AFRL

NONDESTRUCTIVE EVALUATION FOR ENGINEERED RESIDUAL STRESS ASSESSMENT

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Outline

- Motivation / Impact
- Background
- Review of Initial Development Program
  - Confounding factors
  - Prototype NDE Technologies
- Status of Follow-on SBIR
  - Technology maturation
  - Testing and optimization
  - Preliminary capability assessment
  - Capability demonstrations
- Summary
- Way Forward

• Photograph by author

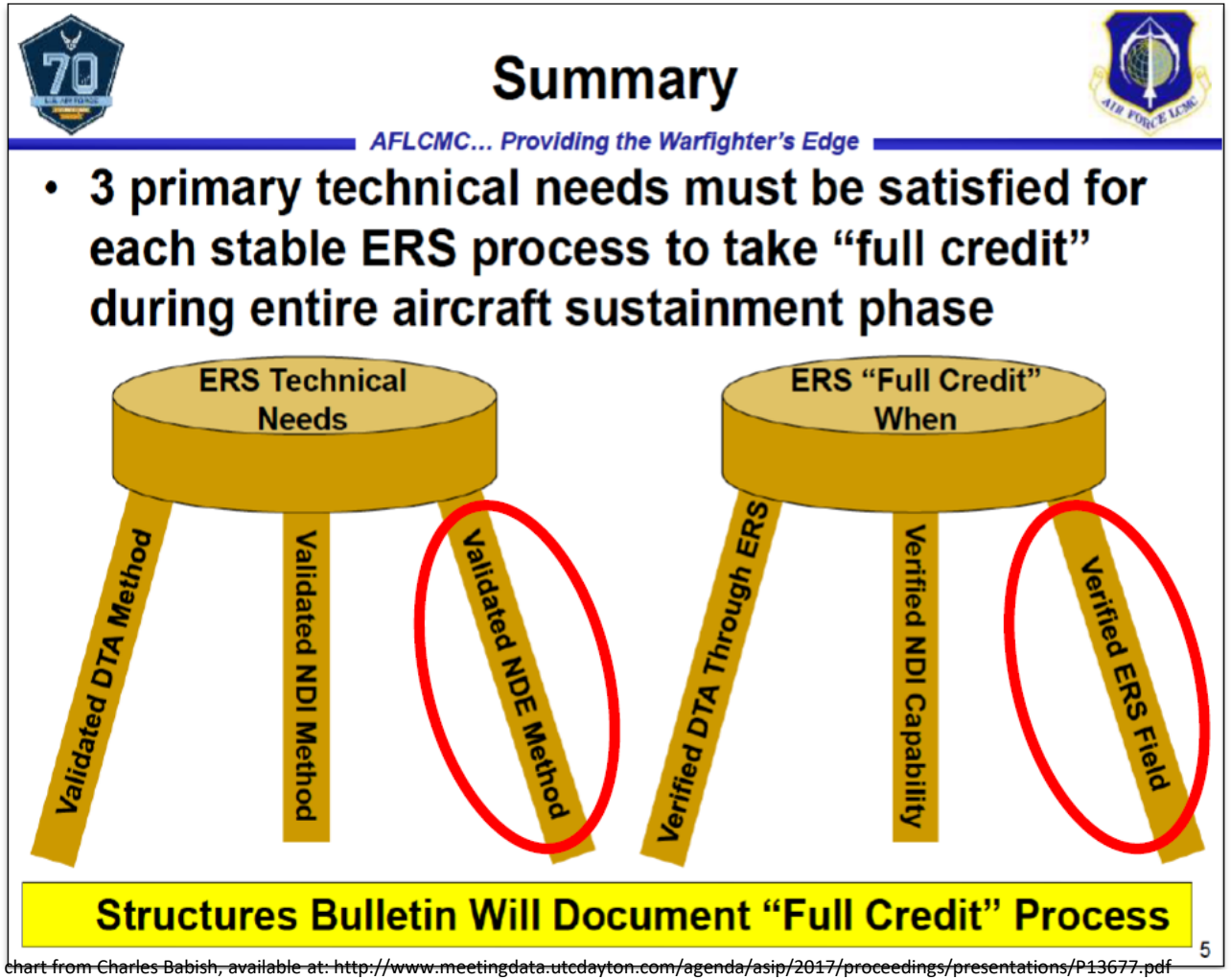
Motivation / Impact

Defining the need

- QA of Cx process to ensure residual stresses are present
- Verification residual stresses remain present during life

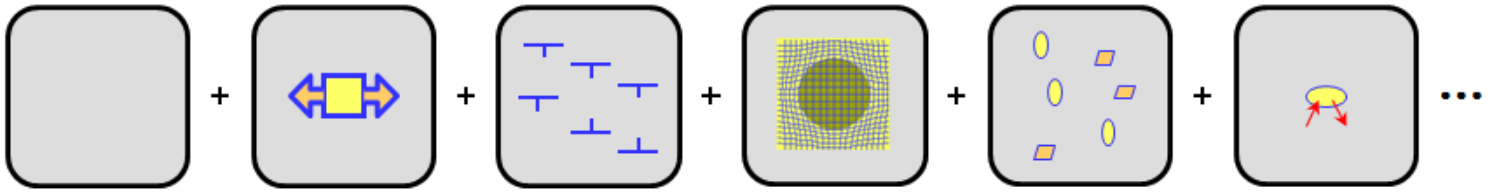
Impact of solution

- Enhanced life management
- Extended inspection intervals



Briefing chart from Charles Babish, available at: http://www.meetingdata.utcdayton.com/agenda/asip/2017/proceedings/presentations/P13677.pdf

Background – Challenges for NDE of Residual Stress in Metals



conducting matrix T	residual stress τ_{res}	dislocation density η_{disl}	coherency strain ε_{ii}	precipitate size V_f	solute partitioning x_n
<< 1%*	1-1.5%	up to 3%	% ?	% ?	% ?

* Temperature controlled environment

- **Lots of factors affect measurement in addition to residual stress**
  - **Microstructural complications simplified with aluminum alloys**
  - **Macro-scale considerations: temperature and geometry**
  - **USAF considerations: manufacturing (e.g. fit-up stresses), maintenance, modification, repair, use**
- **Deconvolve or control as much as possible**
- **Maximize sensitivity analysis**

Initial Development Program

Objectives, Scope, and Outcomes

- Developed and demonstrated prototype NDE techniques for QA of Cx residual stress
- Focused on straight shank holes, 2024 and 7075 aluminum alloys
- Evaluated a wide array of confounding factors

- Eddy Current centric

Factor	Influence on NDE response – ET
Electrical Conductivity: Global	High
Electrical Conductivity: Through Thickness Variation	Medium
Hole Diameter	Medium
Plastic Strain	Medium
Coatings/Paint	Medium
Hole Skew	Medium or Low
Operational Overloads	Medium or Low
Temperature Variation – Long Term Changes	Medium or Low
Temperature Variation – Short Term Fluctuation	Medium or Low
Acoustoelasticity	Low
Chemical Composition	Low
Cross-Section Changes	Low
Hole Edge Margin	Low
Hole Pitch	Low
Hole Roundness	Low
Microstructure – Global	Low
Microstructure – Local	Low
Static Loads	Low
Surface Corrosion	Low
Surface Flatness	Low
Surface Roughness	Low
Surface Treatment	Low
Thermal Conductivity	Low
Thermal Exposure	Low

