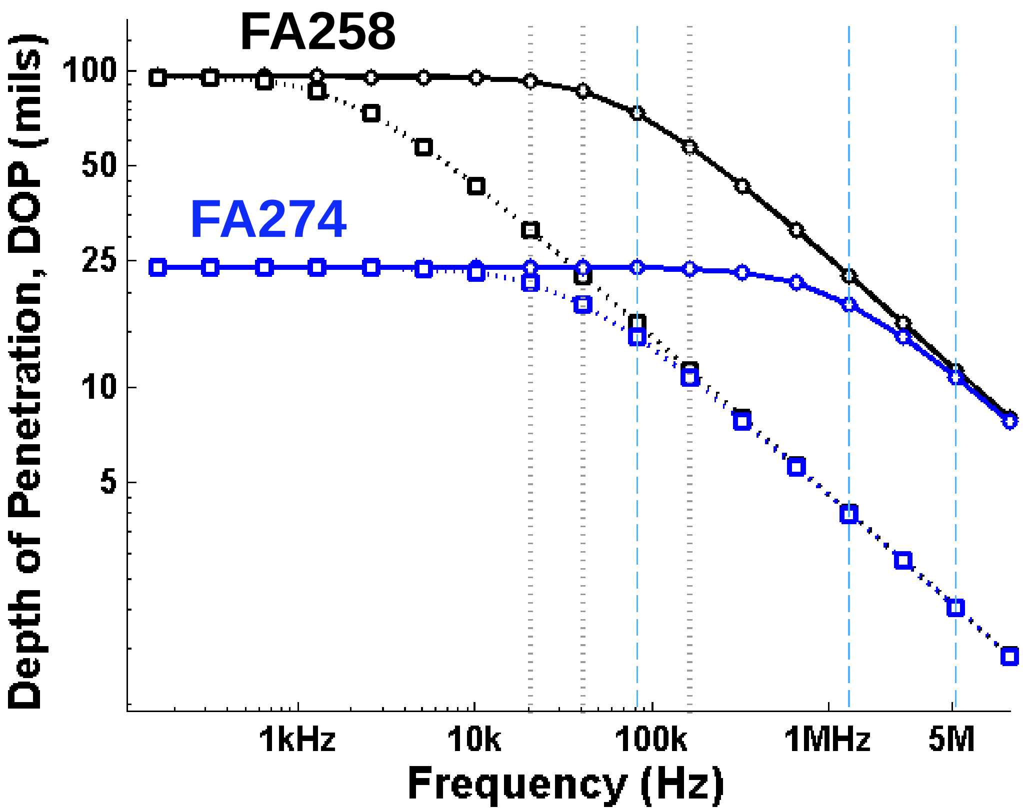
½ of physical geometry (using symmetry)

Induced current density contour plots [100 kHz; 0.05 in. lift-off; 0.4 in. long larger notch]

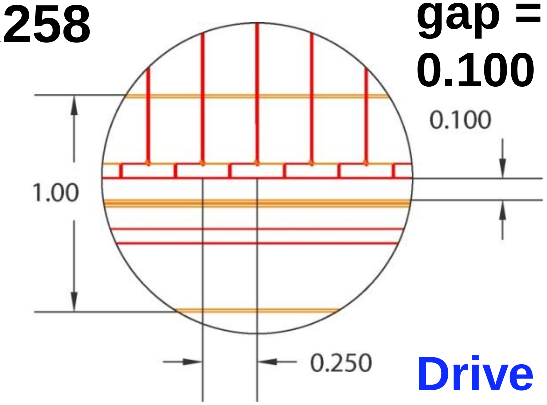
Depth of penetration comparison

Dual Rectangle drive: FA258 and FA274 can provide improved sensitivity to subsurface flaws in the Ti-6Al-4V alloys.

Single Rectangle drive: FA278 enables small surface breaking cracks.

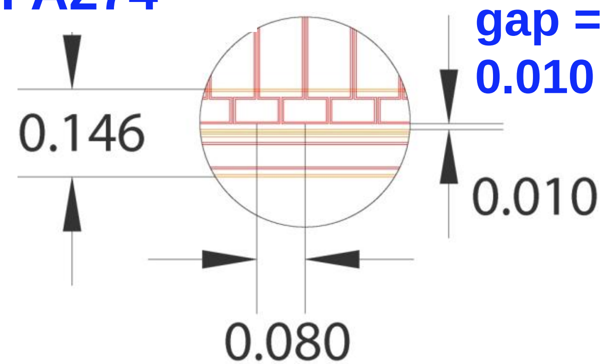


FA258



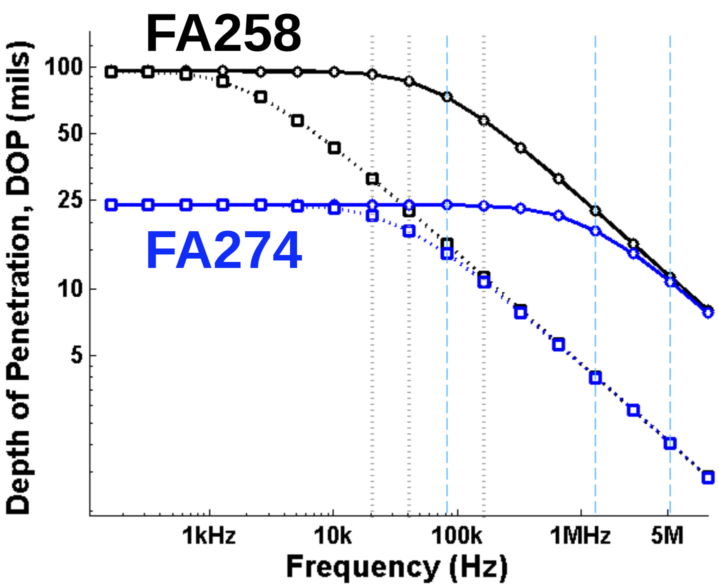
Drive to Sense gap = 0.100

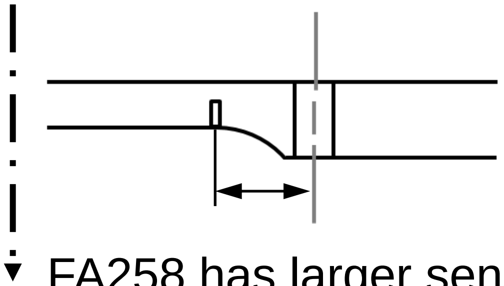
FA274



Drive to Sense gap = 0.010

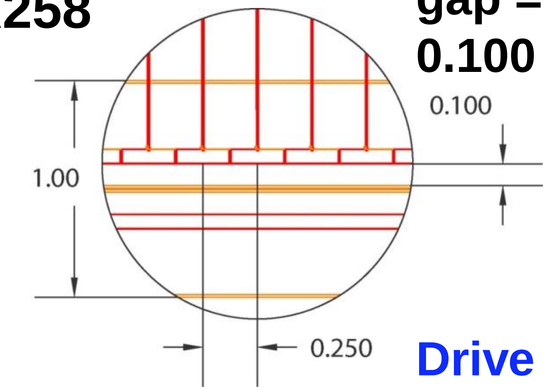
Depth of penetration comparison to thickness





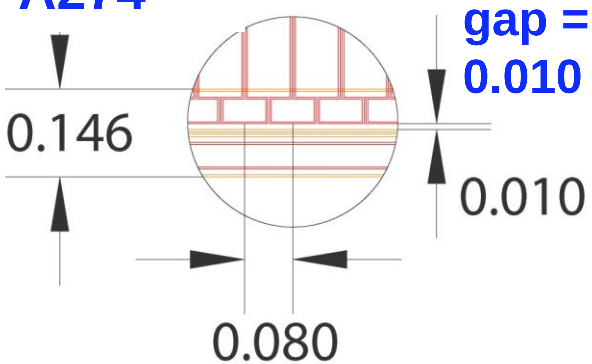
FA258 has larger sensing footprint = bigger hole interference and bigger edge effects

FA258



Drive to Sense gap = 0.100

FA274



Drive to Sense gap = 0.010

ASTM Standard E2884-13

Designation: E2884 – 13

INTERNATIONAL

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.

