Detection of Cracks in Aluminum Structure beneath Inconel Repair Bushings

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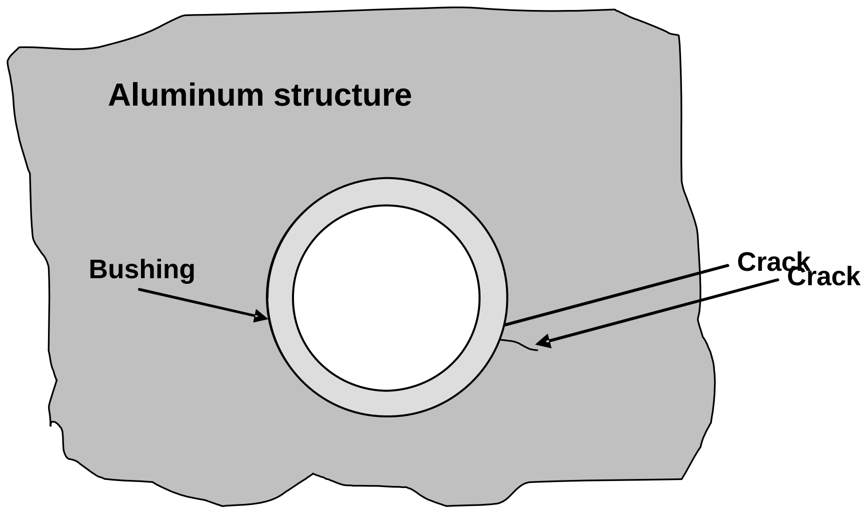
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Introduction

- Fatigue cracking at fastener holes is a common problem in military and commercial aircraft
- Some repair methodologies resort to oversizing the hole to remove the crack
  - Reaming
  - Installing a repair bushing to return the hole to its nominal size



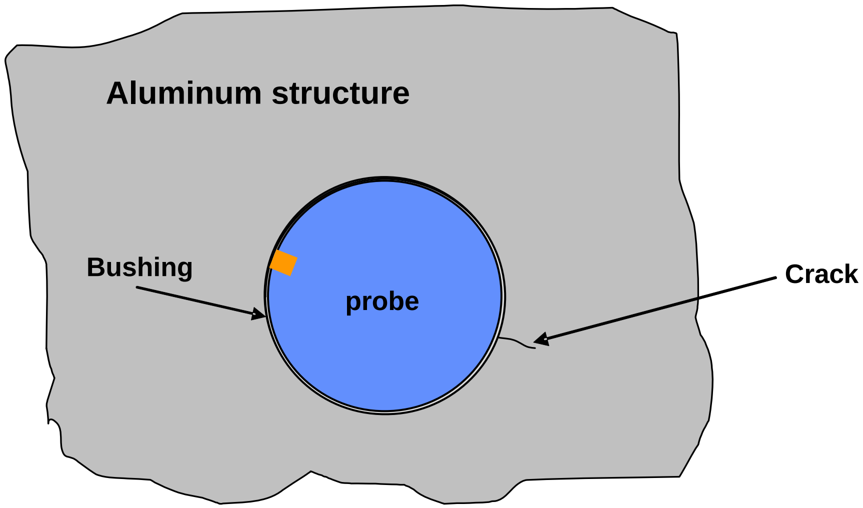
  - New cracking is now obscured by bushing

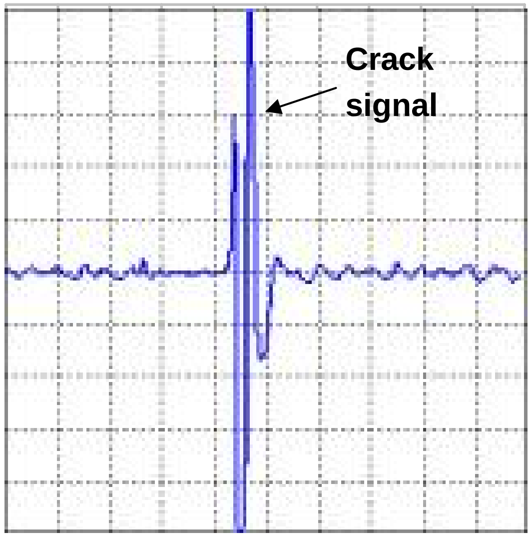
Introduction

- For <u>thick multi-layer structures</u>, inspection options are often limited:
  - Ultrasound
    - Cannot penetrate unbonded/unsealed layers
  - Radiography
    - Contrast sensitivity may be inadequate
    - Two sided access may not be possible

Introduction

- Subsequent reinspection often requires
  - Conventional high-frequency (200-500kHz) bolt hole eddy current
    - Requires removal of the repair bushing for probe access
    - Inspection coil is placed against the inside diameter of the bolthole where the cracking initiates and rotated to produce inspection data

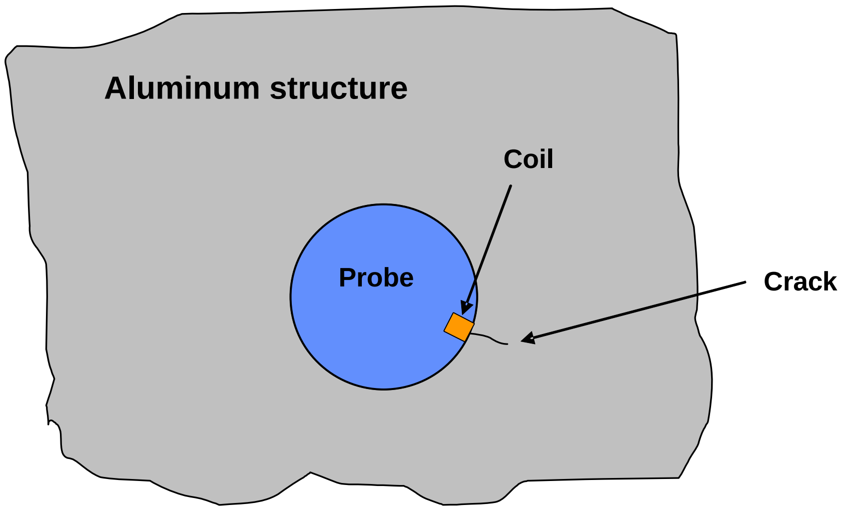




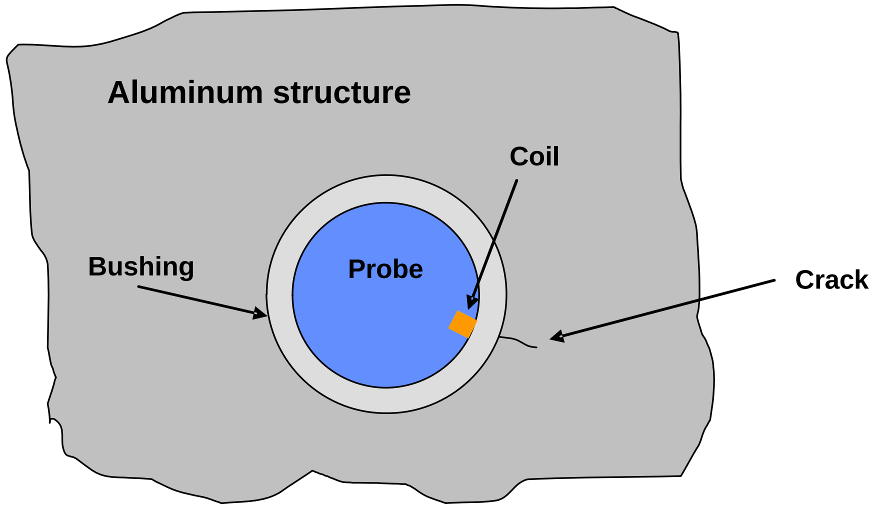
- Significant downtime and manhours impact.