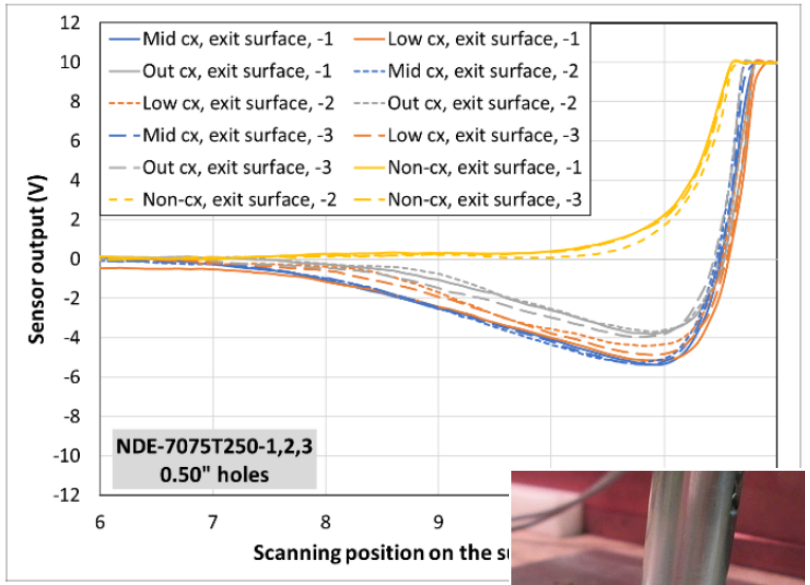
- Ultrasound centric

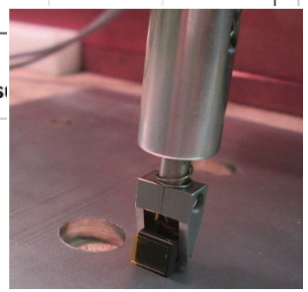
Factor	Influence on NDE response – UT
Acoustoelasticity	High
Coatings/Paint	High or Low
Chemical Composition	Medium
Hole Diameter	Medium
Hole Edge Margin	Medium
Hole Pitch	Medium
Microstructure – Global	Medium
Microstructure – Local	Medium
Operational Overloads	Medium
Surface Corrosion	Medium
Surface Flatness	Medium
Temperature Variation – Long Term Changes	Medium
Temperature Variation – Short Term Fluctuation	Medium
Cross-Section Changes	Medium
Thermal Conductivity	Low
Electrical Conductivity: Global	Low
Electrical Conductivity: Through Thickness Variation	Low
Hole Roundness	Low
Hole Skew	Low
Plastic Strain	Low
Static Loads	Low
Surface Roughness	Low
Surface Treatment	Low
Thermal Exposure	Low

Explored Technical Approaches

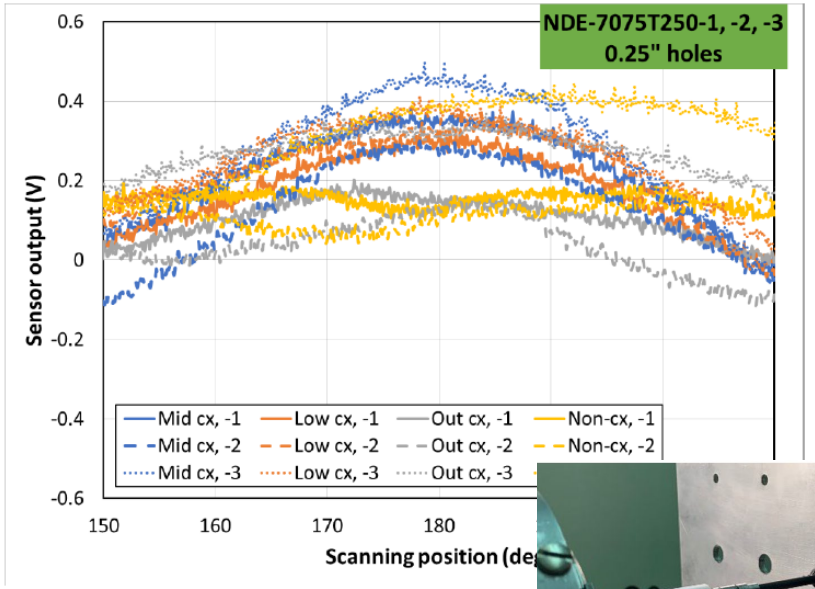
- **Down-selected to three approaches: eddy current surface scan, low frequency eddy current in fastener hole, longitudinal critically refracted (LCR) ultrasound**
- **Initial results reported at ASIP Conference 2023**

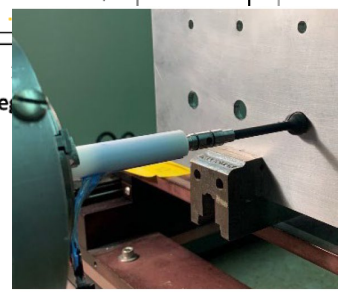
EC Surface Scan



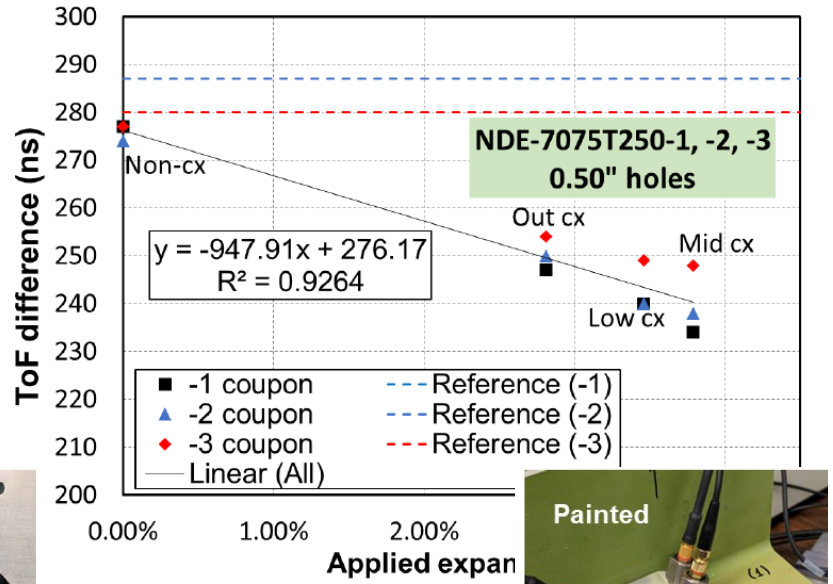


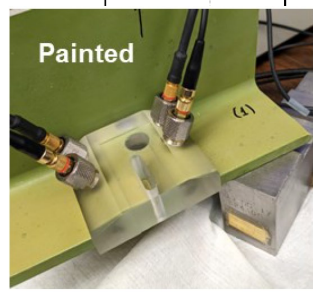
EC In-Hole Scan





UT Surface Scan





Current SBIR Program

Goal: mature and prepare NDE technology(ies) for implementation for quality assurance of Cx fastener holes

- **Leverages results from previous effort**
- **Focuses on through-holes in aluminum**