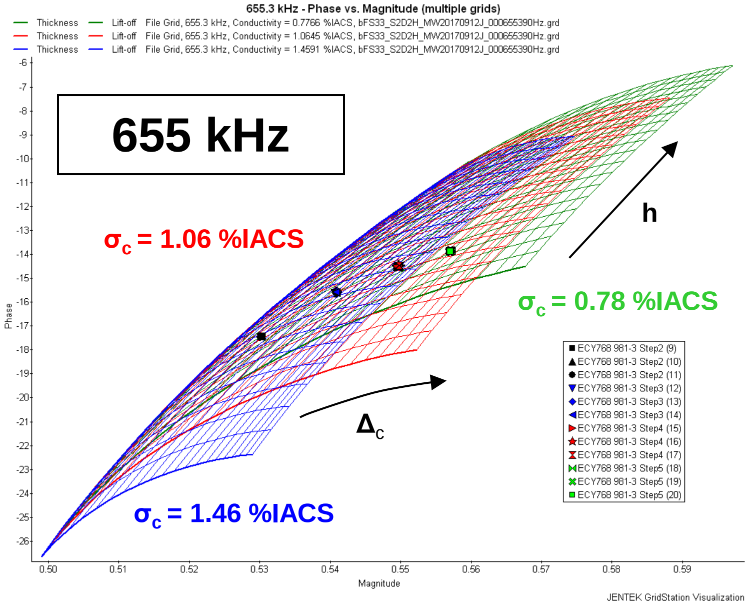
3.2 *Definitions of Terms Specific to This Standard:*

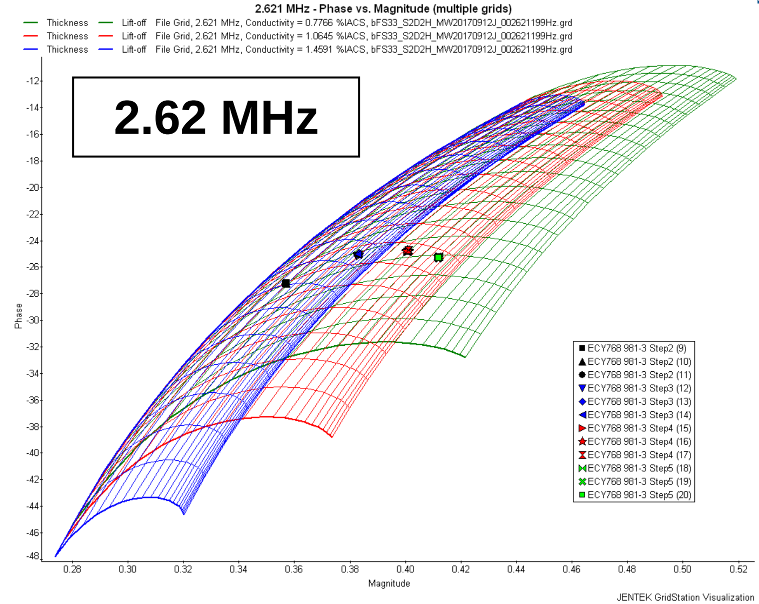
3.2.1 *B-Scan*—a method of data presentation utilizing a horizontal base line that indicates distance along the surface of a material and a vertical deflection that represents a measurement response for the material being examined.

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.

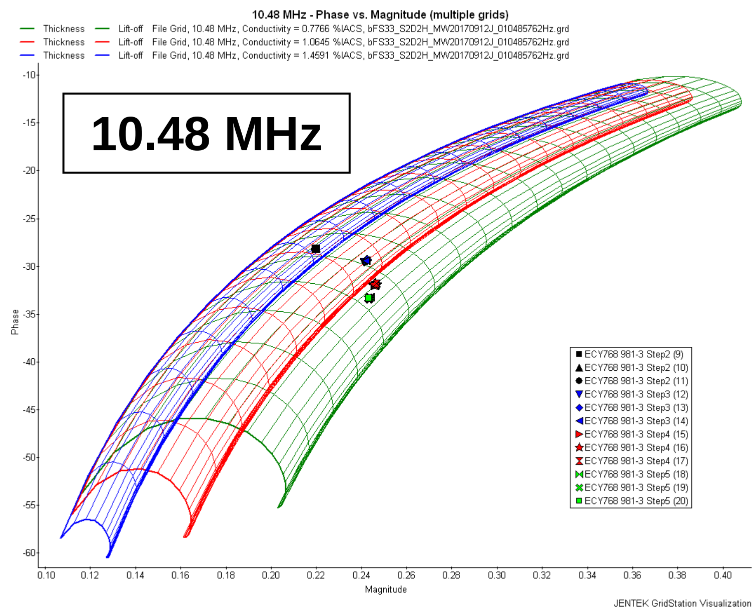
3.2.3 *conformable*—refers to an ability of sensors or sensor arrays to conform to non-planar surfaces without significant

σ_c-Δ_c-h Lattices for 655 kHz, 2.62 MHz, 10.48 MHz ; FA258





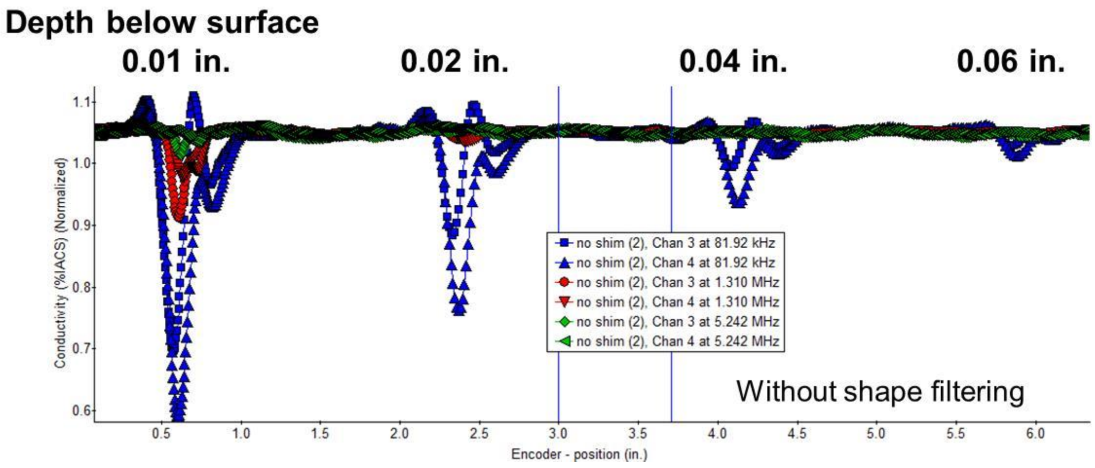
FA258 is sensitive to the layer thickness for 0.2 in. thick layers, even at higher frequencies.

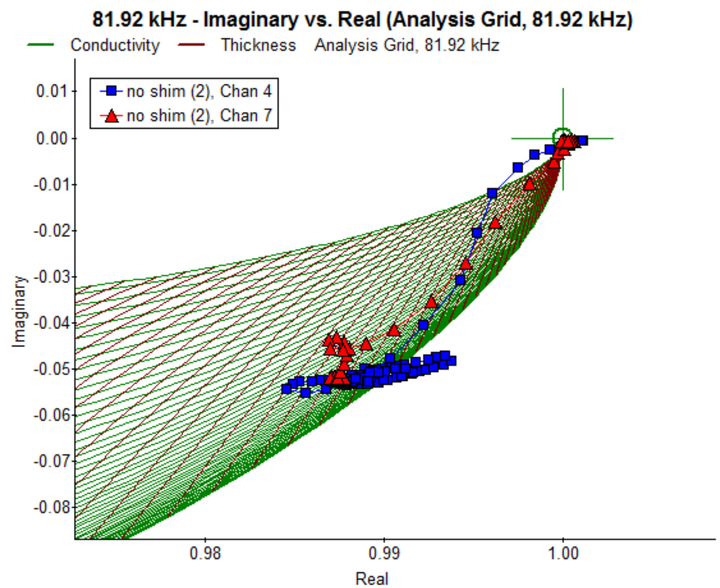


σ_s = 1.97 %IACS

Technical approach: FA274 and 2-Unknown, 2 Frequency, with Model-based Multivariate Inverse Methods (MIMs)

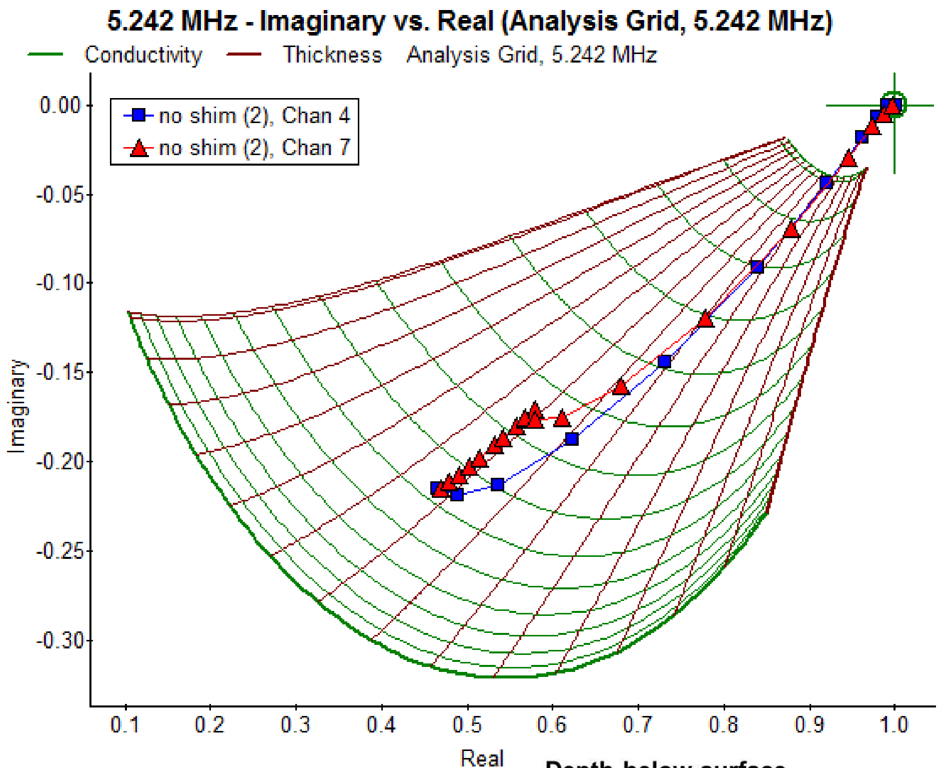
- ❑ Choose FA274 (to reduce sensitivity to thickness variations and to holes and edges.
- ❑ Operate at 80kHz and one or two high frequencies
  - Not sensitive to thickness variations
  - Higher frequencies enable differentiation between surface and subsurface cracks (high freq does not detect subsurface cracks and is even more sensitive to surface breaking cracks)
- ❑ Scan with sensor at 20-45 degree angle to provide sensitivity to transverse oriented cracks