Introduction

- Bushing repairs
  - Bushing becomes a physical barrier between the eddy current coil and the crack,
  - Significantly affects sensitivity



coil near crack in unbushed hole



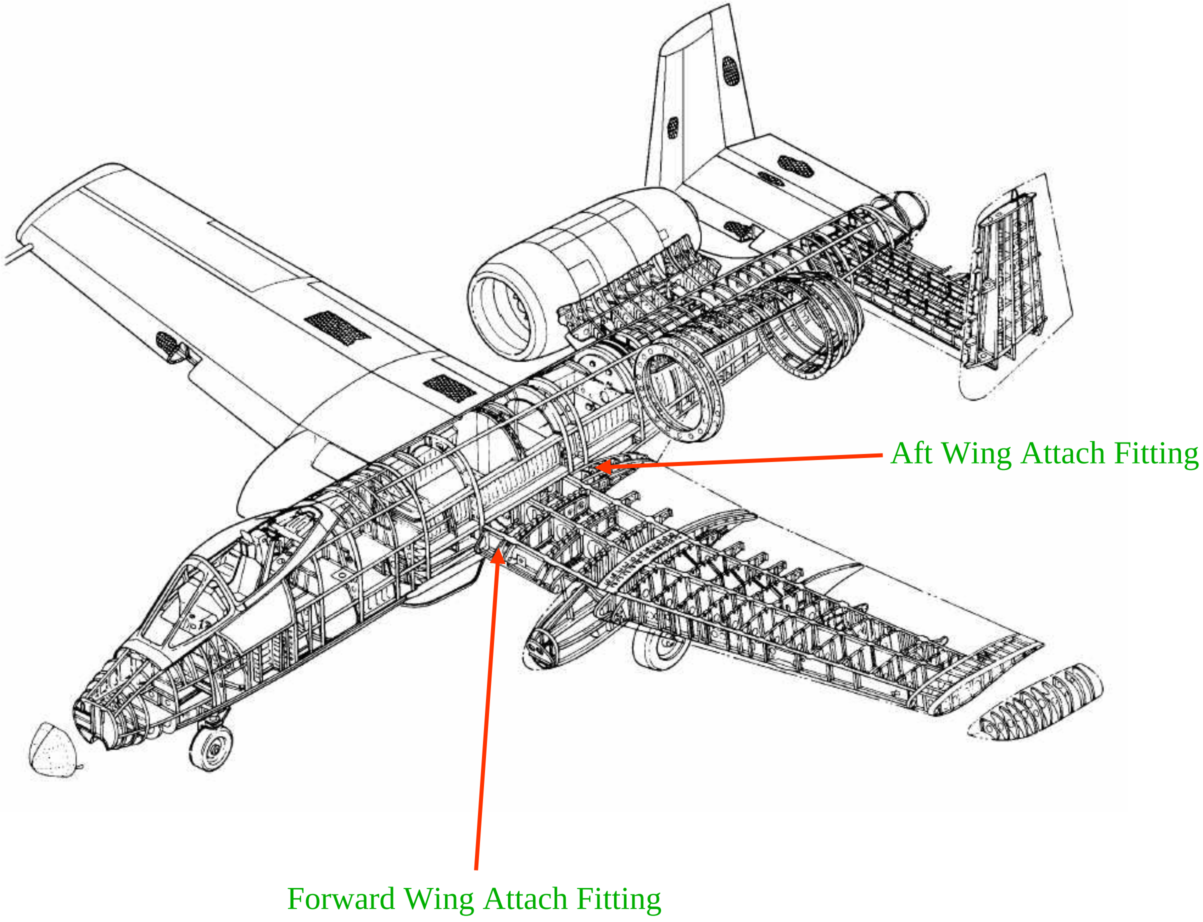
coil and crack separated physically by bushing

Introduction

- The United States Air Force has been working with Innovative Materials Testing Technologies (IMTT) Inc.
  - Small Business Innovative Research (SBIR) Program
    - Remote Field Eddy Current (RFEC)
    - Inspection <u>without</u> removal of repair bushings
      - If the bushing material can be “selected for NDI”
        - Low permeability and conductivity (i.e. Inconel 718)
      - Primary challenge then becomes detecting the weak eddy current field in the structure beyond the <u>bushing wall</u>

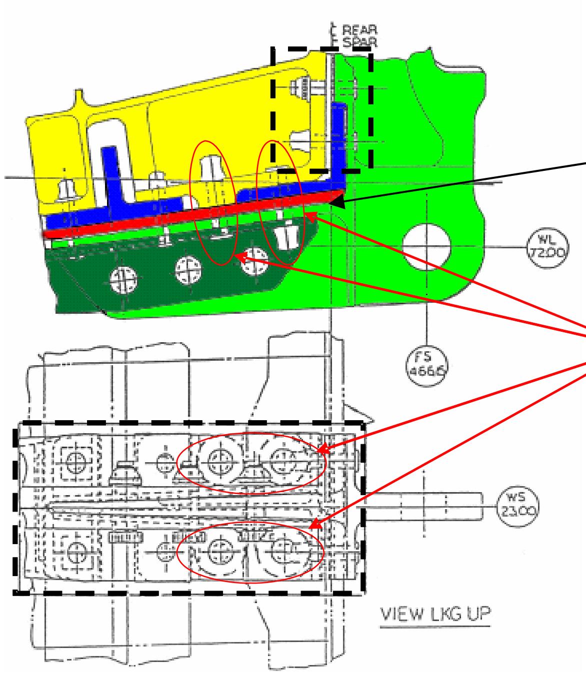
Inspection Challenge

- A-10 Wing Station 23 Aft Wing Attachment Fitting



Inspection Challenge

- Multi-layer stackup
- Corner cracks in ½ inch diameter <u>aluminum</u> fastener hole
  - Wing skin, spar cap, or rib layers



<u>Steel</u> layer adjacent to crack in some instances!

Inspection areas of interest

Rib (Y) – 0.310” 7075-T73 Al
Shim – ≤0.094” Al Laminate
Spar Cap (Bl) – 0.344” 2024-T3511 Al
Skin (Red) – 0.300” 2024-T3511 Al
Shim – ≤0.125” Al Laminate
Attach Fitting (Lt Gr) – 0.320” 4340 Steel
Shim – ≤0.094” Al Laminate
Longeron (Dk Gr) – 0.200” 9Ni-4Co-.03C Steel

Aft Fitting

Approach

- **RFEC is commonly used in inspection of ferromagnetic pipe or tubing, because…**
  - **Conventional eddy current has strong "skin effect" in ferromagnetic materials**
    - **Eddy current depth of penetration equation:**

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$

where

δ = standard depth of penetration in meters

f = test frequency in hertz

μ = permeability in (H/m), μ = μ0 = 4$\pi\times$10-7 for non-ferrous materials

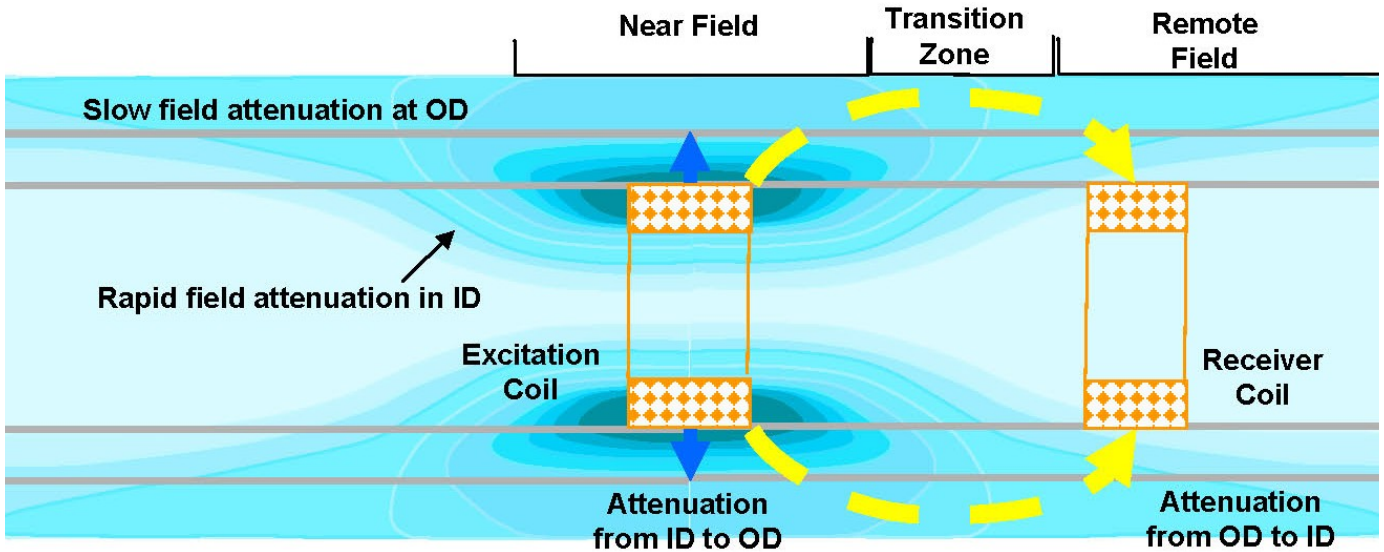
σ = conductivity in (Ωm)-1

Approach

- RFEC senses the “remotely” coupled rather than “directly” coupled eddy current field
  - Directly coupled eddy current field is generated by the exciter coil.
  - These eddy currents, in turn produce their own magnetic field, which opposes the magnetic field from the exciter coil.