Key Objectives

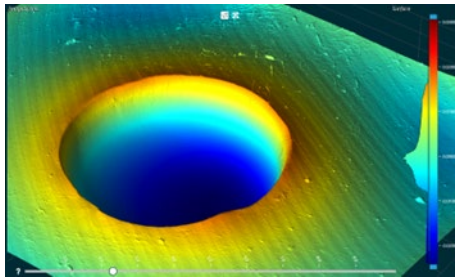
- **Mature capabilities developed on previous program**
- **Resolve source of eddy current surface scan results**
- **Expand applications to include countersunk and filled holes**
- **Optimize approach using additional experimental testing**
- **Characterize reliability of measurement techniques**
- **Refine system components to enable transition**
- **Preliminary validation and demonstration in relevant environment**

Eddy Current Surface Scan Diagnostic Study

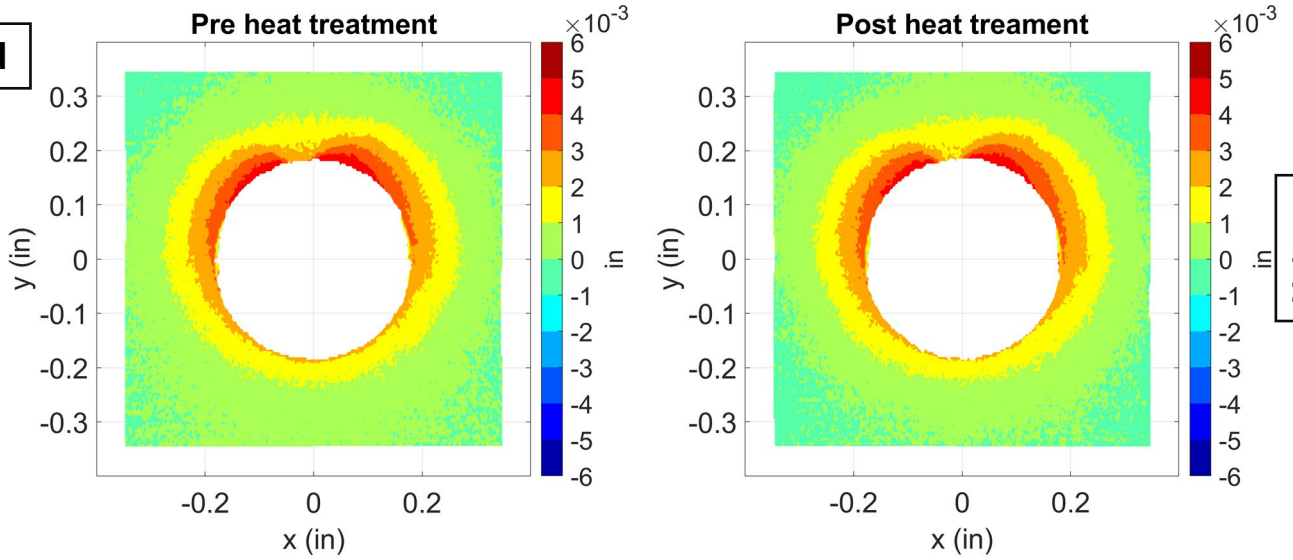
Response is due to geometry, not residual stress

- Heat treat option (volcano + no Cx RS)
- Low stress grinding (no volcano + Cx RS)
- Laser Shock Peened coupon (no volcano + LSP RS)

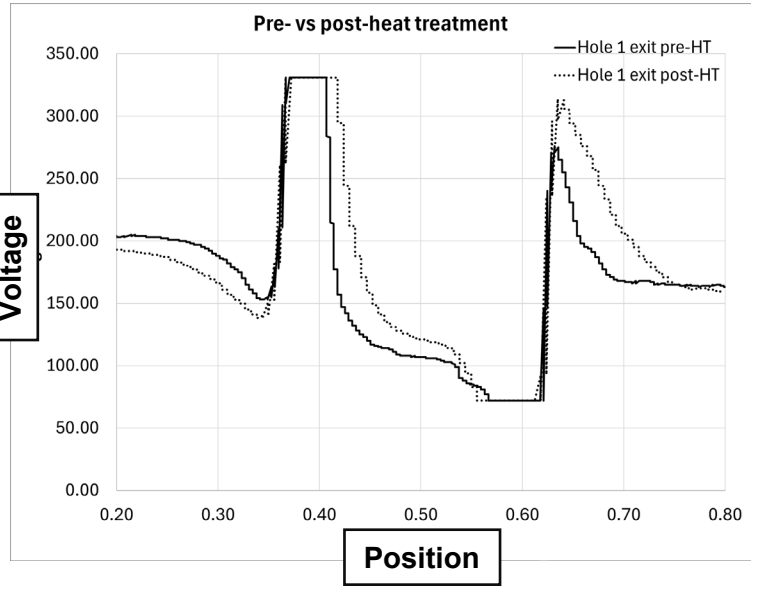
Representative fastener hole



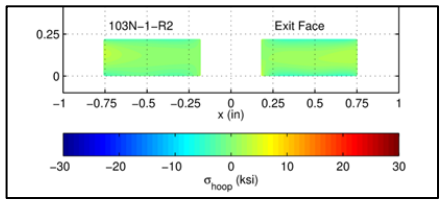
Surface profilometer



ET surface probe



Post heat treat stress field



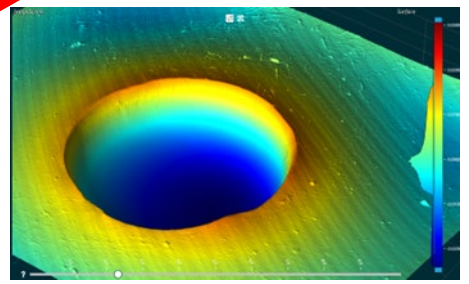
Eddy Current Surface Scan Diagnostic Study

Response is due to geometry, not residual stress

- Heat treat option (volcano + no Cx RS)
- Low stress grinding (no volcano + Cx RS)
- Laser Shock Peened coupon (no volcano + '