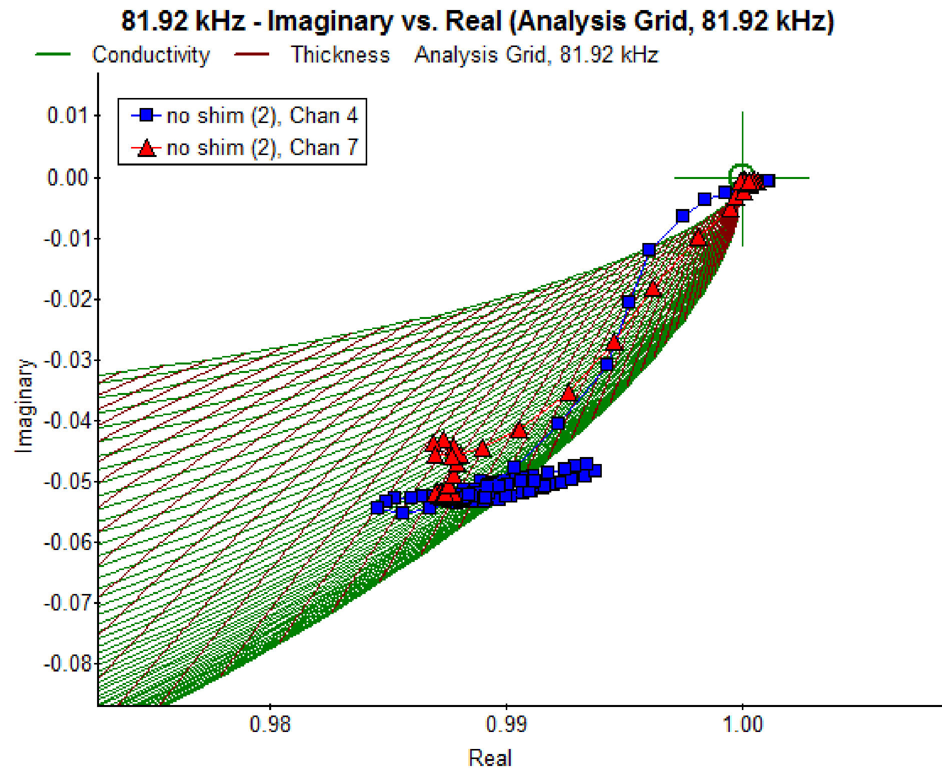


Technical approach: FA274 and 2-Unknown, 2 Frequency, with Model-based Multivariate Inverse Methods (MIMs)

5.2 MHz No Crack Response



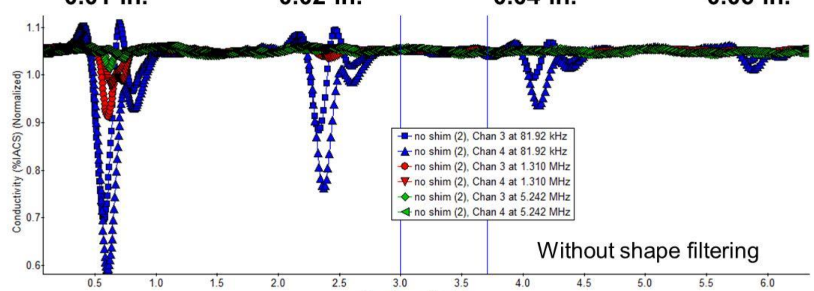
82 kHz Large Crack Response



JENTEK GridStation Visualization

Depth below surface

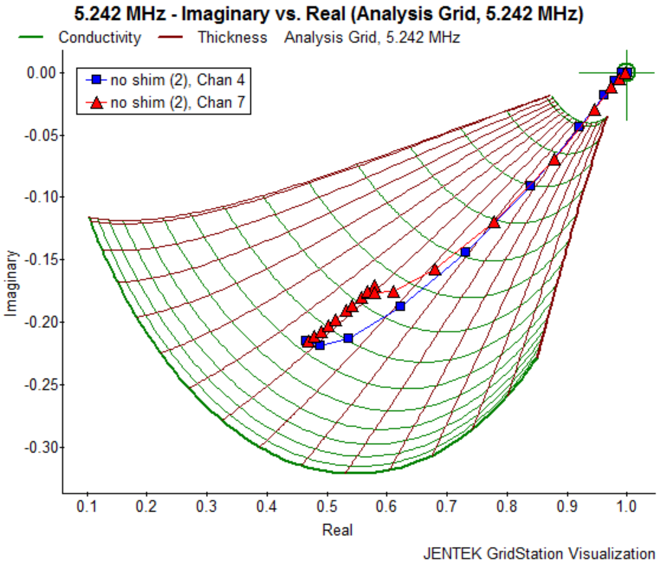
0.01 in. **0.02 in.** **0.04 in.** **0.06 in.**

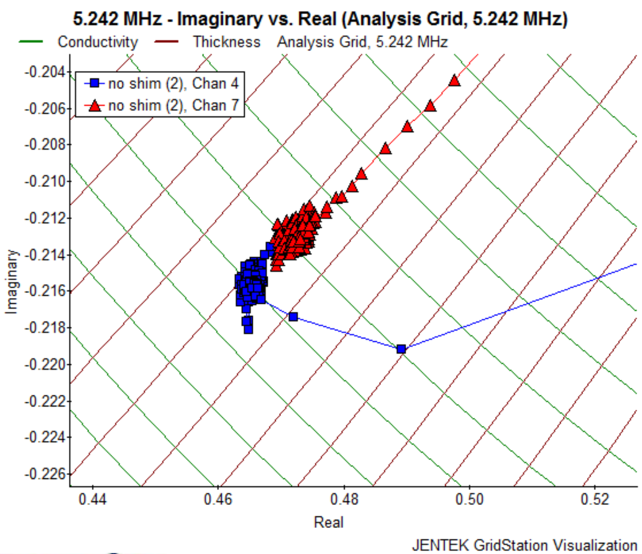


Technical approach: Model-based Multivariate Inverse Methods (MIMs)