RFEC

- Three primary zones:
  1) the direct coupling zone (nearest the exciter coil)
  2) the transition zone, and
  3) the remote field zone



– Since the directly coupled field decays at a faster rate, coil placement can be optimized to sense only the remote field

Approach

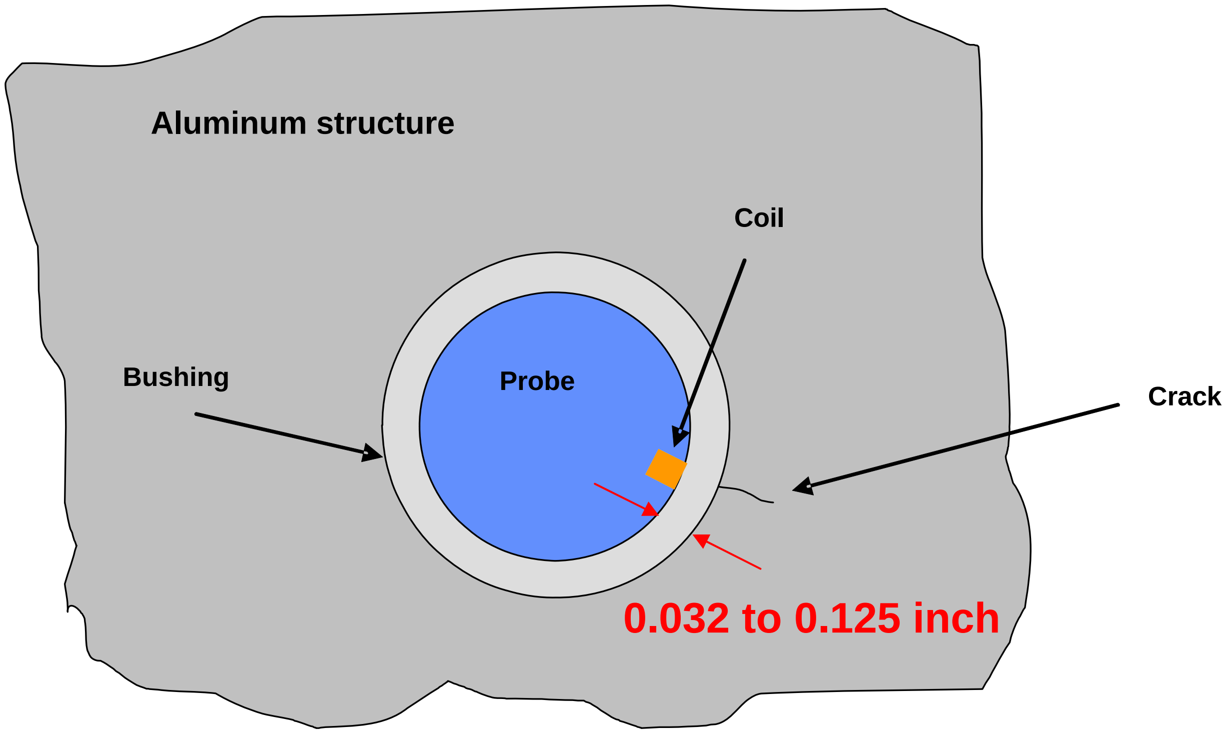
- **For this application, the bushing material was able to be selected with inspectability as a goal.**
  - **Inconel 718**
    - **low permeability (~μ_0)**
    - **low conductivity (< 2% IACS)**

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$

- **Combined with low inspection frequency, depth of penetration is maximized**

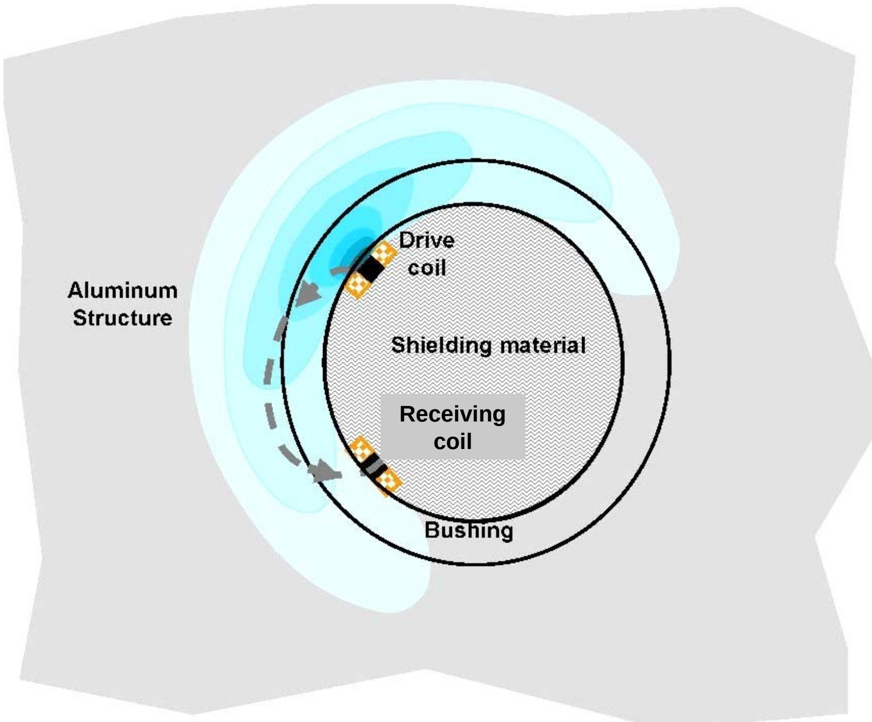
Approach

- **However, for this application, conventional eddy current still struggles to produce a detectable crack response**
  - **Bushing wall thickness is a major factor**



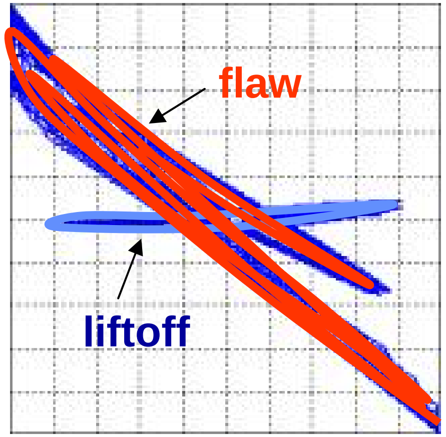
RFEC

- **IMTT RFEC approach:**
  - **Two probe coils in same rotational plane**
  - **Probe coil shielding prevents direct coupling**
  - **Receiving coil detects only the remote field**

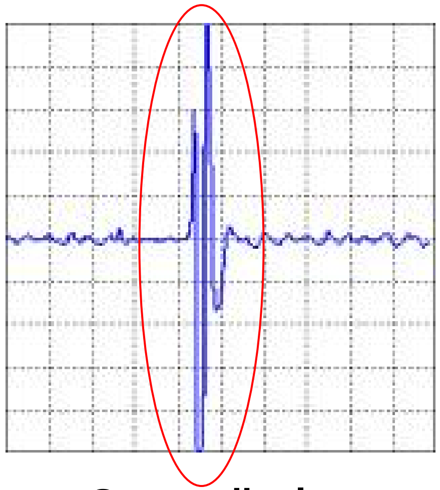


RFEC

- **Signals are similar to conventional bolt hole eddy current**
  - **Impedance plane**
    - **Probe liftoff, “real” component, oriented in X-direction**
    - **Flaw response, “imaginary” component, appears at a rotated phase**
  - **Sweep display**
    - **Indicates clock position of flaw in hole**