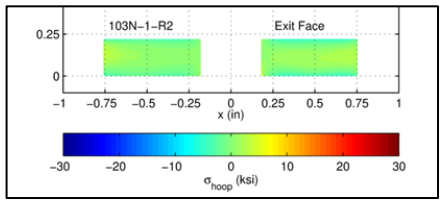
Not pursued further

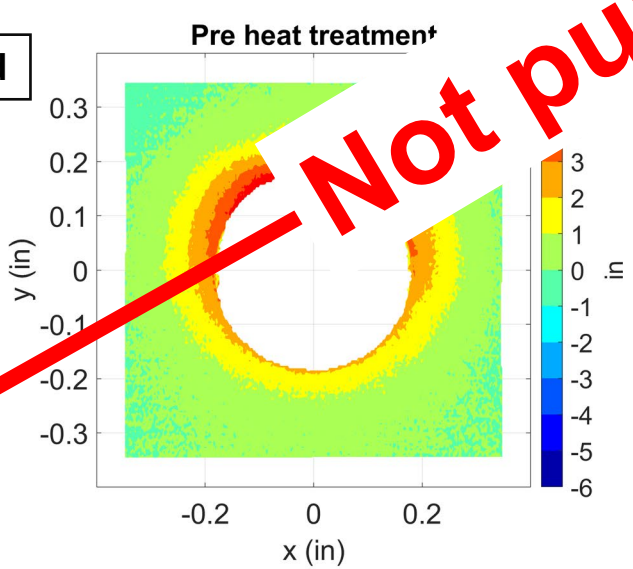
Representative fastener hole



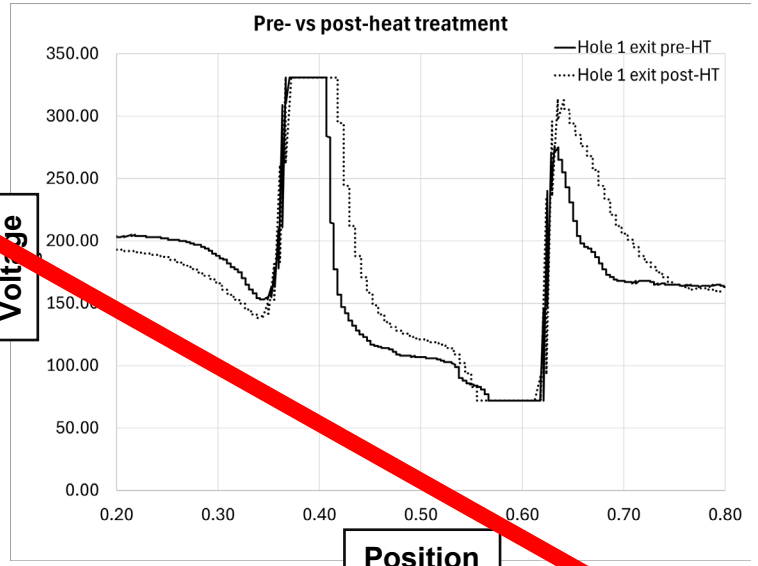
Surfa

Post heat treat stress field





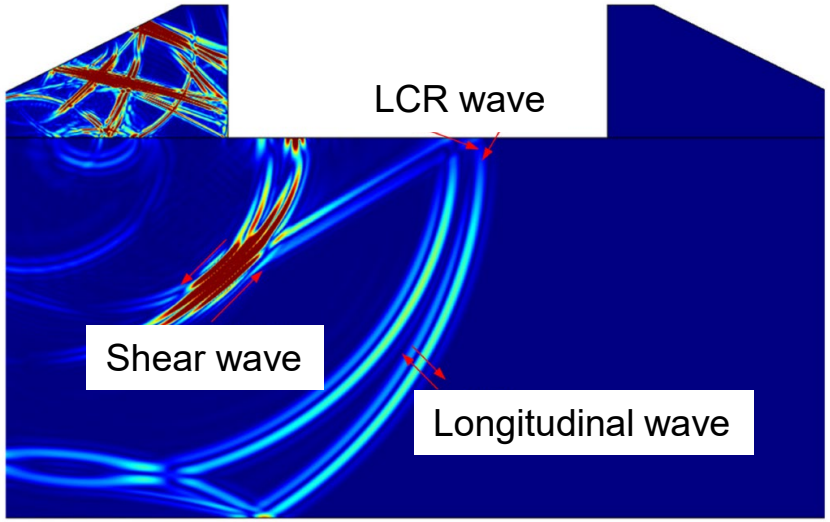
ET surface probe

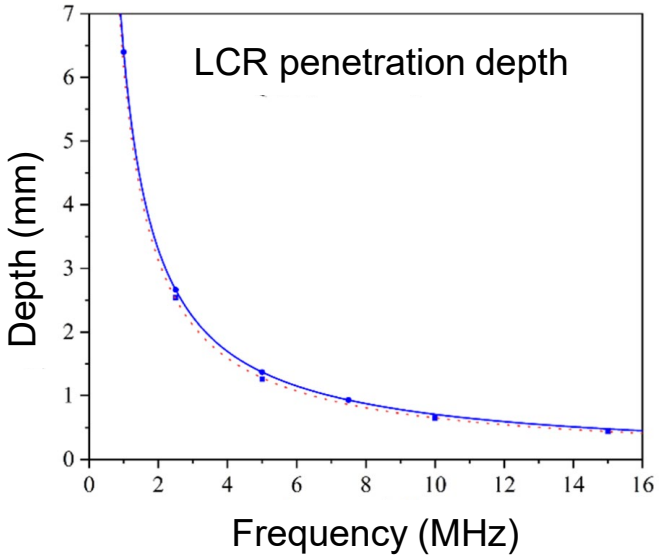


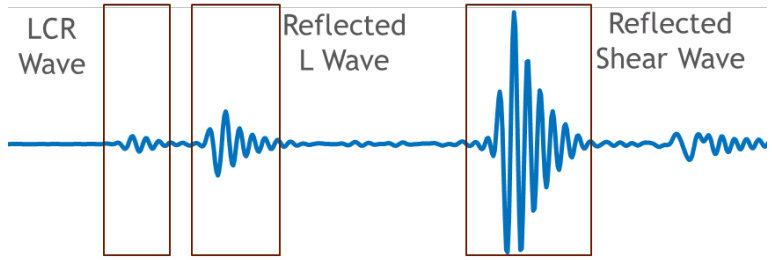
Residual Stress Measurement with Ultrasound

Critical attributes:

- **Requires specialized propagation mode: longitudinal critically refracted (LCR) waves**
- **Differential time-of-flight measurement eliminates multiple confounding factors**
  - **But requires high-precision time-of-flight measurement**
- **Special mode conversion wedge angle function of material properties (Snell's Law)**
- **Relatively insensitive to surface roughness**



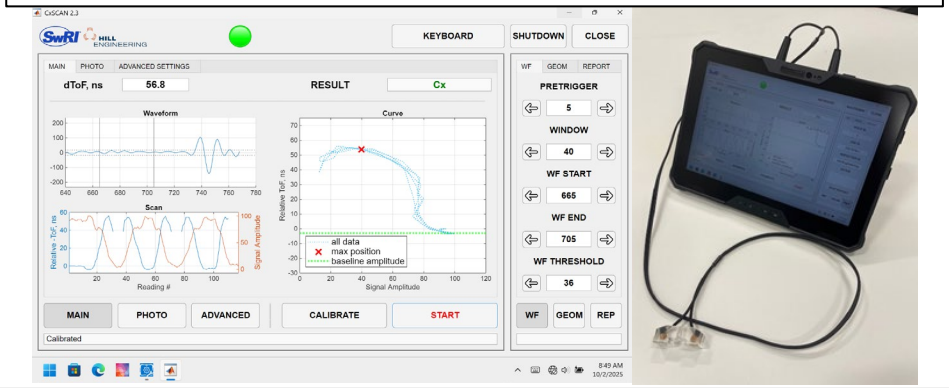




LCR Measurement Options

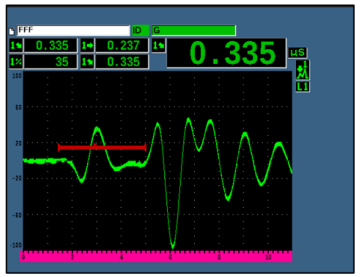
- **High fidelity measurements requires specialized equipment**
  - **Lower precision with current USAF portable ultrasonic systems**