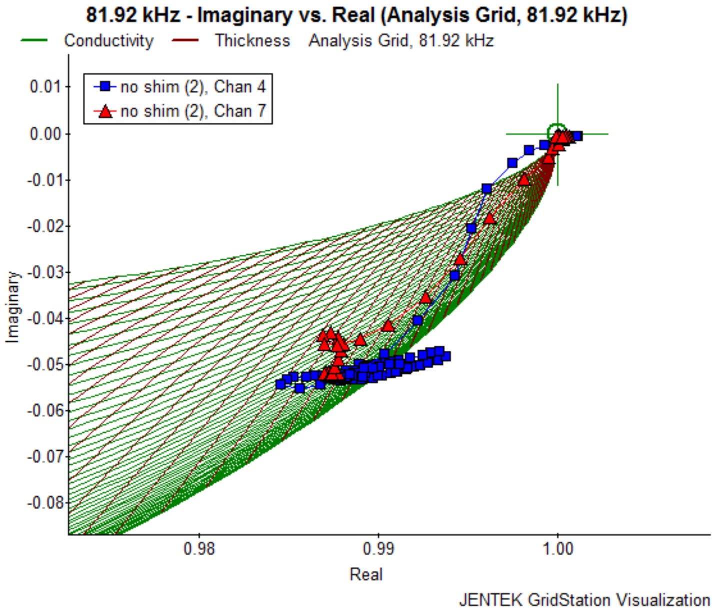
JENTEK Sensors

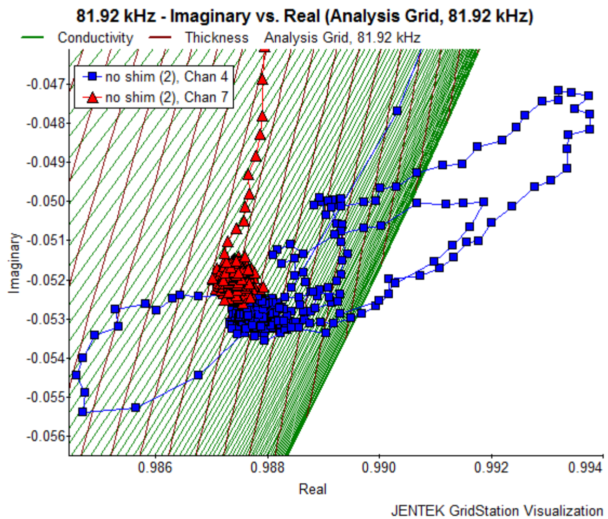
5.2 MHz No Crack Response





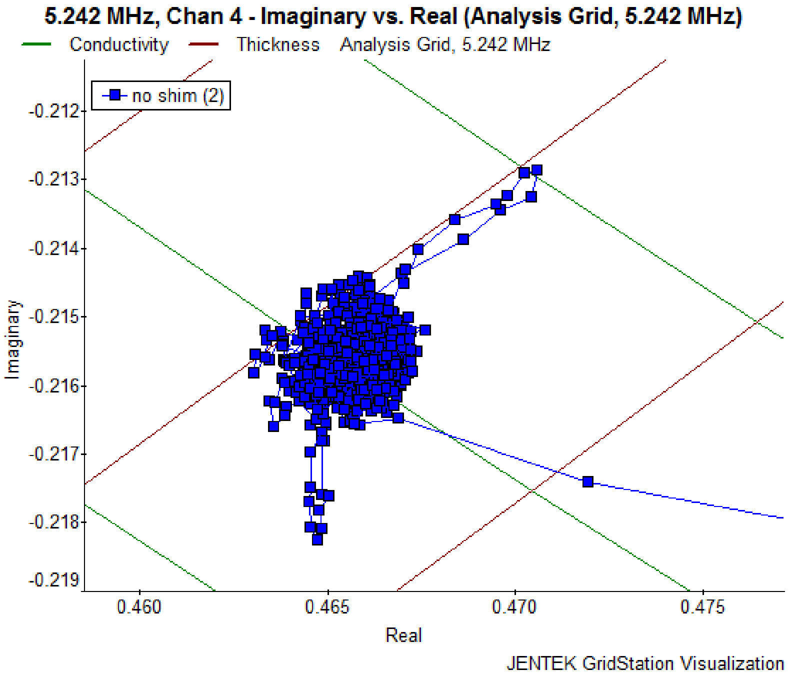
82 kHz Large Crack Response



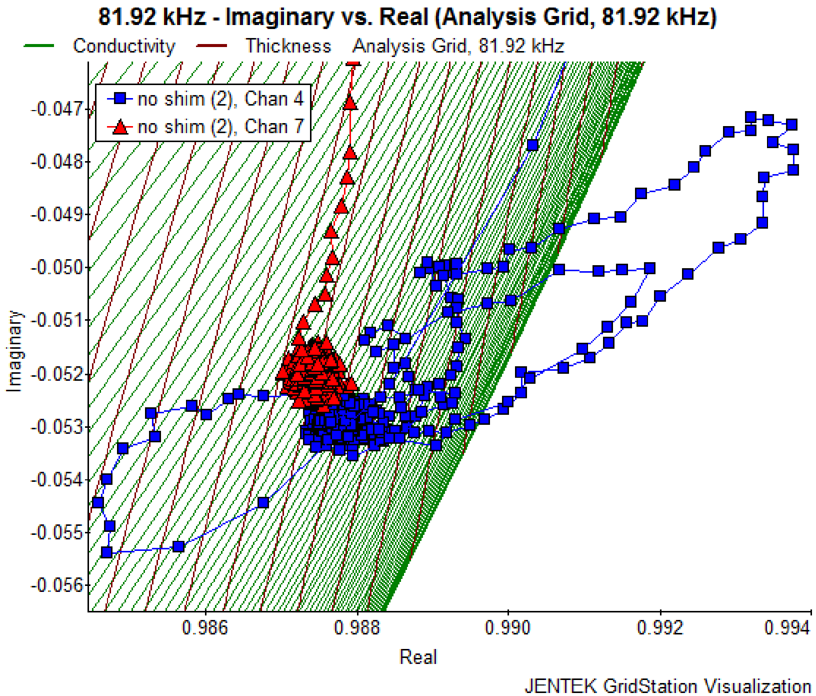


Technical approach: Model-based Multivariate Inverse Methods (MIMs)

5.2 MHz Essentially No Crack Response



82 kHz Relatively Large Crack Response

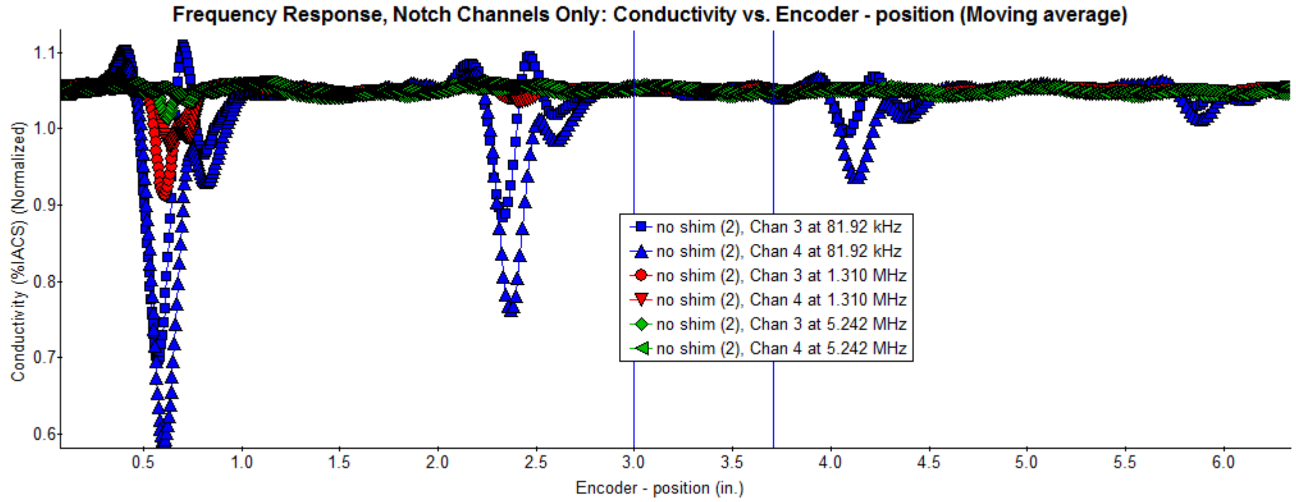


Note: See earlier slide that show 5MHz response is essentially zero except for the defect nearest to the surface

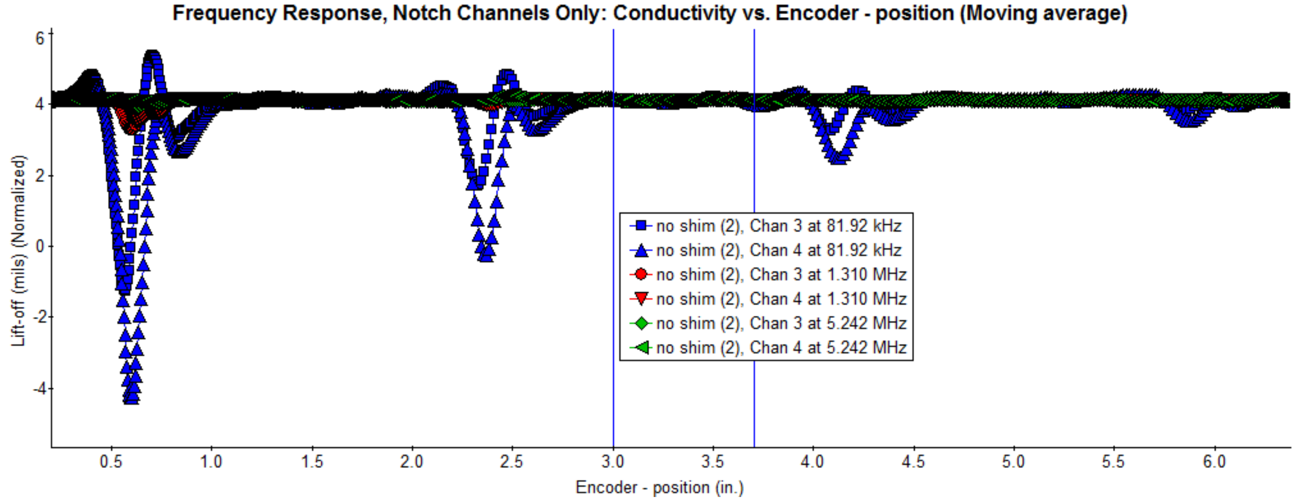
Technical approach: Model-based Multivariate Inverse Methods (MIMs)