Impedance plane



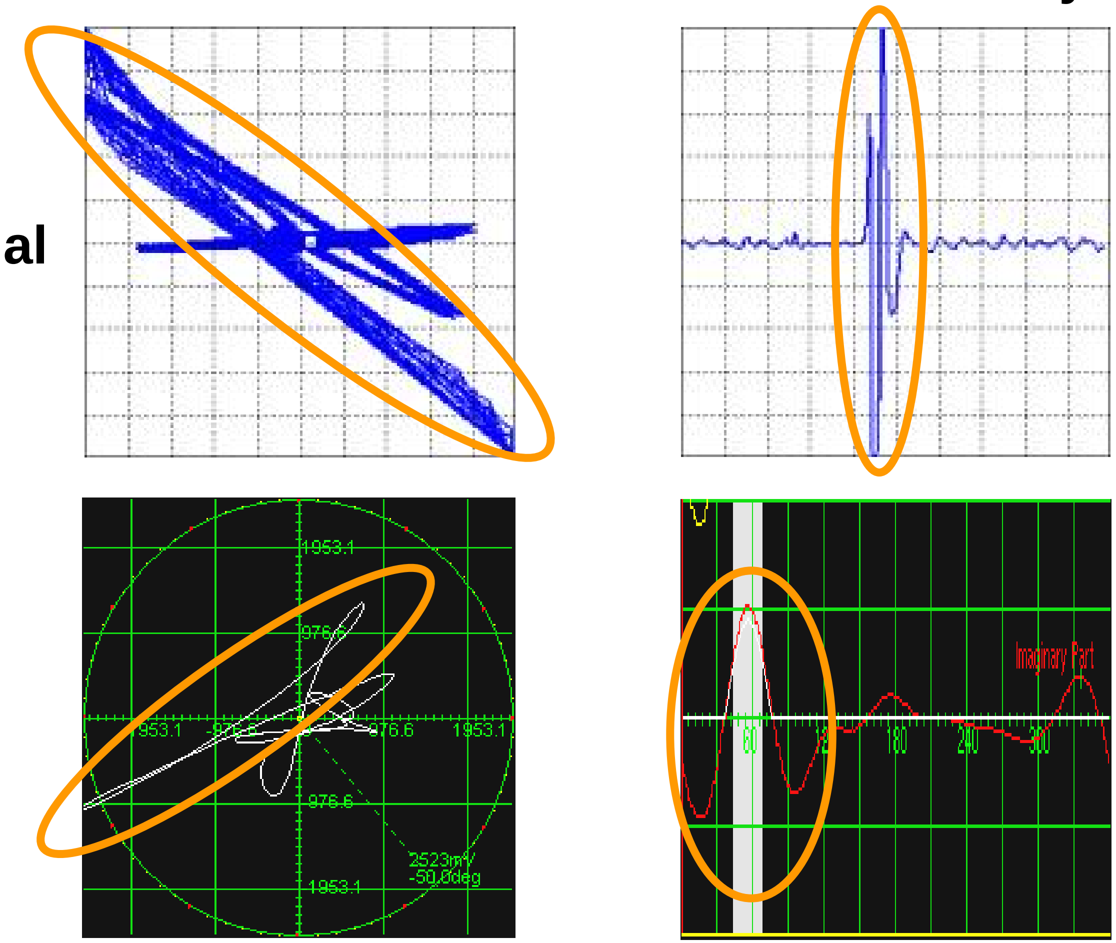
Sweep display

RFEC

- **Signals are similar to conventional bolt hole eddy current**

Conventional

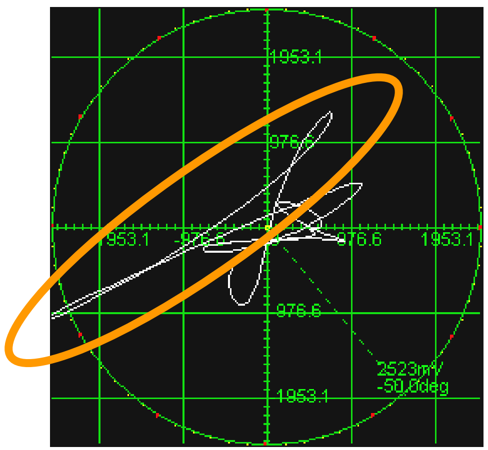
RFEC



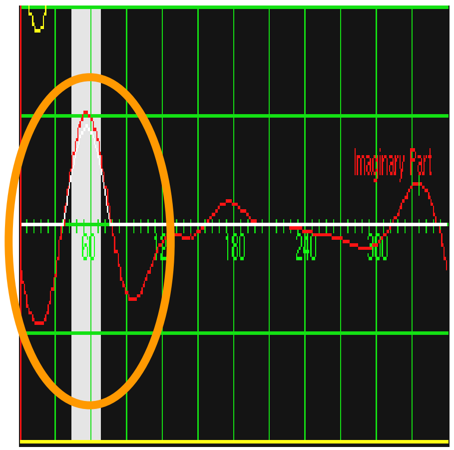
Impedance plane **Sweep display**

RFEC

- **Remote field signal**
  - **Relatively weak, broad, “noisy”**
  - **Influenced by local geometry and materials**
  - **<u>Signal Recognition Algorithm</u> employed**



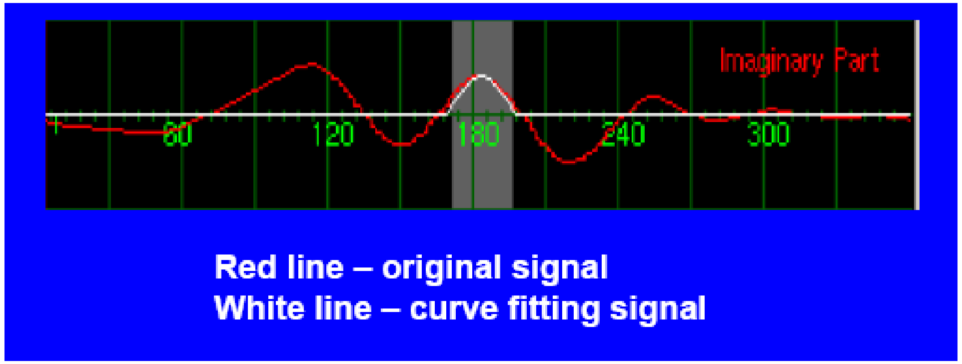
Impedance plane



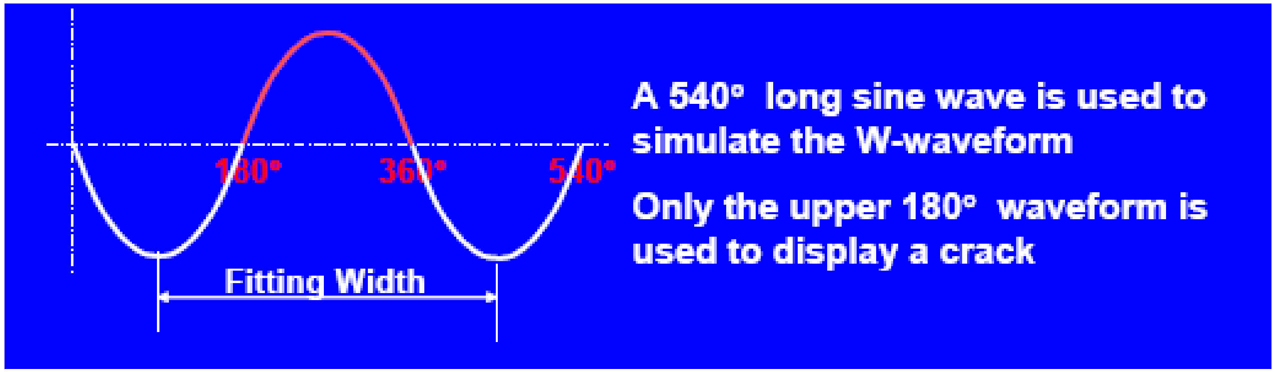
Sweep display

RFEC

- **Signal Recognition Algorithm**
  - **Flaw produces broad “W” shaped response**

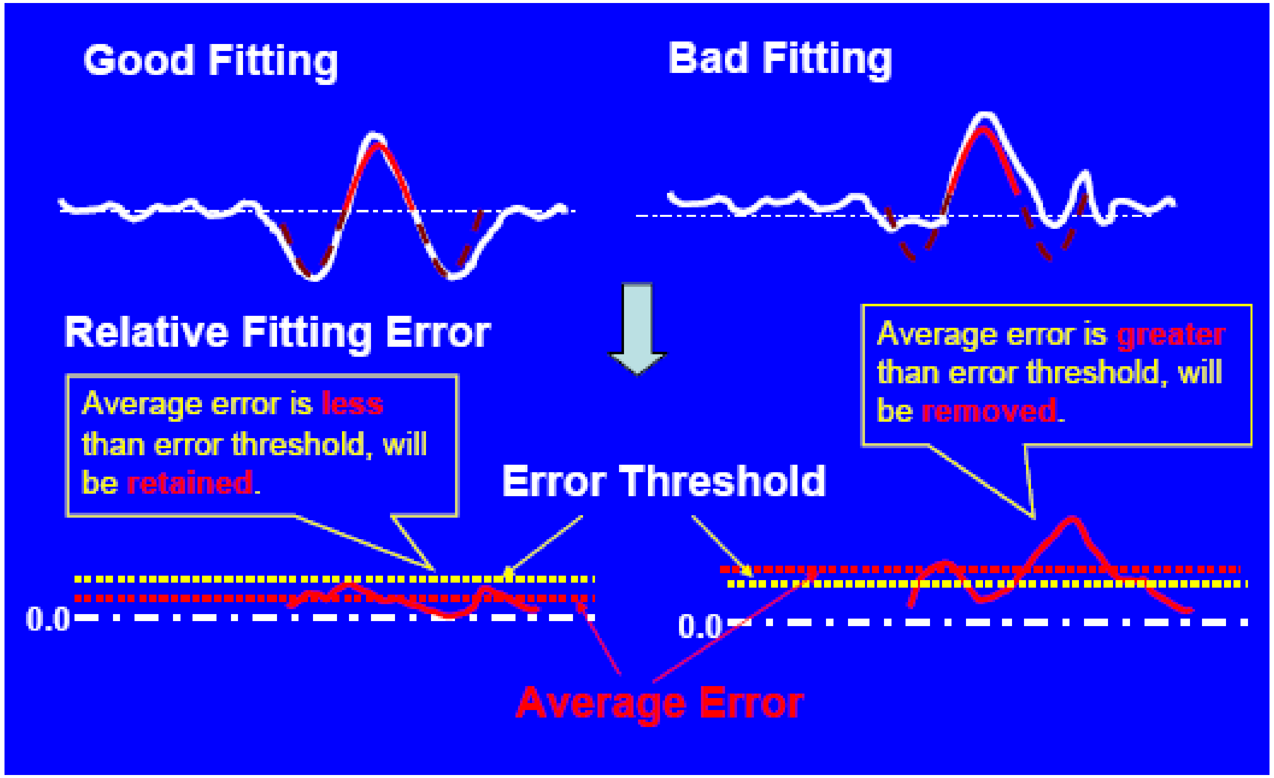


  - **Artificial waveform automatically generated to represent flaw response (RMS)**