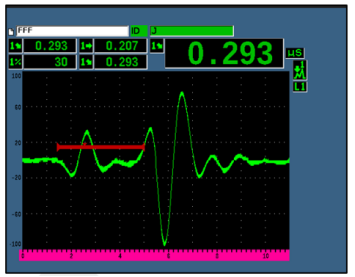
SwRI Custom System Evaluation Mode

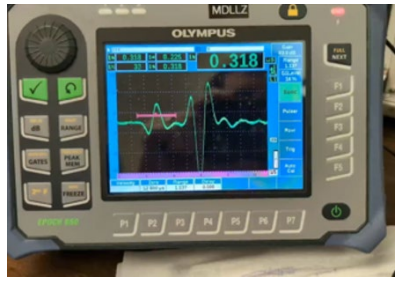


Cross-correlation for high precision T-o-F measurement

EPOCH 650 Screening Mode







Manual T-o-F measurement

UT Wedge Optimization

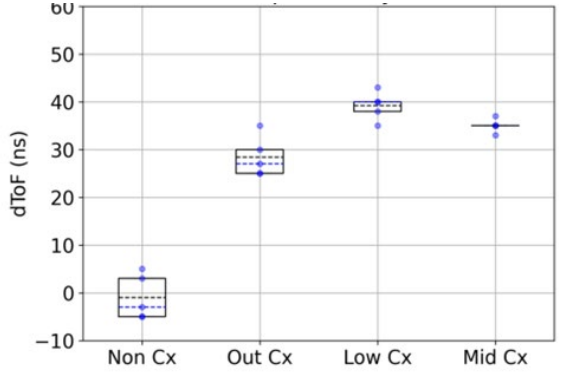
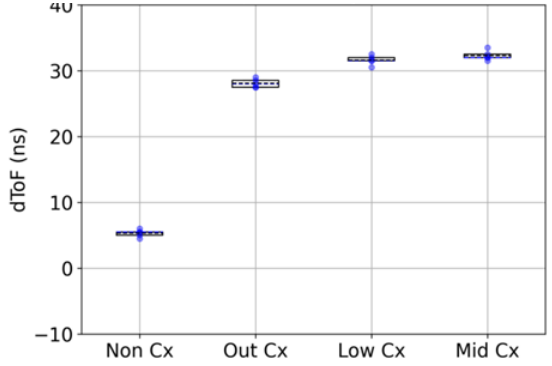
Separate Transducers
Fixed Wedge

Separate Transducers with
Holder, Scanning Wedge

Integrated Crystal
Scanning Wedge

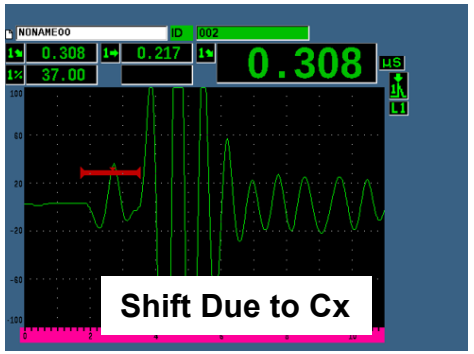
LCR Testing Results – Key Takeaways

- **Both approaches work – linear change in T-o-F as function of percent expansion**
- **Custom approach: high accuracy and repeatability, plus digital data (e.g. for thread)**
- **COTS portable system: lower accuracy and repeatability (hardware limitation)**

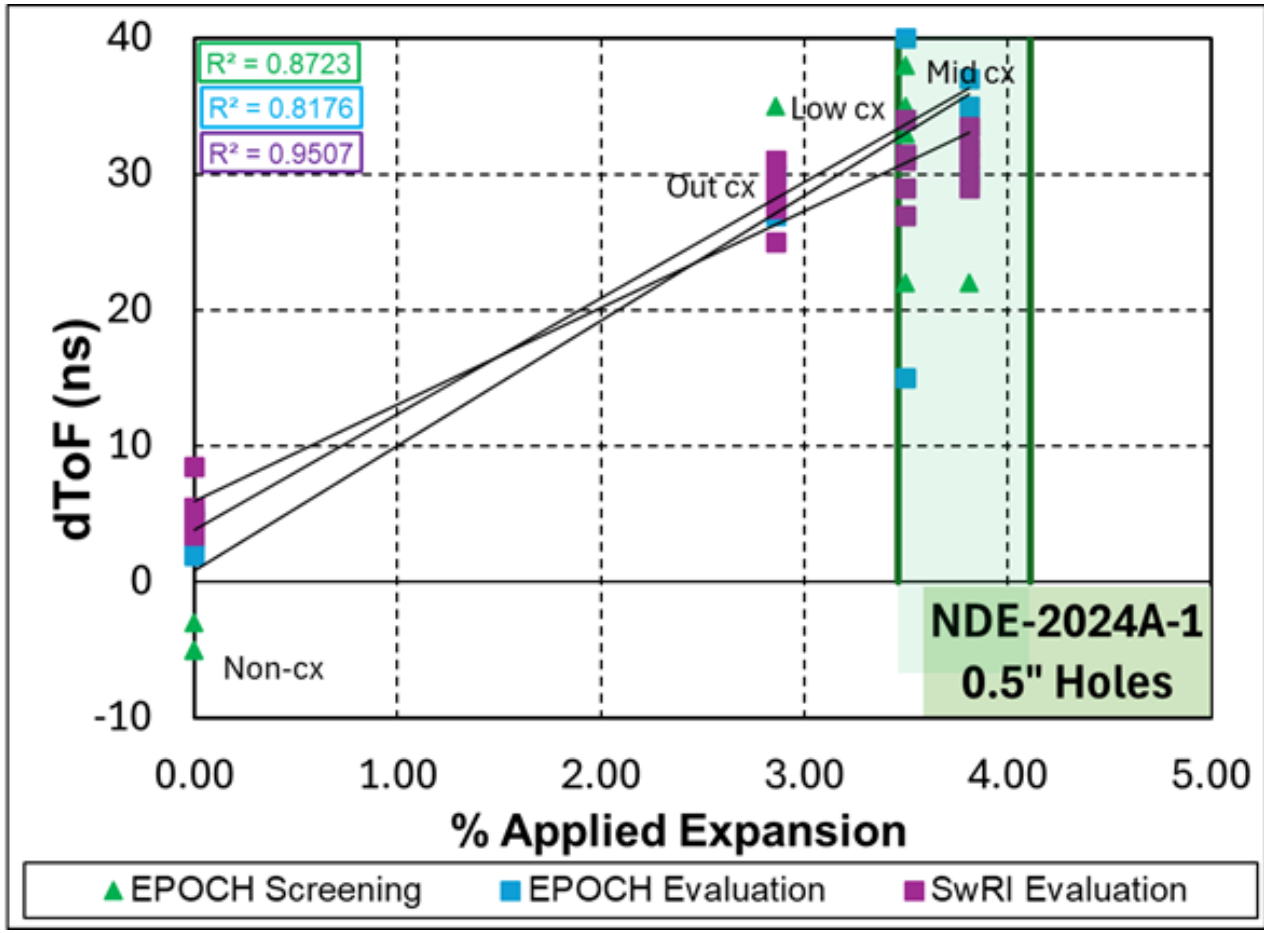
Parameter	System	
	COTS Flaw Detector	SwRI Custom System
Average Inspection Time (Seconds)	16	64
Linear Goodness of Fit Mean and (Standard Deviation)	0.899 (0.105)	0.966 (0.045)
Coefficient of Variation Repeatability Scans	21.40%	2.45%
Example Repeatability Data		