Uniform Layer Model does not include crack (EDM) modelling

Conductivity Estimate



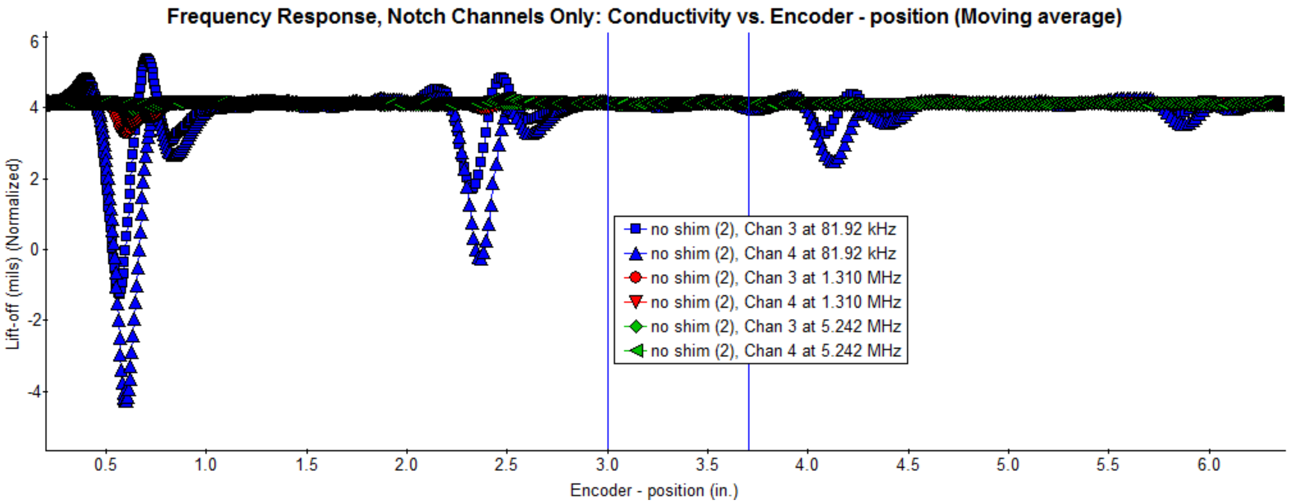
Liftoff Estimate



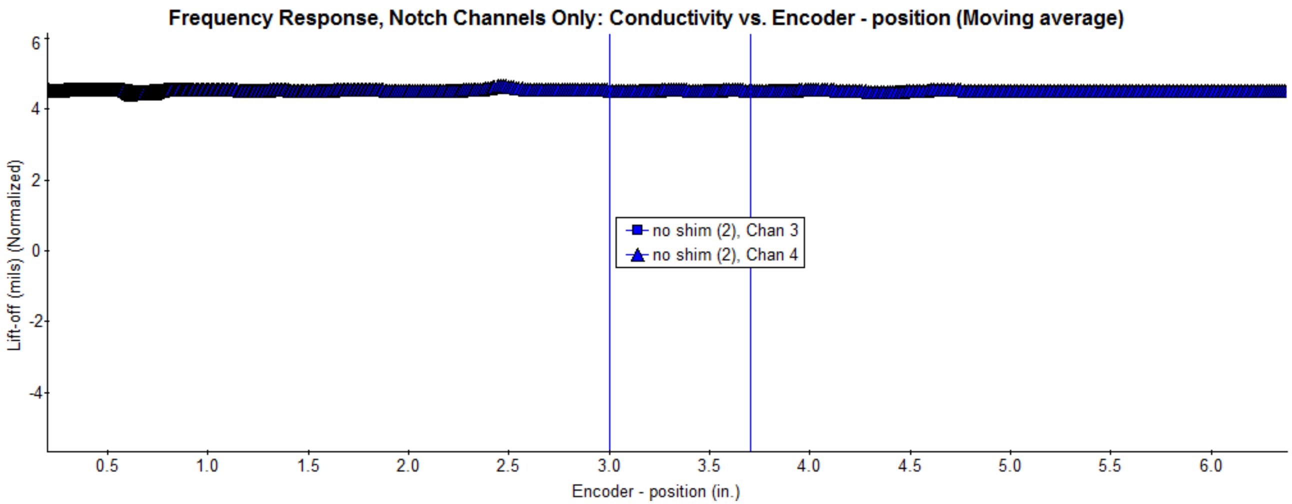
Technical approach: Model-based Multivariate Inverse Methods (MIMs)