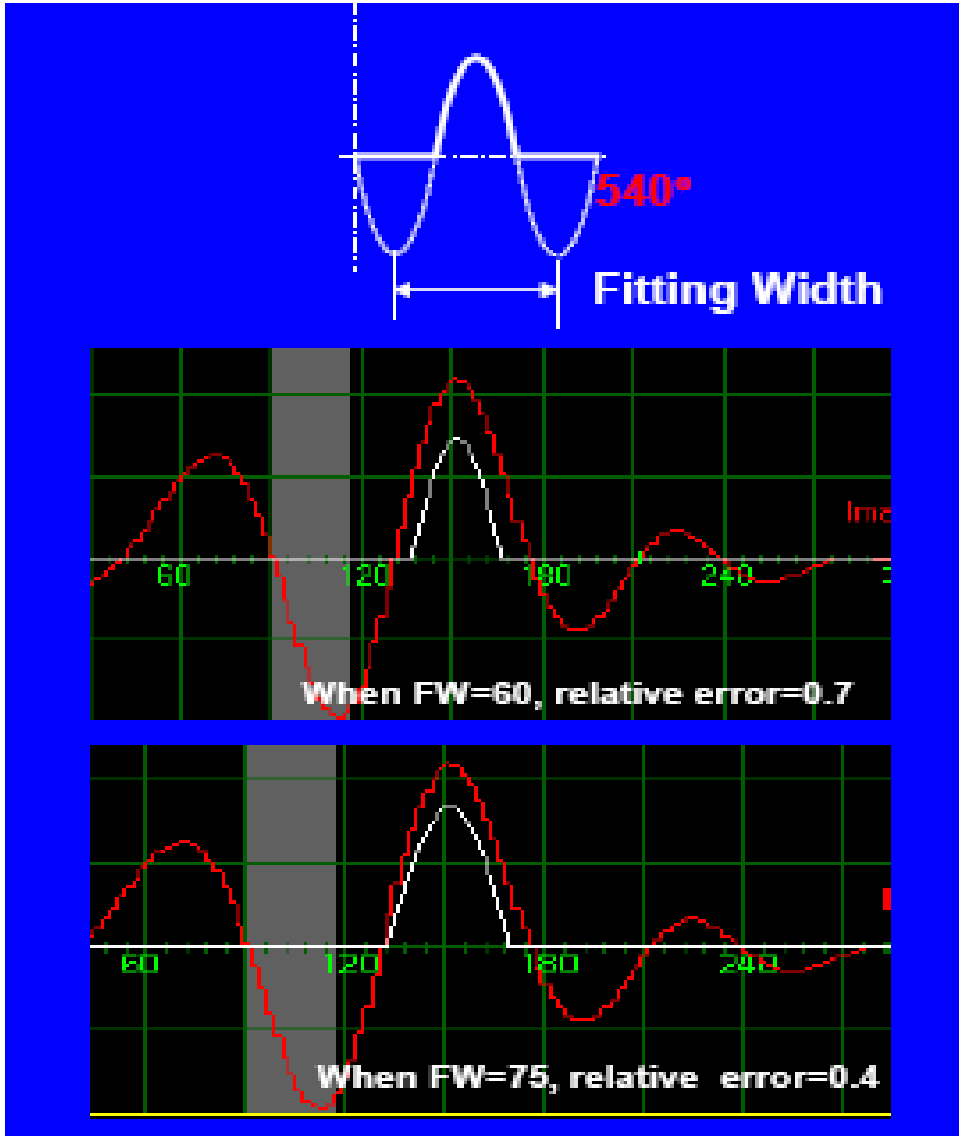
RFEC

- **Error threshold selected by user**
  - **Defines how well artificial waveform must match real signal**



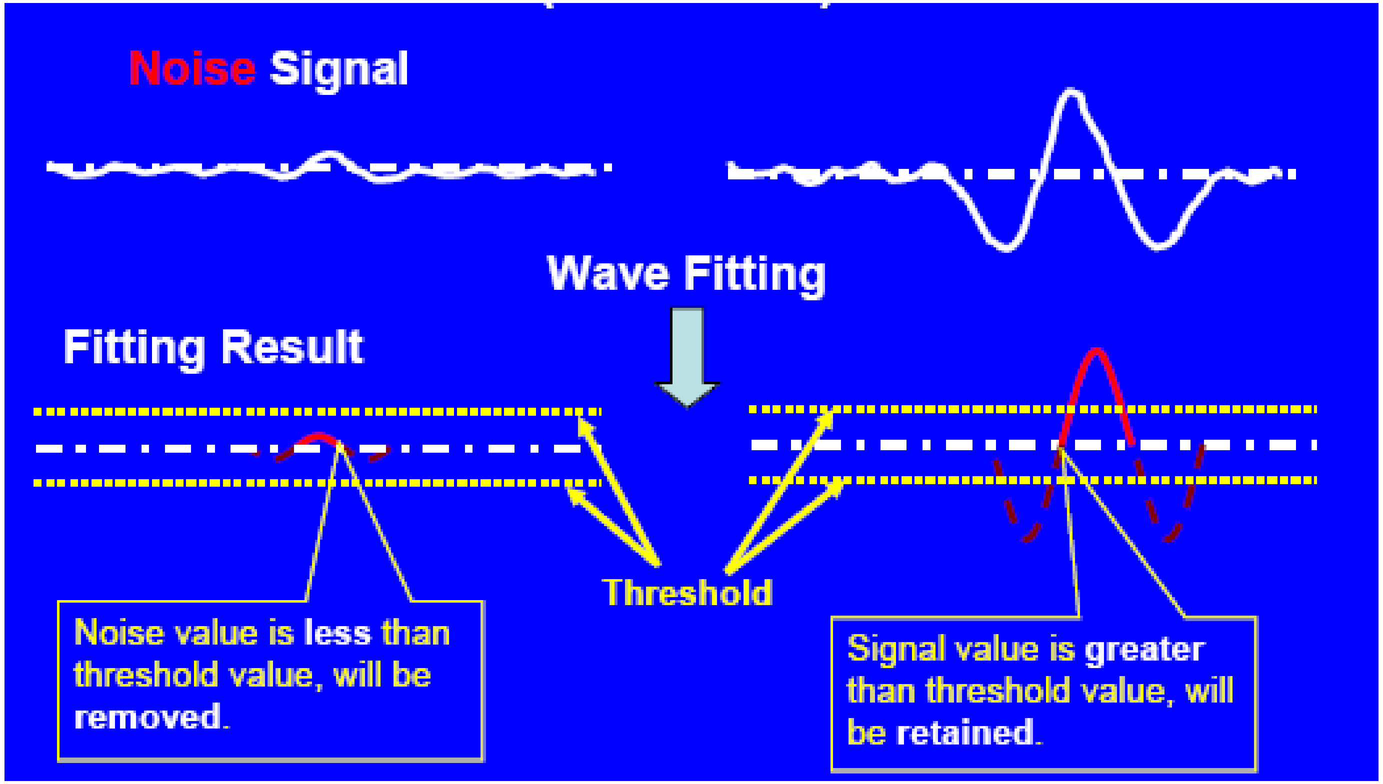
RFEC

- "Fitting width" selected by user
  - Width of a flaw response is fairly repeatable
    - Physical width of a crack does not vary significantly
    - Narrower width response than many non-relevant features such as oblong holes, mechanical contact during scanning, uneven liftoff, etc.