LCR Representative Data

EPOCH Screening



SwRI Evaluation

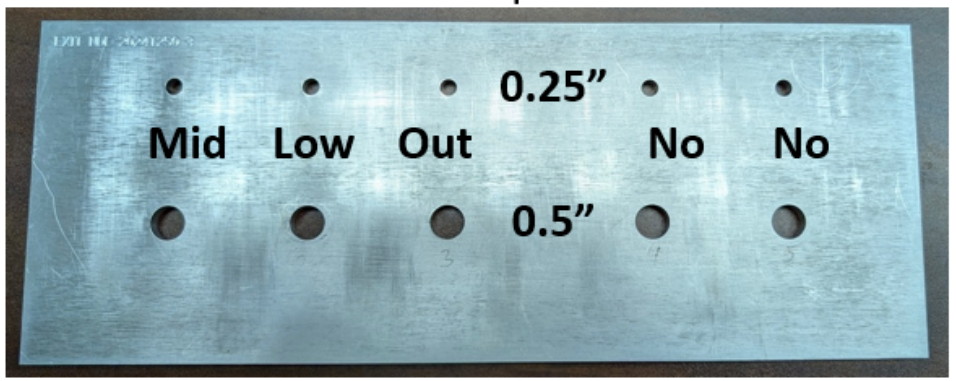


High Fidelity LCR Representative Data

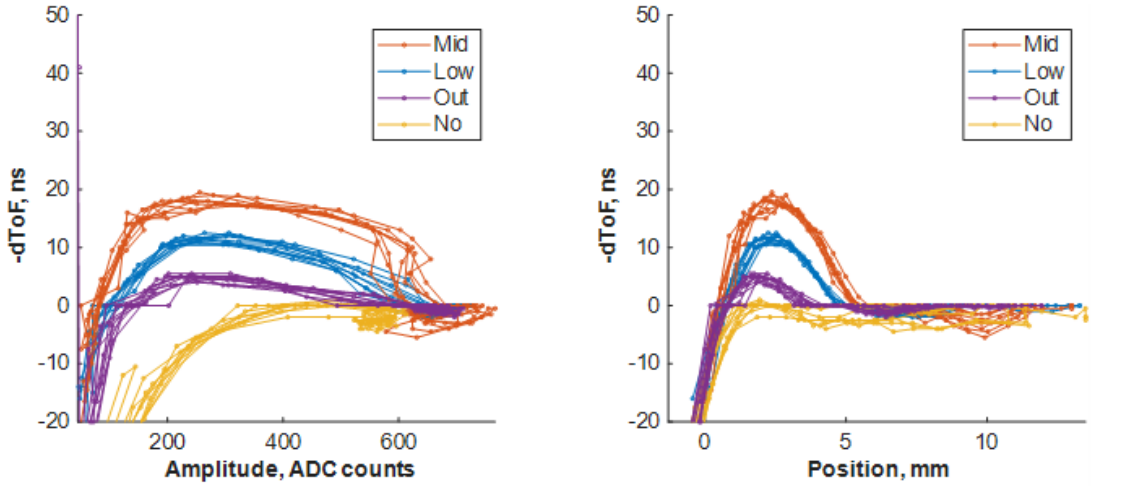
Diameter	Mid Cx	Low Cx	Out Cx	No Cx
0.25”	4.02%	3.36%	2.07%	0%
0.5”	3.79%	3.46%	2.81%	0%

Expansion values are according to
FTI Specification 8101
Mid – mid spec range
Low – low spec range
Out – out of spec range
No – no cold expansion

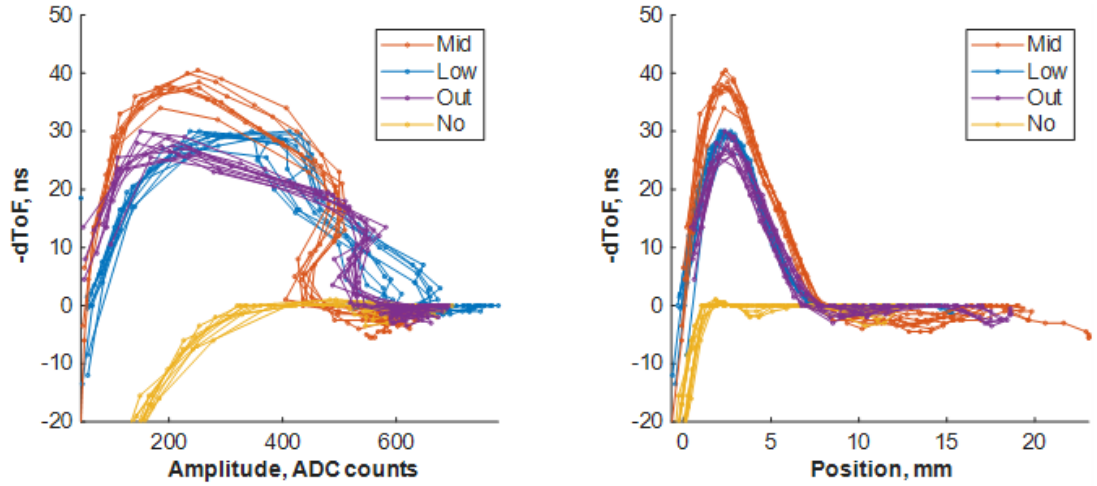
2024-T351 aluminum coupon 0.25 in thickness