Uniform Layer Model does not include crack (EDM) modelling

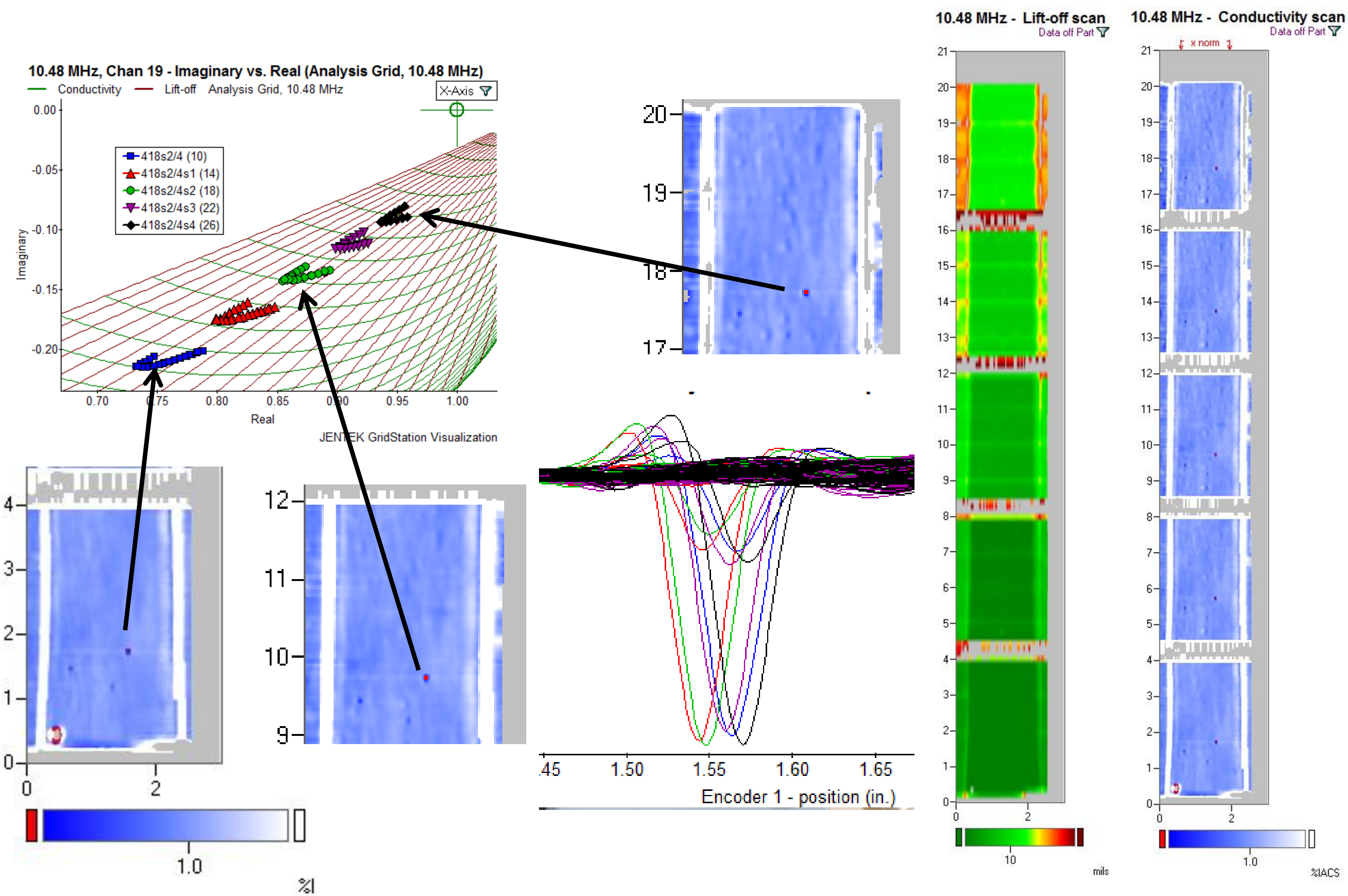
Liftoff Estimate



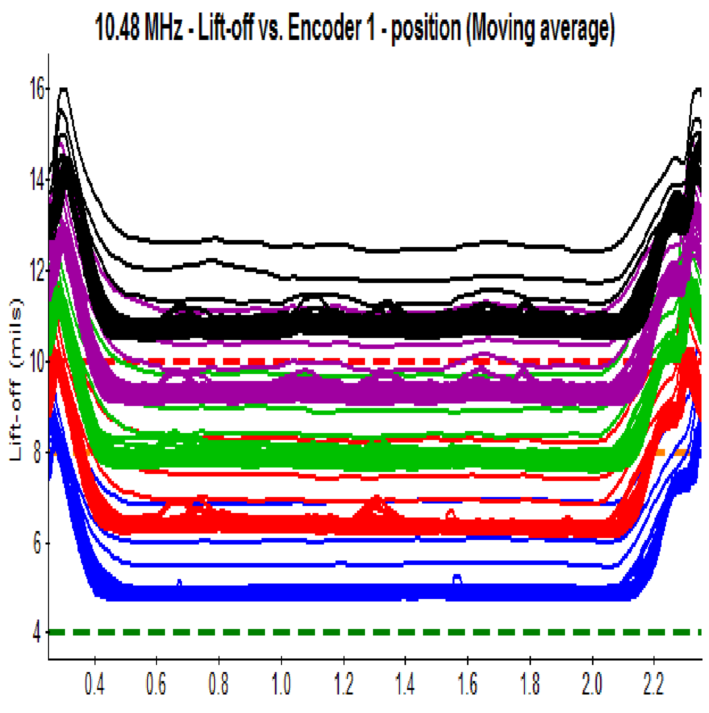
5MHz
Liftoff Estimate

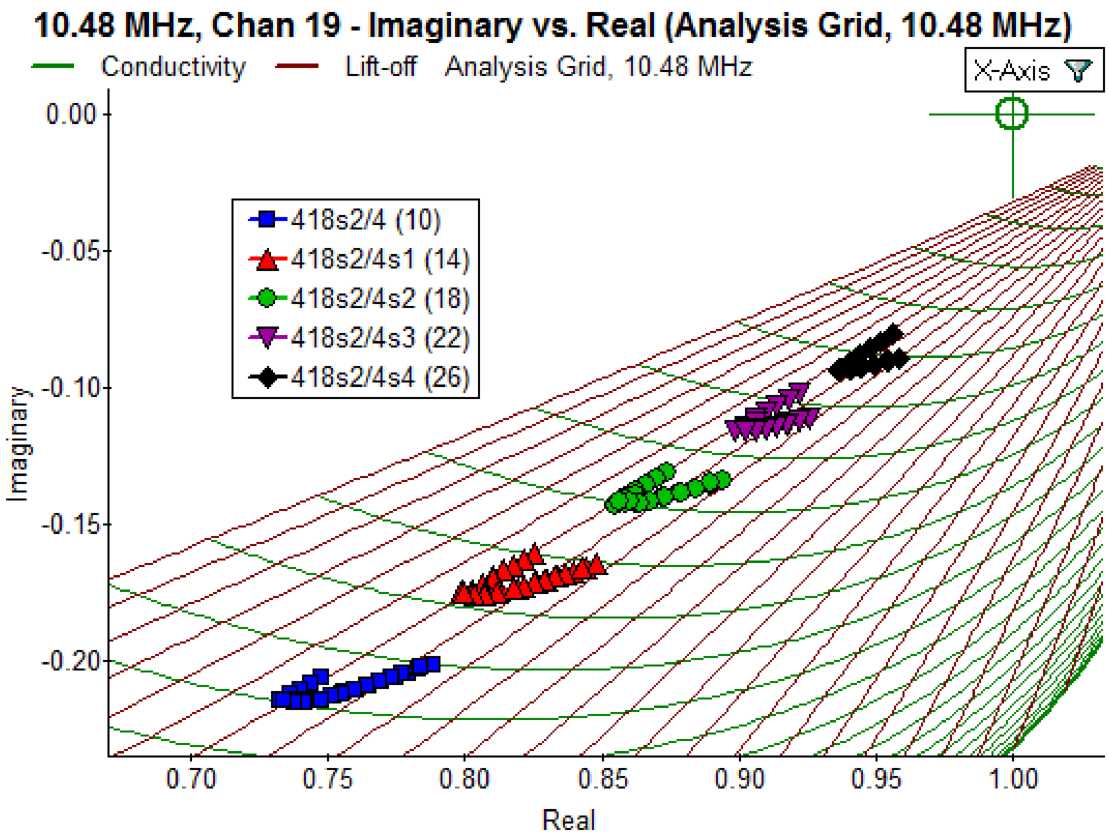


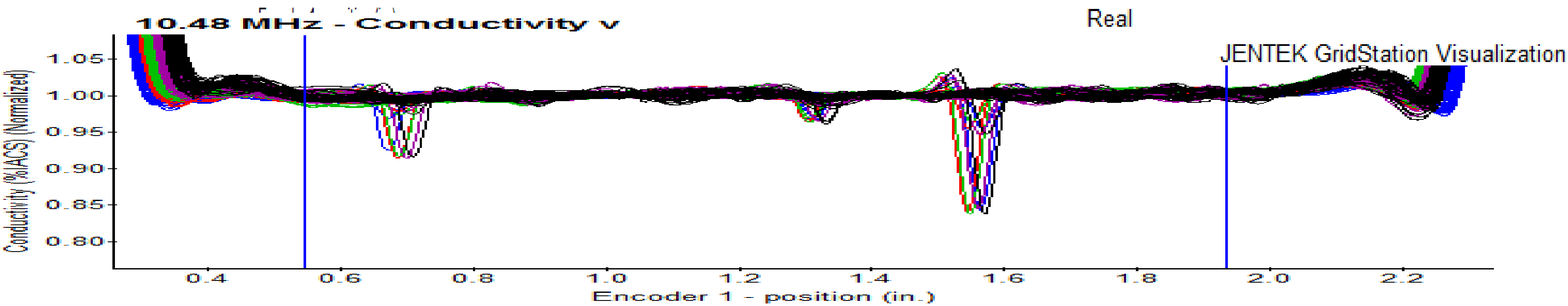
Surface Cracks at high frequency produce larger response
GridStation automatically rescales crack response with Lift-off



Surface Cracks: Rescaling of Conductivity Response with Lift-off

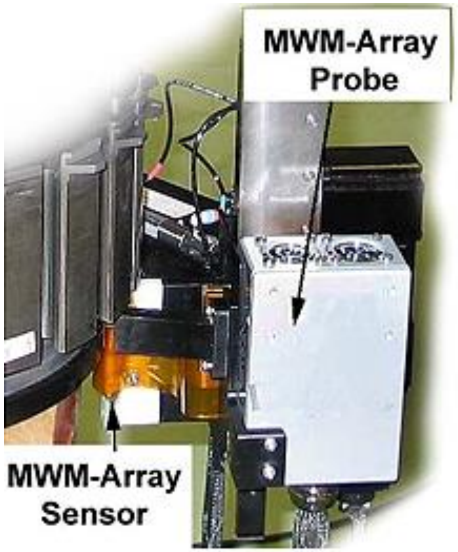


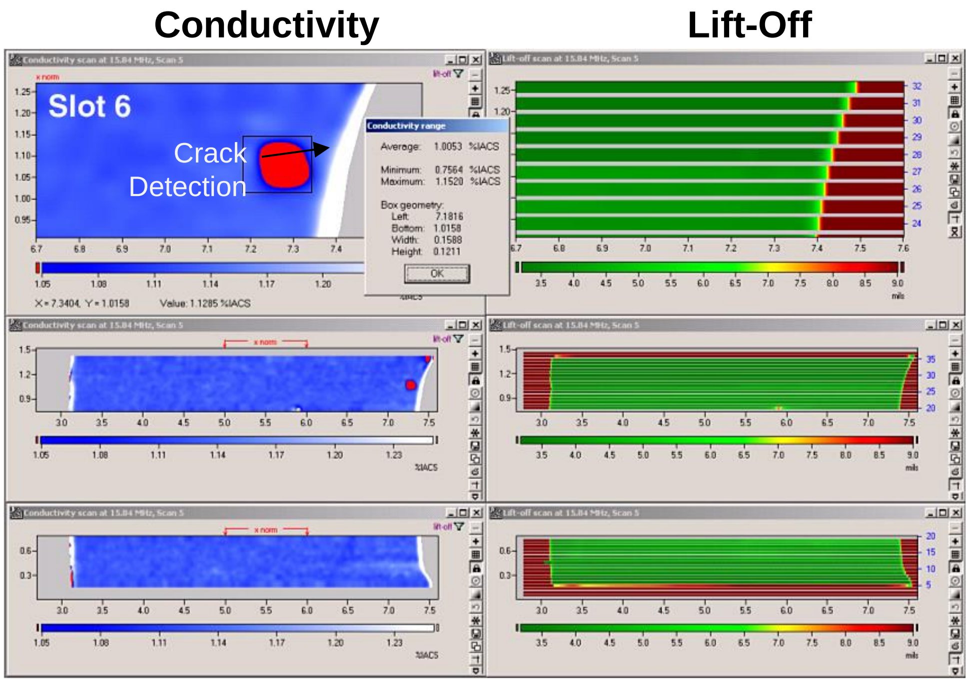




Historical Success: NAVAIR Engine Disk Inspection

- 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)