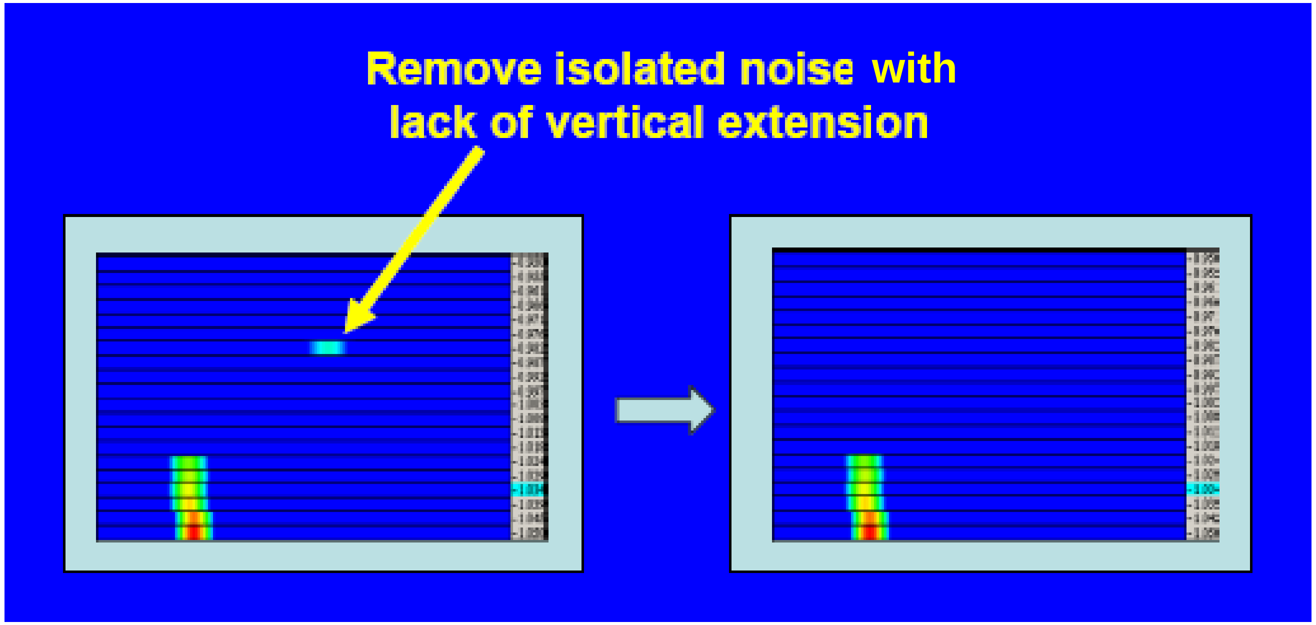
RFEC

- **Magnitude (noise) threshold is selected by user**
  - **Similar to noise threshold selection in conventional eddy current**

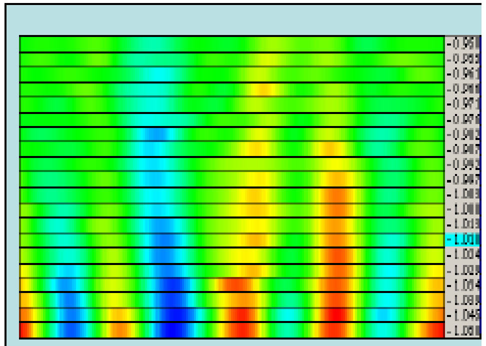


RFEC

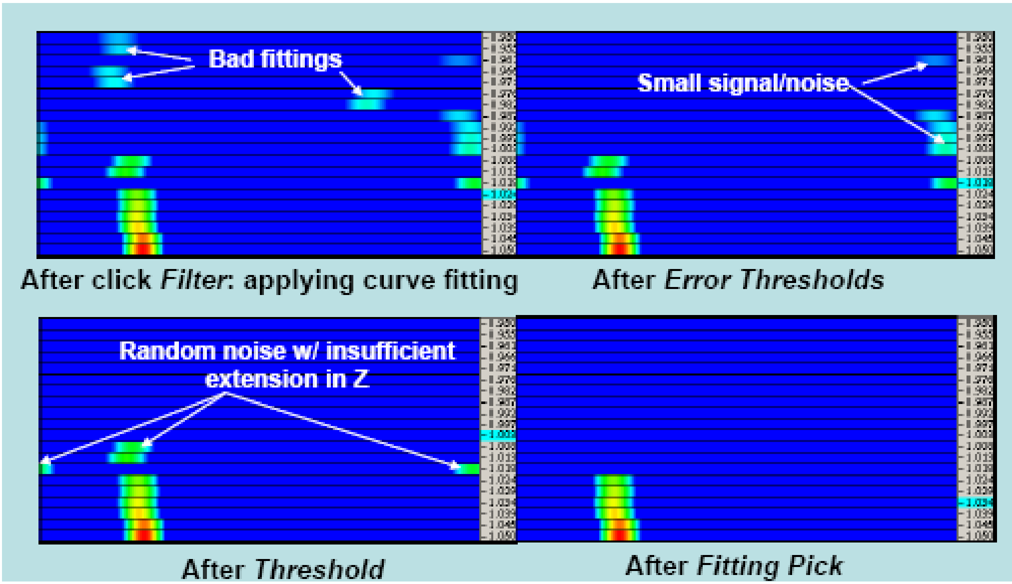
- "Fitting pick" is selected by user
  - Inspection noise can appear "crack-like"
    - But typically very localized, intermittent
      - Does not continue in z-direction of scan



- **Combination of signal recognition algorithms:**



Original Image



After click *Filter*: applying curve fitting

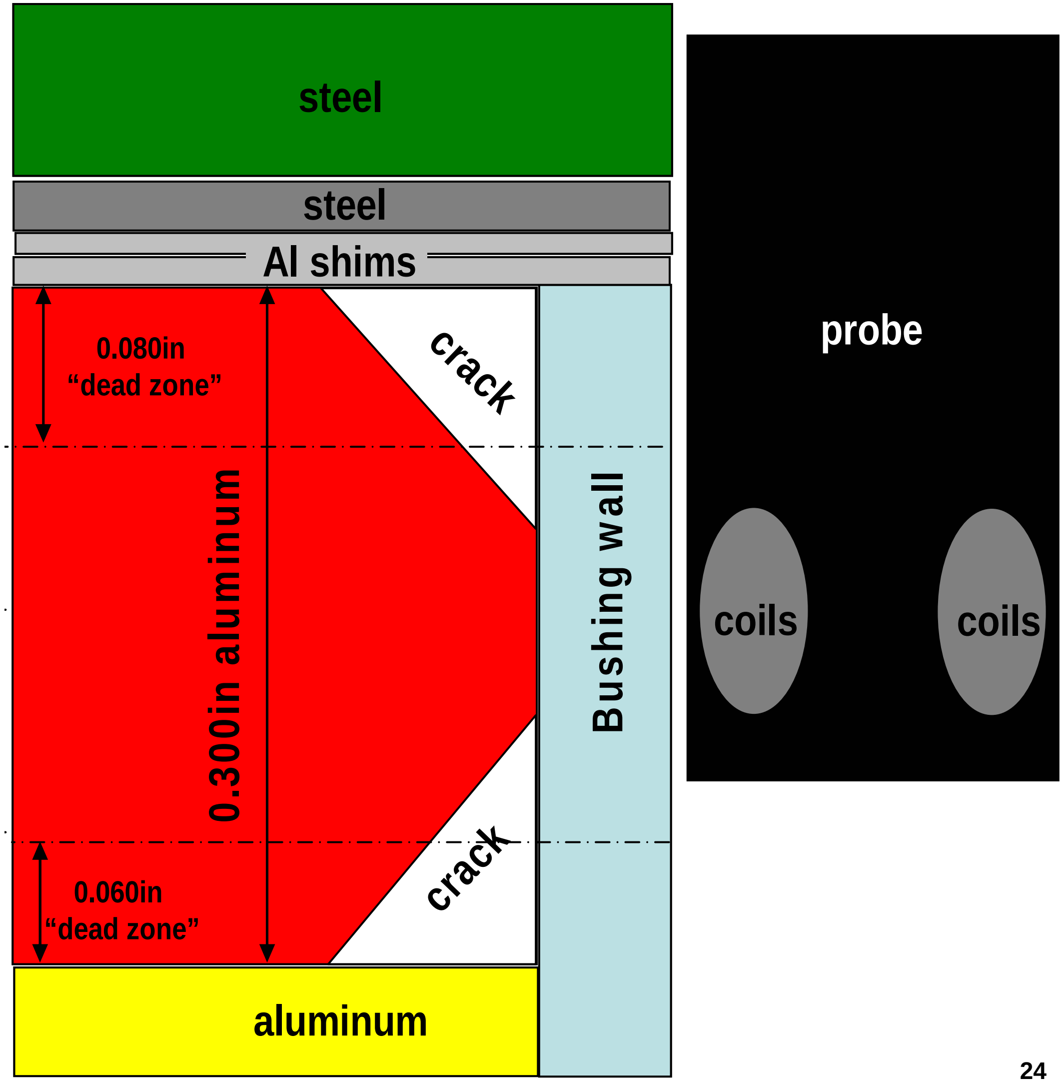
After *Error Thresholds*

After *Threshold*

After *Fitting Pick*

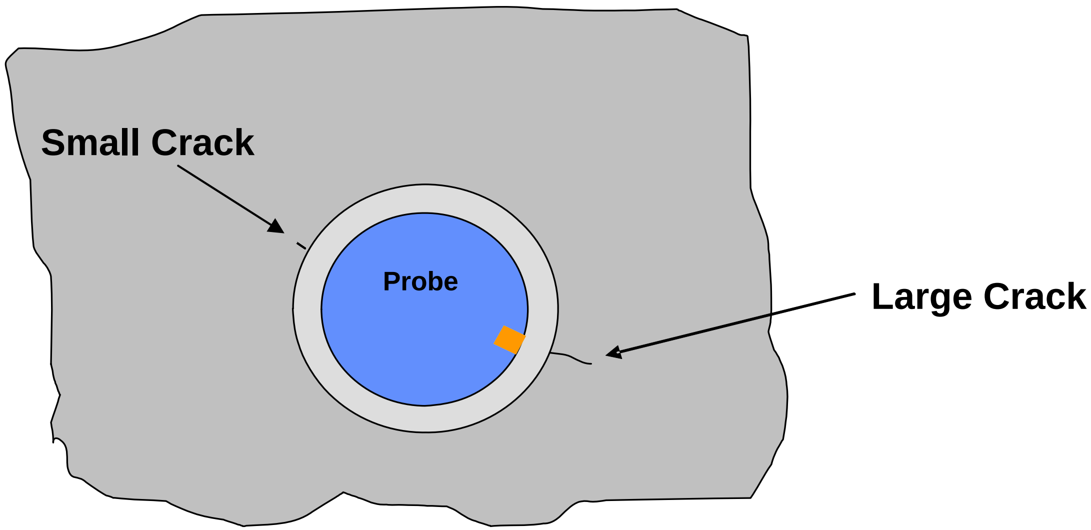
Limitations

- "Dead zones" near interfaces
  - Discontinuous surface produces a crack-like response 5-10 times larger in amplitude than a 0.050-0.100 inch corner flaw
  - Size of "dead zone" varies with bushing configuration and adjacent material layers
  - Fortunately, cracks as small as 0.050 x 0.050, can still be detected beyond the dead zones!