0.25” holes



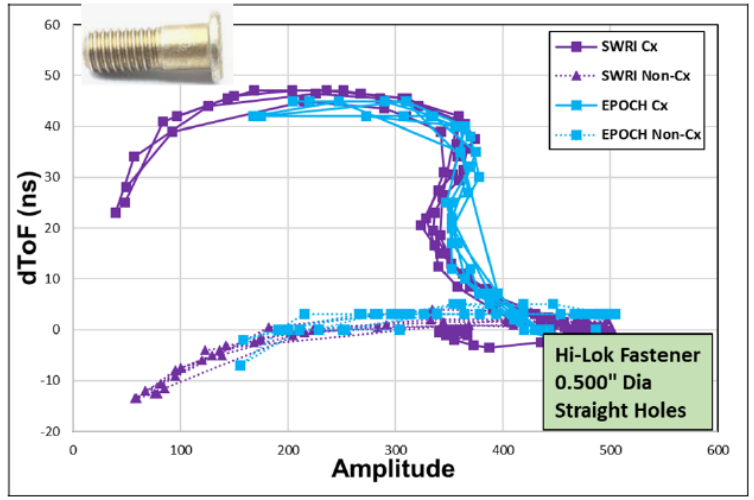
0.5” holes

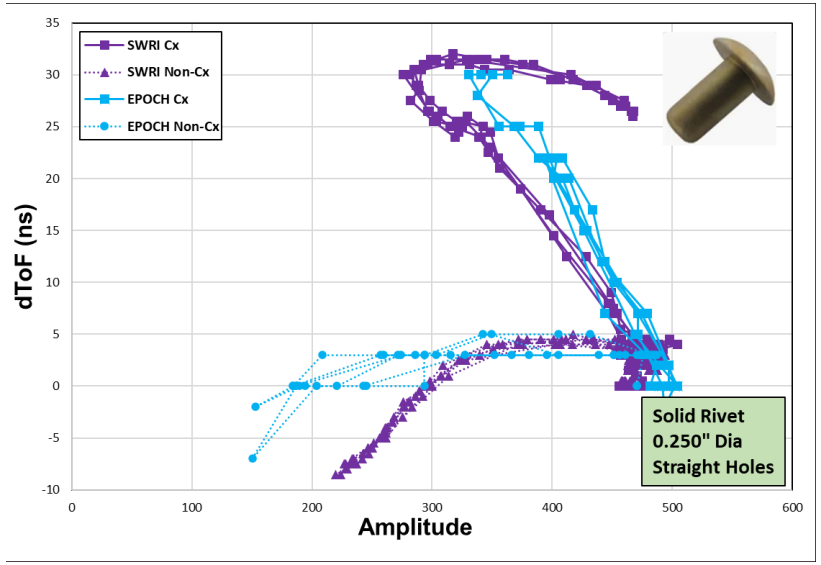


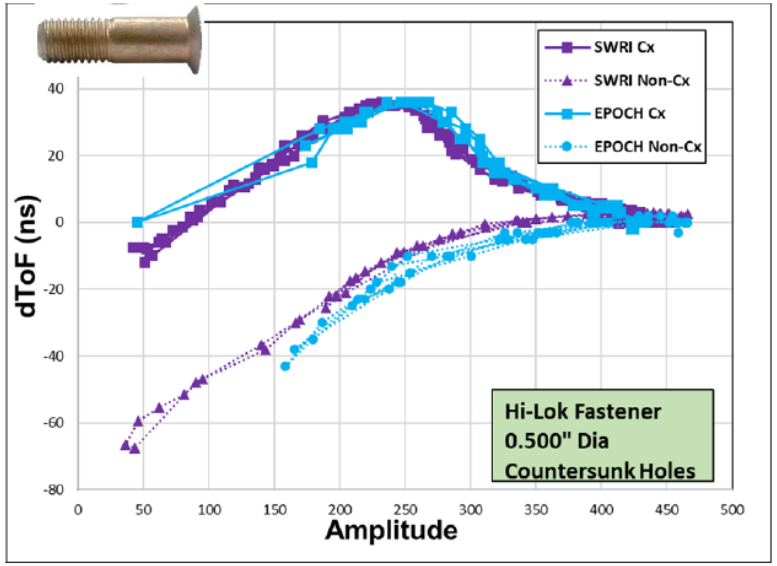
LCR Applied to Installed Fasteners and Countersunk Holes

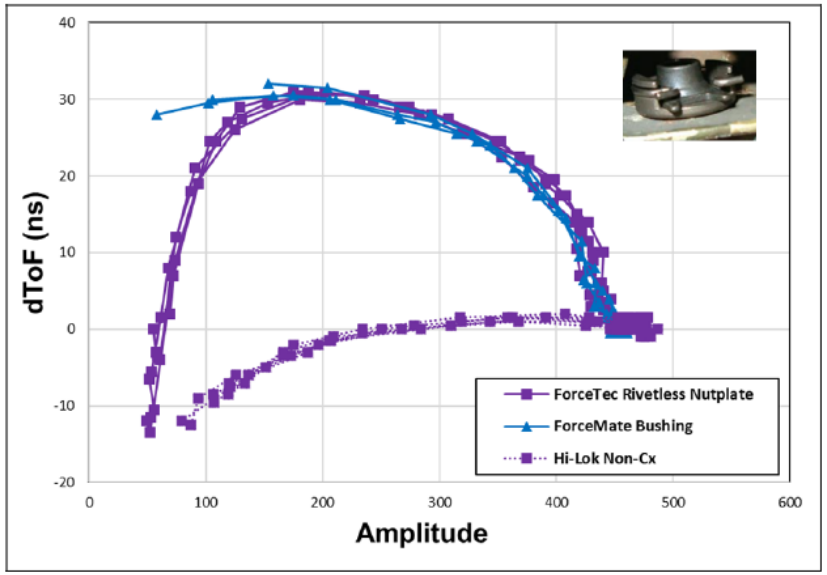
Analysis of T-o-F must account for:

- **Interference fit fasteners can allow sound to propagate through fastener**
- **Countersunk geometry causes T-o-F shift**
- **Capability applies to ForceMate and ForceTec conditions**







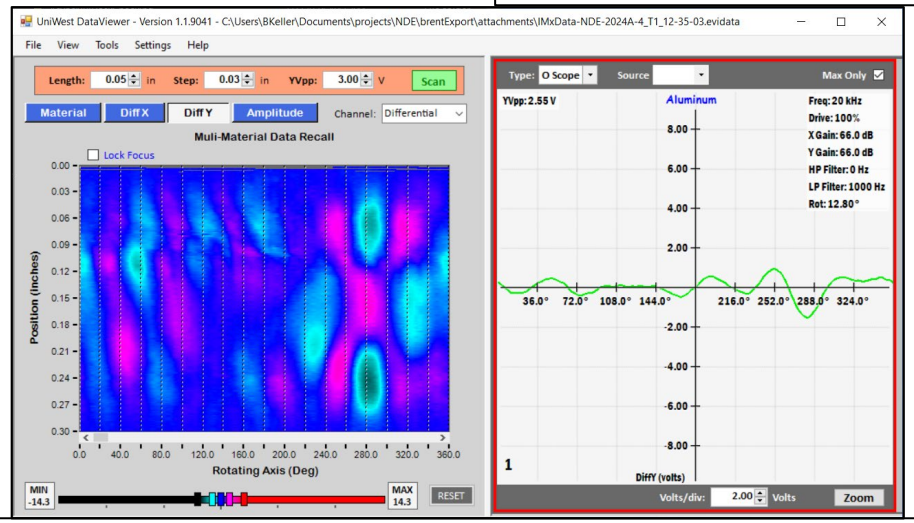


Low Frequency In-Hole Eddy Current (LFIHEC)

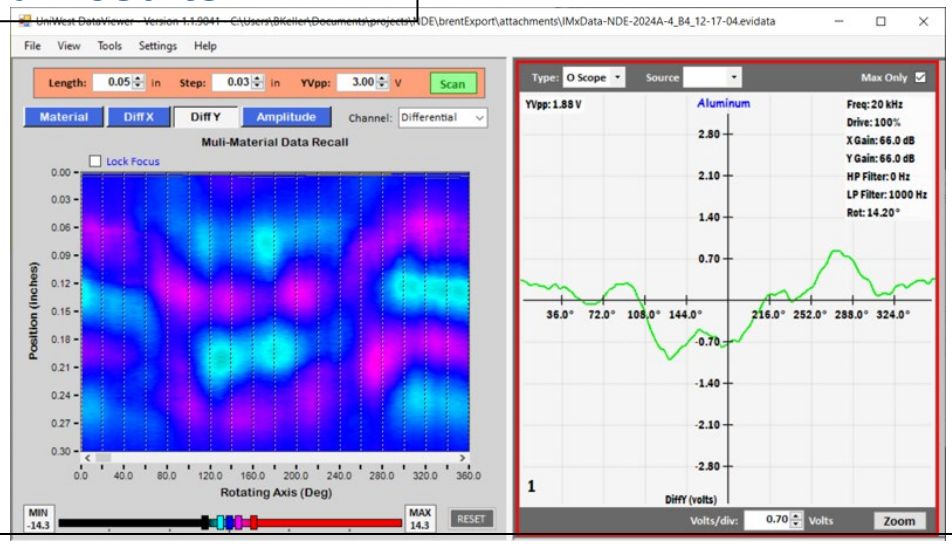
Explored as risk mitigation and possible enhanced capability