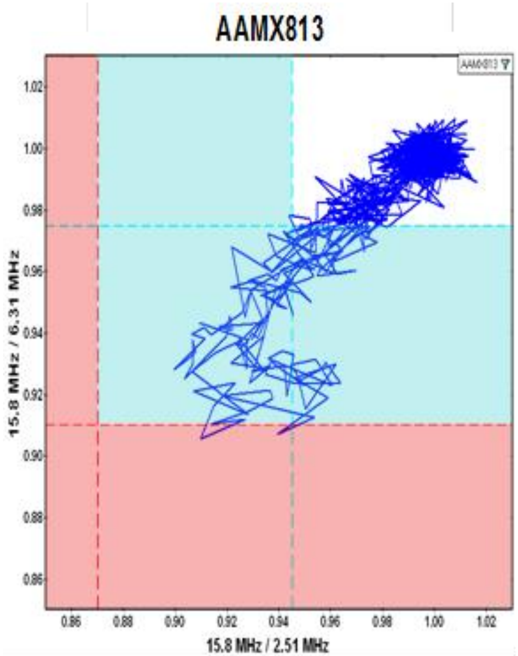


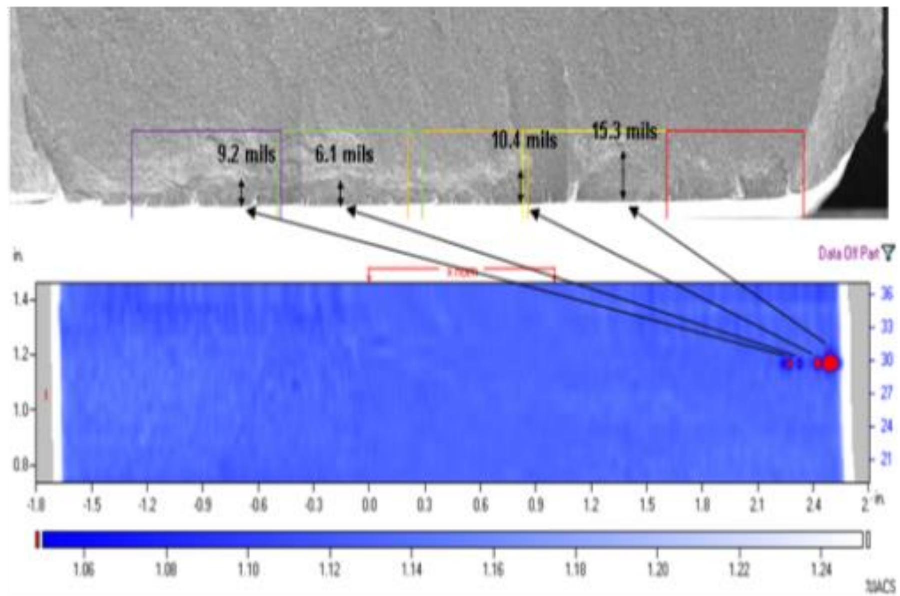


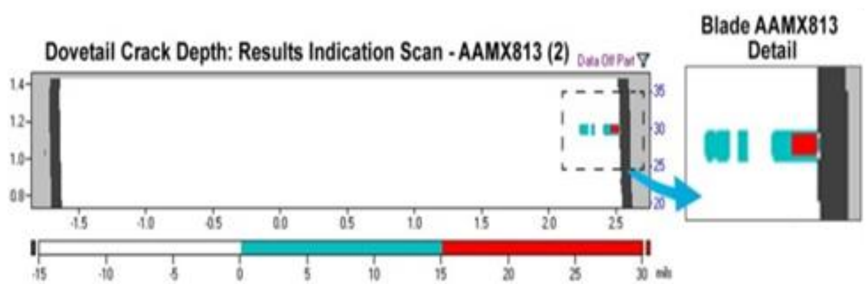
Winner, FAA-Air Transport Association 2007 "Better Way" Award for "MWM and MWM-Array Engine Component Inspection Technology"

Historical Success: Crack Detection and Depth Estimation (Titanium Alloy Blade Dovetail) NAVAIR application

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



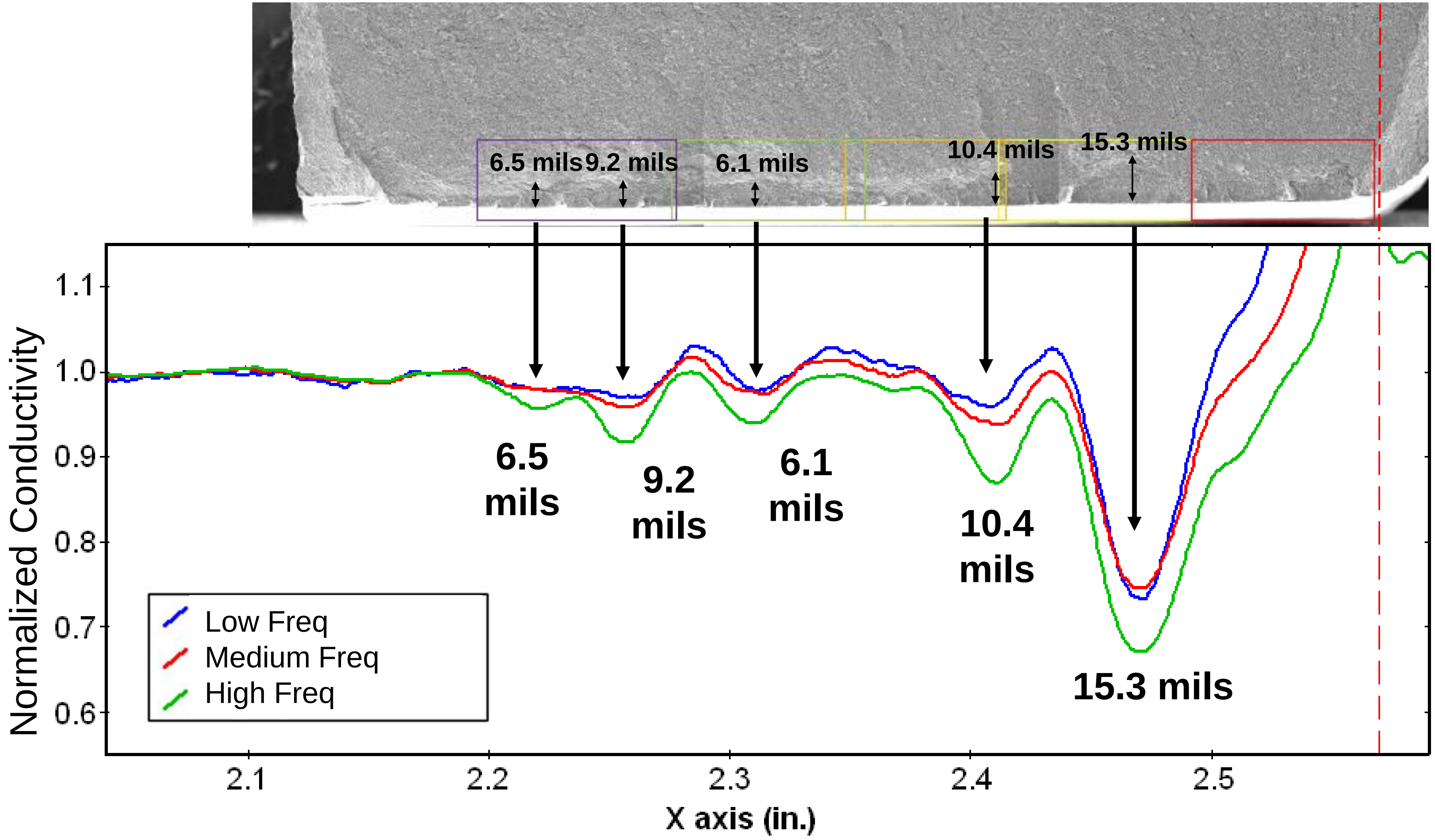




Crack Depth Image

Historical Success: Crack Detection and Depth Estimation (Titanium Alloy Blade Dovetail) NAVAIR application

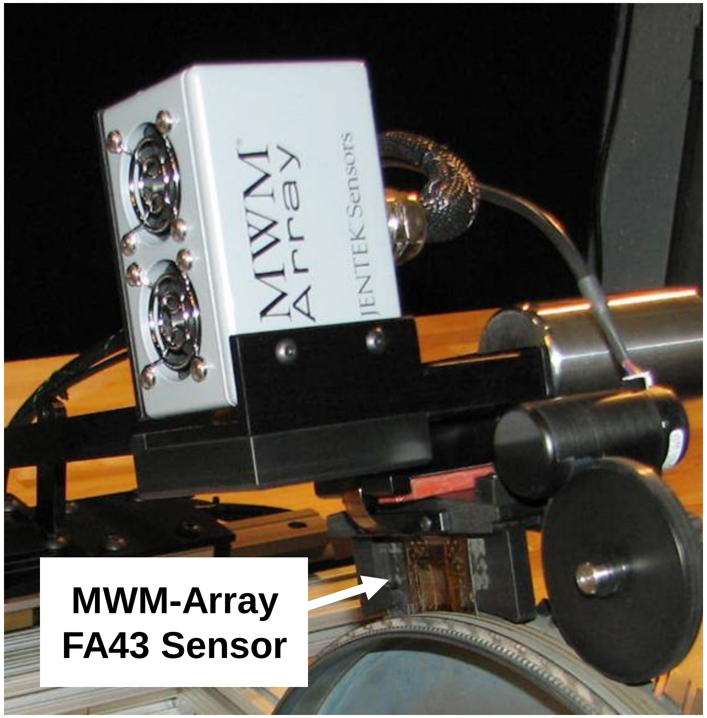
Blade #13



Distribution Statement A -- Approved for public release; distribution is unlimited, as submitted under NAVAIR Public Release Authorization Tracking number 2015-217.