Limitations

- **Multiple cracks in the same plane**
  - **The current algorithm will only identify the largest flaw in a plane and assign the artificial signal to it**
    - **A second (smaller) crack in the same plane will be ignored**



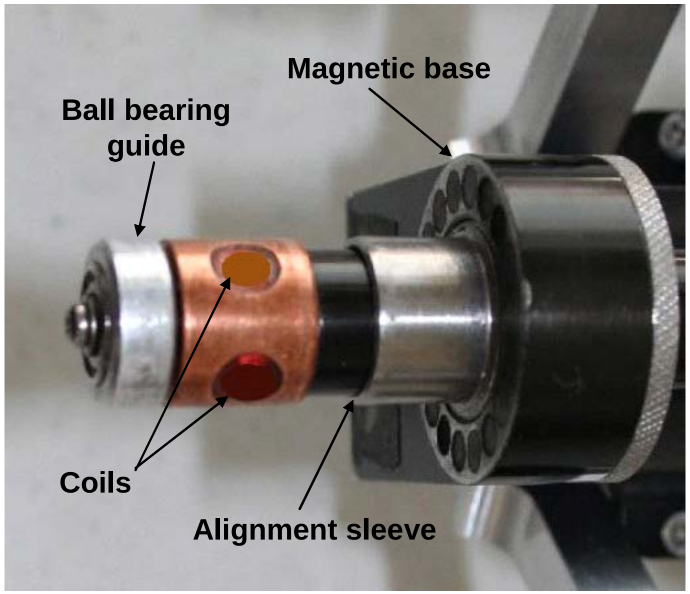
  - **Spacing of cracks may also affect algorithm performance**

Prototype Instrument

- SSEC II is a laptop computer based eddy current instrument
  - Controls the probe and scanner
  - Impedance plane, sweep, and C-scan formats in near real time
  - Custom software
    - unique signal recognition algorithms

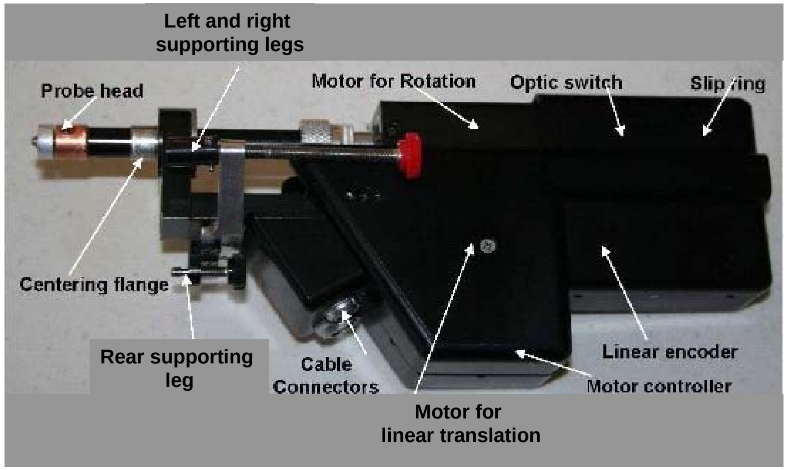
Prototype Instrument

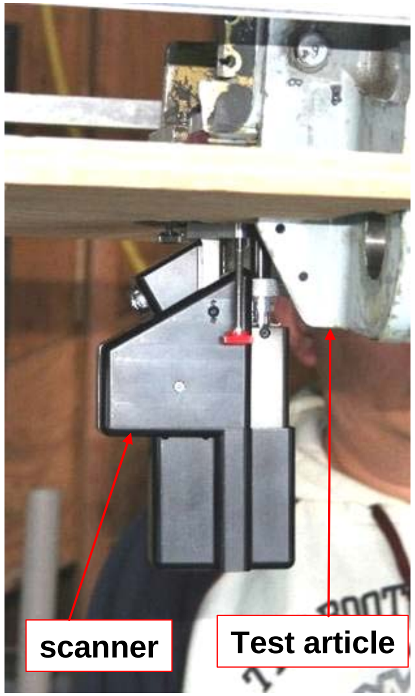
- **Probe**
  - **shielded coils (8-50kHz range)**
    - **aligned circumferentially**
  - **self-centering ball-bearing guide to prevent coil contact with the bushing wall**



Prototype Instrument

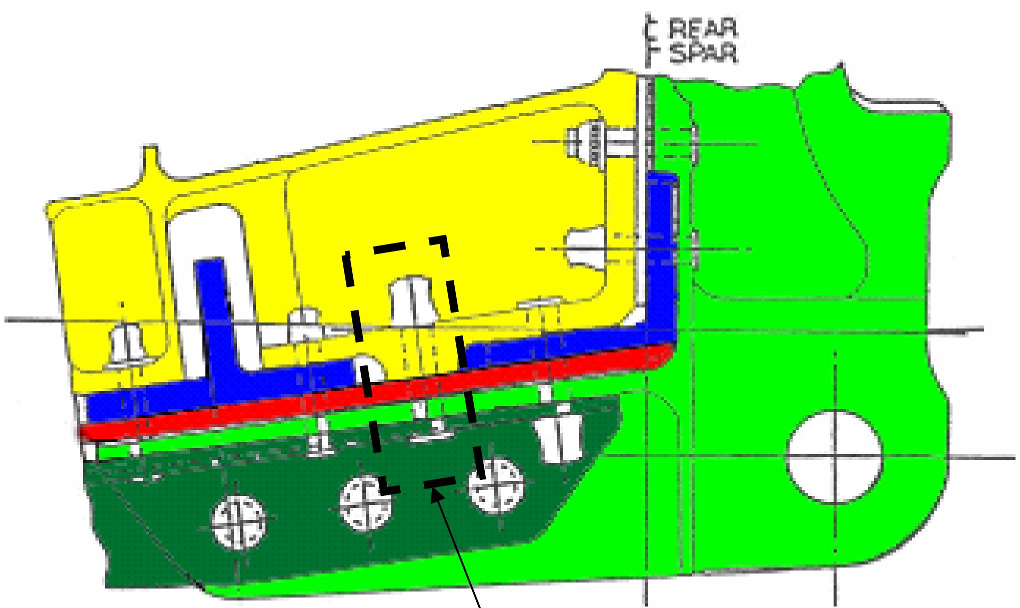
- Rotary scanner
  - Slip ring (sliding electrical contact) design
  - Probe adapter - alignment collar
  - Magnetic base - to attach to the steel external layer
    - “hands-free” inspection in inverted position
  - Scan times ~ 0.3in/min
    - Conventional high frequency bolt hole eddy current ~ 0.3in/sec.
  - Indexing optimized to 0.010 in for this application (0.003 possible)