- **360° conductive response, requires post data acquisition processing**
- **Uses COTS equipment (Evi, ECS-5s, and LFEC probes)**
- **Issues include: limited differentiation between Cx and non-Cx, higher variability than LCR, greater uncertainty for thicker test samples**

Illustrative Good Results



Fully cold worked

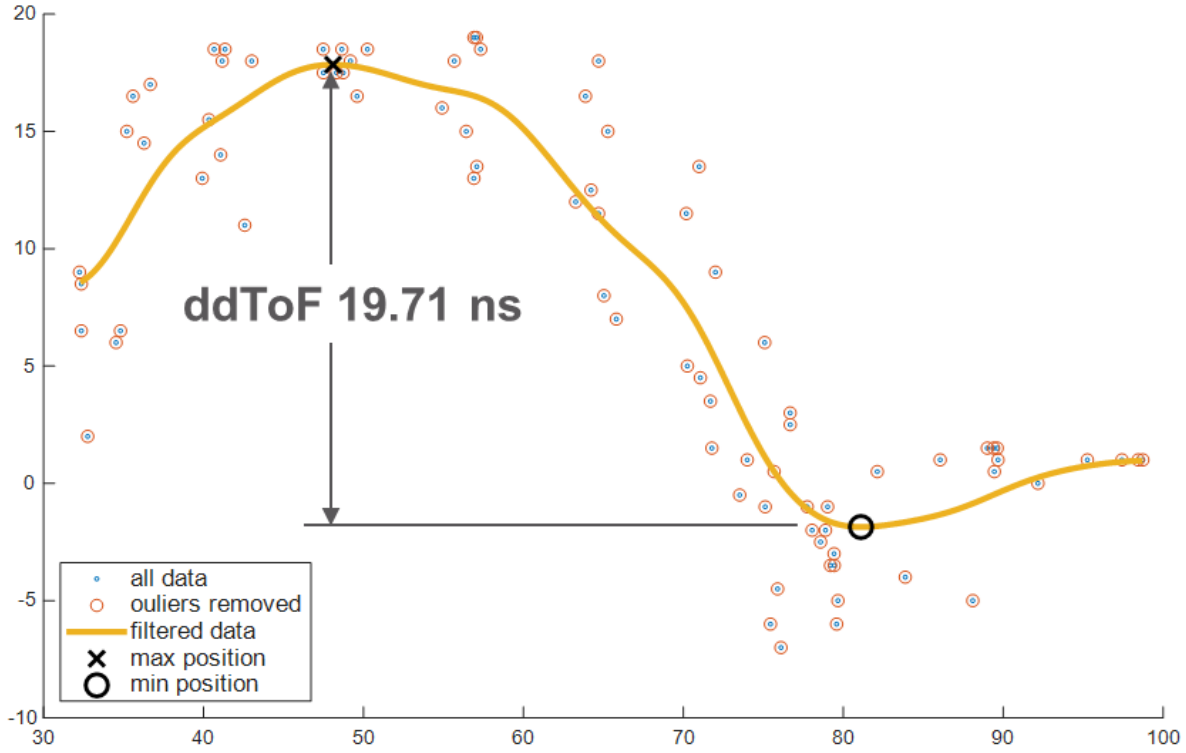


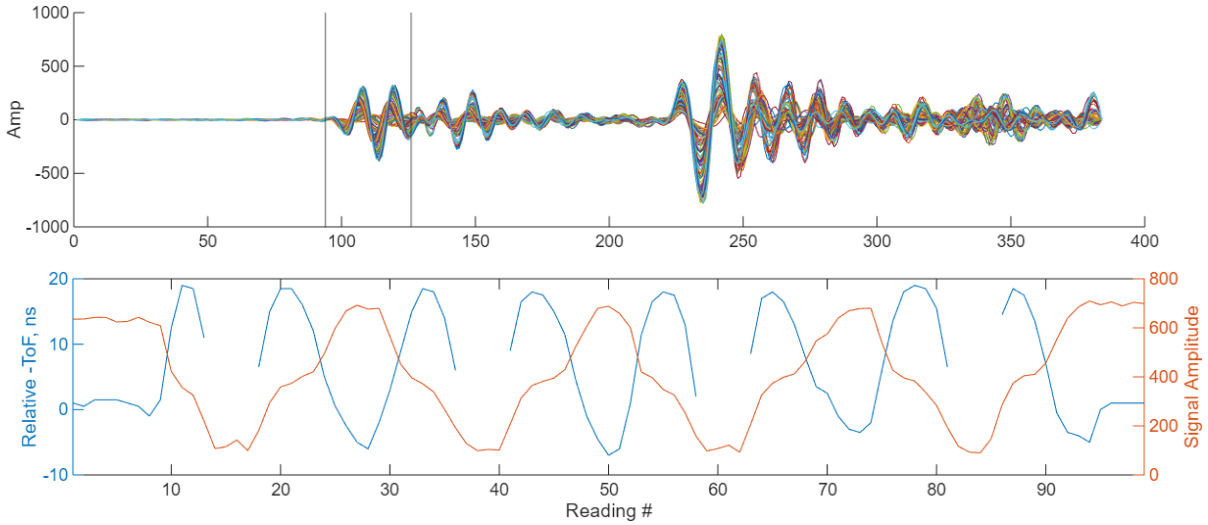
No cold work

On-Aircraft Demonstrations

Successful Demonstrations Completed on A-10 and T-38 Wings

- **A-10 locations – straight and filled straight shank fastener holes**
- **T-38 locations- countersunk and filled fastener holes**





Production Demonstrations

Demonstrations at Hill AFB: F-16 Wing Shop and A-10 Aircraft Maintenance Hanger

Way Forward

New contract to do the following:

- **Full Capabilities Assessment**
  - Capabilities assessment (similar to NDI PoD study) to characterize capability of each approach
- **Additional Materials**
  - Investigate applicability and approaches for titanium and steel applications
- **Expanded Geometry**
  - Additional characterization for countersunk and filled hole configurations
  - Expanded hole diameters and material thicknesses
- **Implementation**
  - System updates to ensure production ready
  - Development of procedures for seamless integration into current NDE practices

Summary

Programs realizing objectives

- Leveraged NDE experience to assess residual stress of Cx holes

Multiple NDE Approaches Evaluated

- LCR shows greatest potential:
  - Differentiates various levels of Cx
  - Achieves required levels of repeatability
- LFIHEC appears to have limitations
- Extensive testing completed
  - Confounding factors, e.g. surface and sub-surface
  - Reproducibility: repeat measurements on similar conditions
  - Variability: hole diameter, magnitude of Cx, and material
  - Demonstrated feasibility of LCR for filled and countersunk holes

POD-based statistical assessments will quantify capability

Heading in the right direction!

Discussion

Caelum Domenari

Photograph by Author