Historical Success: 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)



MWM-Array FA43 Sensor adapted for knife seal inspection

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

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

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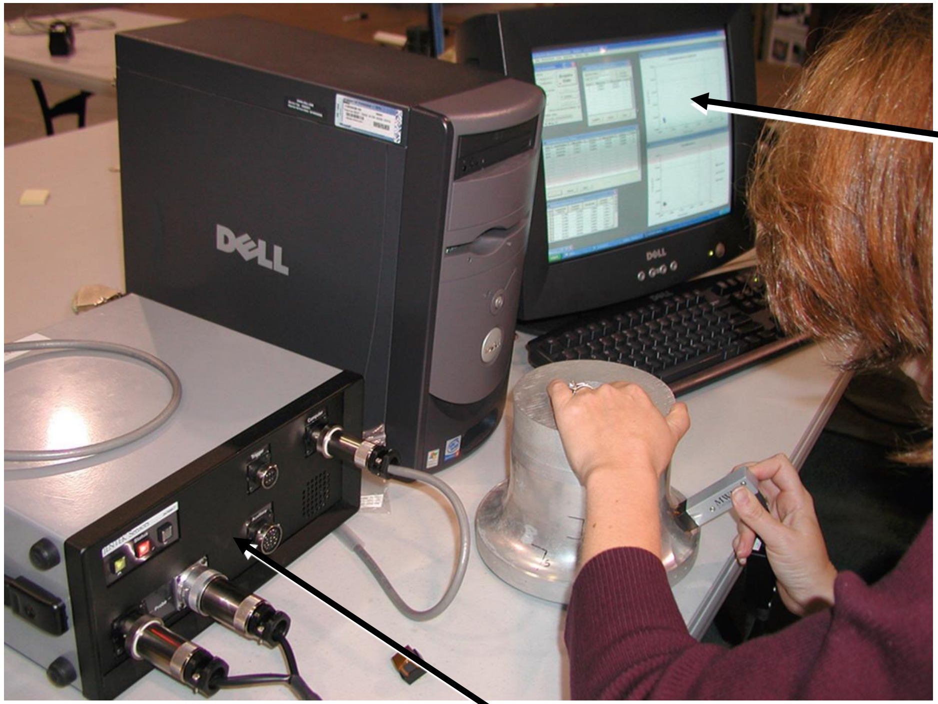
Historical Success: Air Force Inspection
Cold Rolling Integrity on C-130 Propeller Blades

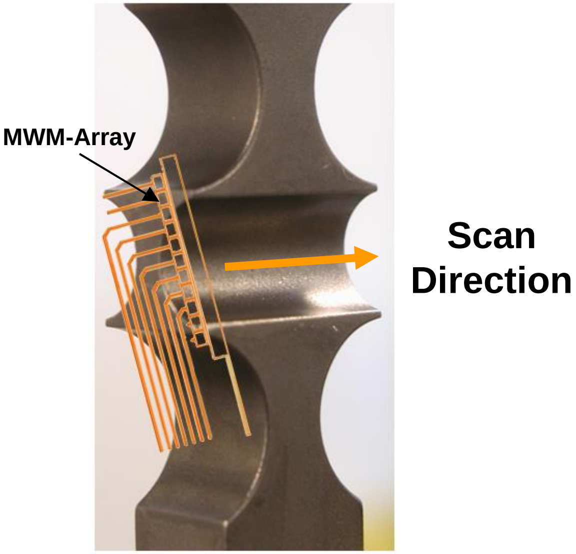


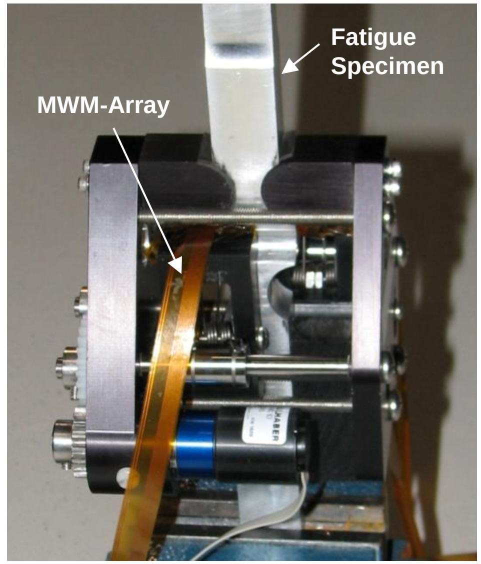
GridStation Display

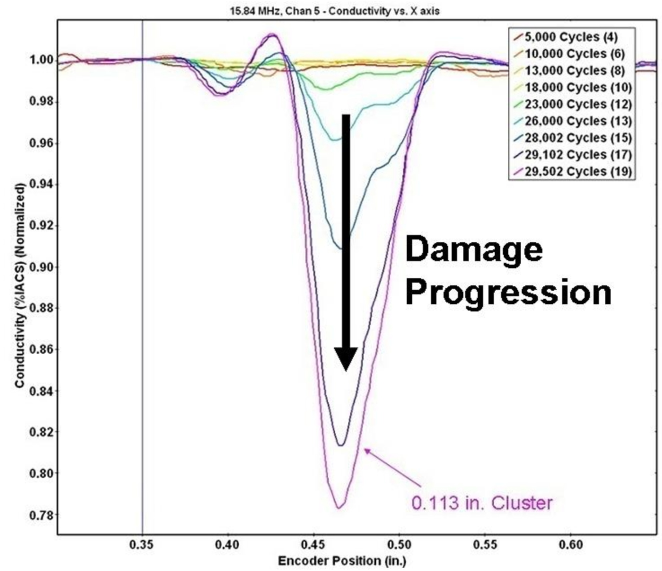
JENTEK GridStation System for C-130
Propeller Cold Rolling Inspection

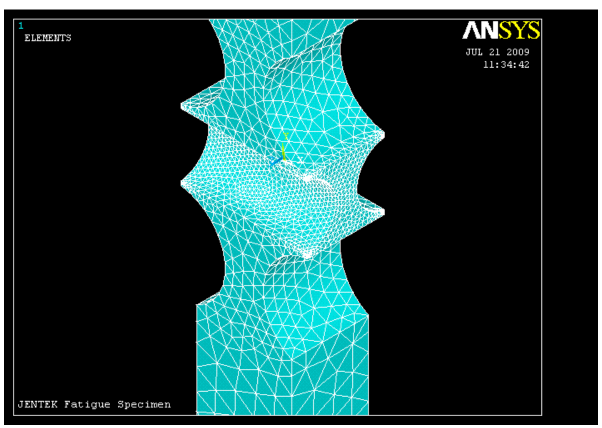
POD Real Crack Sample Fabrication using Fatigue Specimen with Continual MWM-Array Scanning

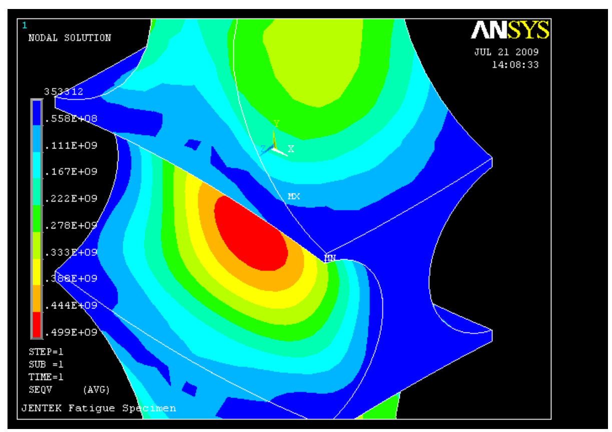
Must be adapted for subsurface cracks

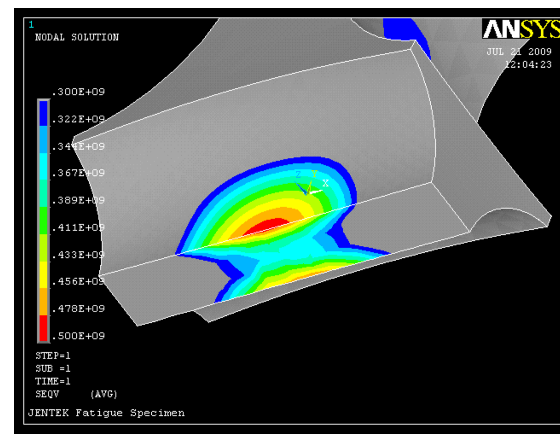












Summary & Remaining Work

- ❑ Subsurface detection capability demonstrated for EDM notches
- ❑ jET with MWM-Array provides convenient tool
- ❑ Model-based Multivariate Inverse Method can differentiate surface breaking from subsurface defects.
- ❑ **Ongoing and recent work funded by Air Force Phase 2.5 SBIR.**

Remaining work

- ❑ Fabricate real crack samples to verify performance and determine “knock down factor”
- ❑ Perform POD study
- ❑ Evaluate value of modeling crack to improve robustness and size estimation