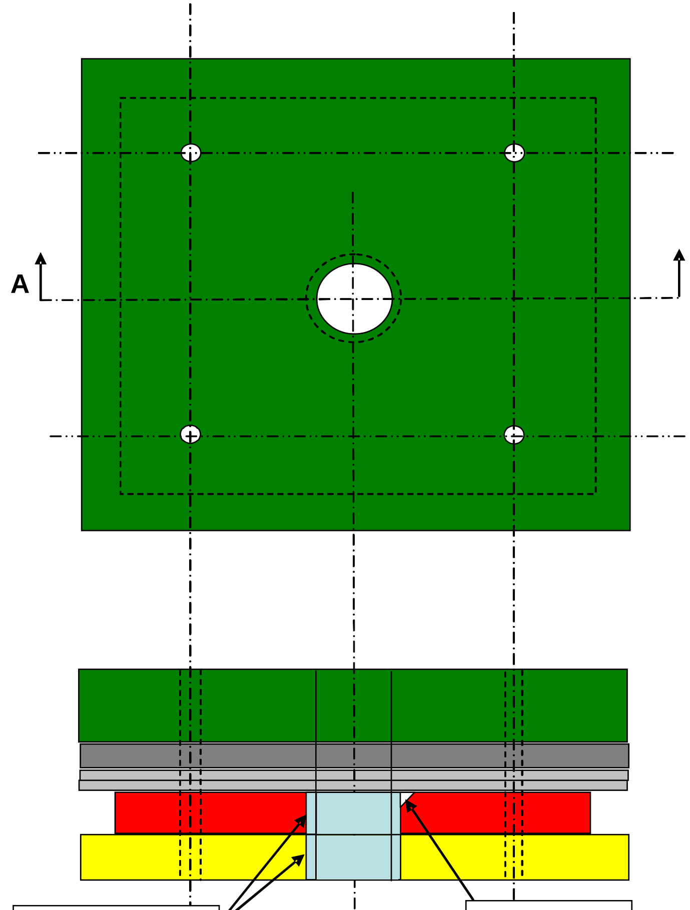


Test Results

- **Laboratory manufactured test standards**
  - Repair bushings of various wall thicknesses
    - 0.032 to 0.125 inches thick
  - Corner cracks or corner EDMs
    - 0.060 x 0.020 inches to 0.120 x 0.130 inches



Cross-section represented



Section A-A

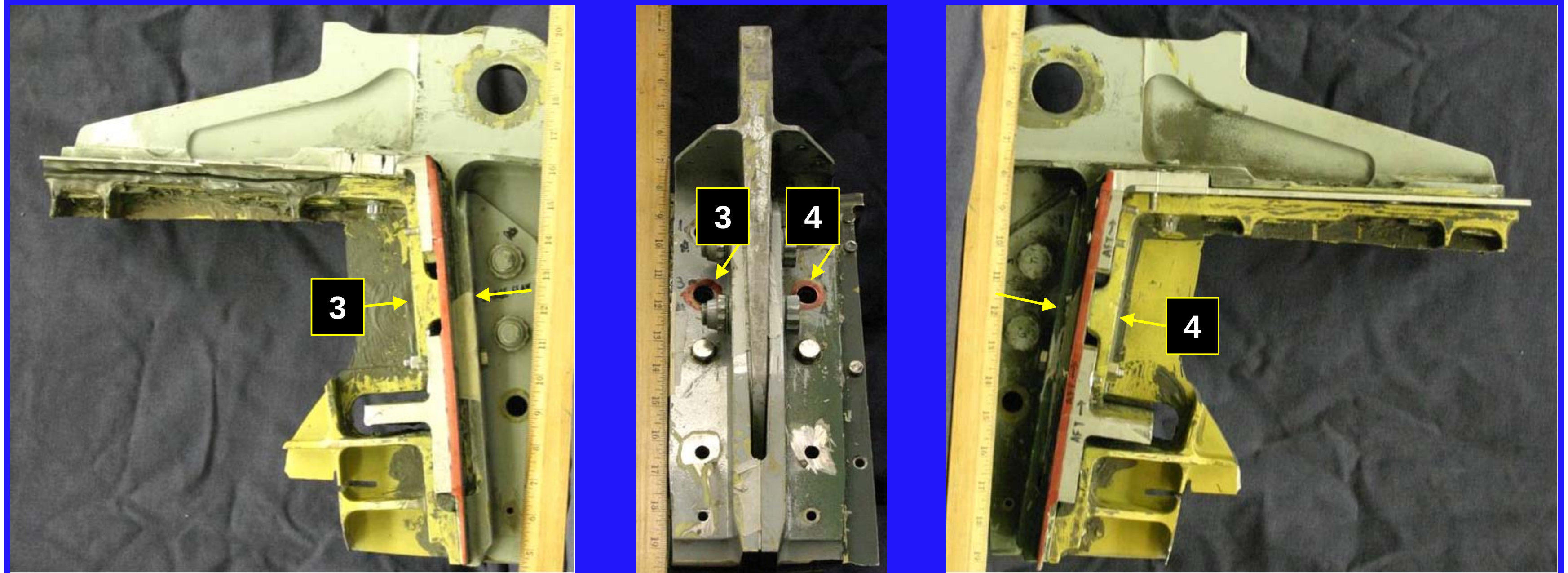
Test Results

- **Aircraft structure**

A-10 Wing Attach Fitting section with bushed holes containing cracks

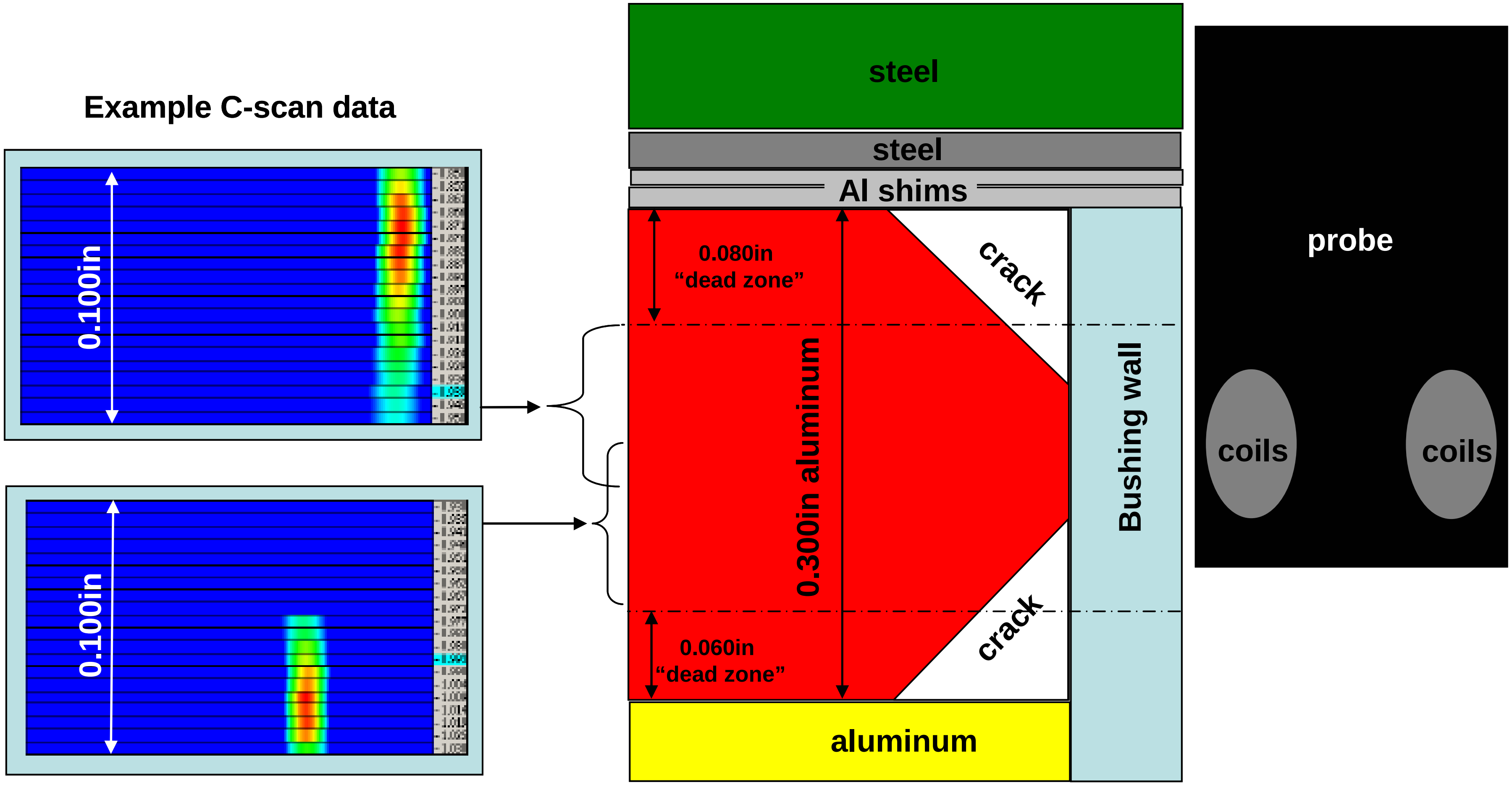
0.090”at interface x 0.075”into bore

0.020”at interface x 0.060”into bore



- Two 0.532” diameter holes with Inconel bushings installed (yellow arrows/red outlined holes).
  - Hole #3, large crack, 0.075 x 0.090
  - Hole #4, small crack, 0.060 x 0.020
- Cracks at wing skin layer (red layer)

Test Results



All flaws detected in all test articles/coupons!

Future Work

- Evaluation of the effect of interfaces
  - discontinuous surface produces a crack-like response
  - virtual “dead zone” near interfaces
- Effect of adjacent steel layers
  - magnitude and phase of the response changes
  - automated phase adjustment will be explored
- Effect of multiple flaws on the signal recognition algorithm
- Effect of larger flaws on the signal recognition algorithm
- Automatic identification of the presence of an Inconel bushing
- Improvements in scanner hardware and software
- More portable/rugged instrument