Stress Monitoring for Composite Overwrapped Pressure Vessels using MWM-Arrays

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Presentation Outline

- **Background**
  - Development program goals
  - MWM-Array technology
- **Example applications**
  - Composite panel and composite overwrapped pressure vessel
    - Rotational measurements – verifying fiber orientations
    - Imaging impact damage
    - Stress monitoring of composites
    - Application to both inspection and monitoring
- **Summary**

Background (1)

- Stress Rupture is a sudden and catastrophic failure of the overwrap of a pressure vessel while holding at a stress level below the ultimate strength for an extended time.
- Currently, there is **no simple method** of determining the stress rupture life of a composite overwrapped pressure vessel (COPV)
- There is **no simple screening technique** to determine the internal stresses of a composite panel or system.
  - The ability to directly measure the internal stress of an overwrap, particularly at the liner/overwrap interface, has the potential to greatly enhance health monitoring and life prediction of COPVs.
- Eddy current methods, **such as MWM-Arrays, have the potential to provide this health monitoring capability for composites**.
  - These methods have application to carbon fiber composites and COPVs.
  - The sensors can provide volumetric information with property measurements through the thickness and for different orientations.
  - These sensors can act as Magnetic Stress Gauges (MSGs) and do not require intimate contact (load transfer) between the sensor and COPV.

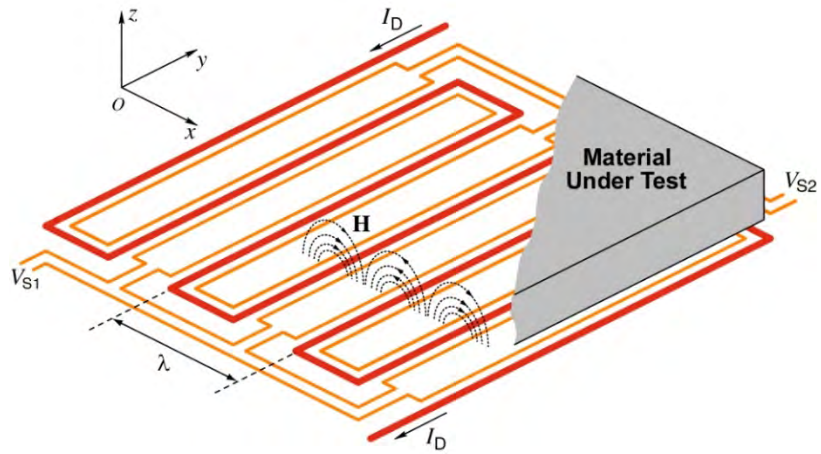
Background (2)

- **Development Program Goals**
  - Develop model-based methods for carbon fiber composite panels and systems
  - Demonstrate high-resolution damage and condition imaging for composites
  - Develop volumetric stress sensing magnetic stress gages for composites
- **Current Program**
  - NASA program for quality assurance of composite panels and systems
  - Status:
    - Year 1 – evaluated MSGs for damage evolution and monitoring
    - Year 2 – focus on improvements to sensors and instrumentation
    - Year 3 – performed 6 month long term test
    - Year 4 – just started, focus on review of long term test results
- **Previous Funding**
  - NASA for micromechanical model development and application to composite overwrapped pressure vessels (COPVs)
  - Army for rotor blade NDT
  - Navy for NDT of aircraft composites

MWM-Array Technology

- Eddy current array geometry designed to match (isotropic) models for responses
- The voltage induced on sense element(s) is measured.
- Measurement grid methods provide conversion of measured responses into physical properties (e.g., conductivity, lift-off, permeability)

Magnetic field interacting with test material

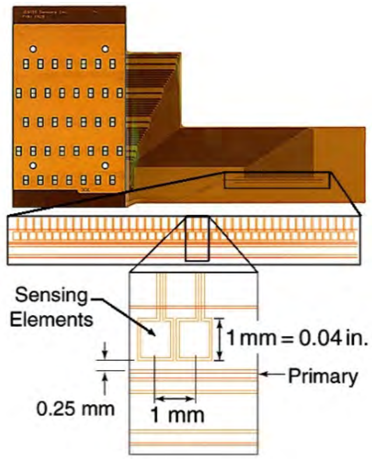


Parallel Architecture Instrument:
Next Generation 8200

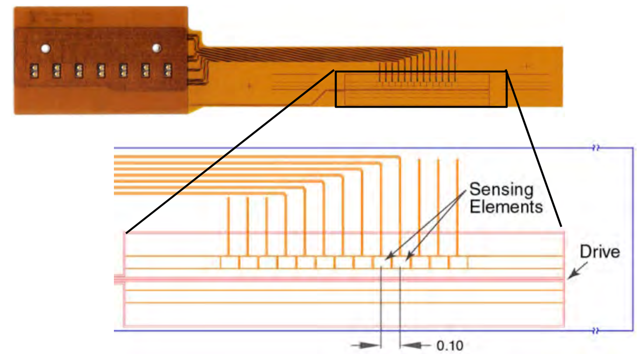
Example MWM-Arrays

- MWM-Array dimensions can be adjusted for the application
  - Drive-sense gap (spatial wavelength) affects penetration depth

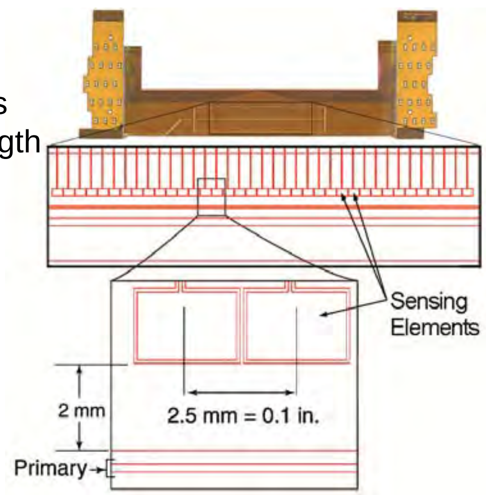
FA28
37 elements
small wavelength



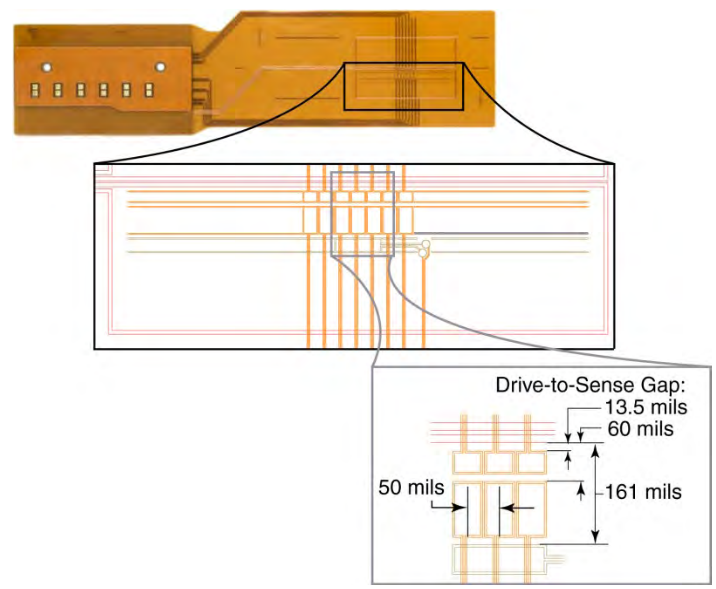
FA154
7 elements
medium wavelength



FA24
37 elements
large wavelength

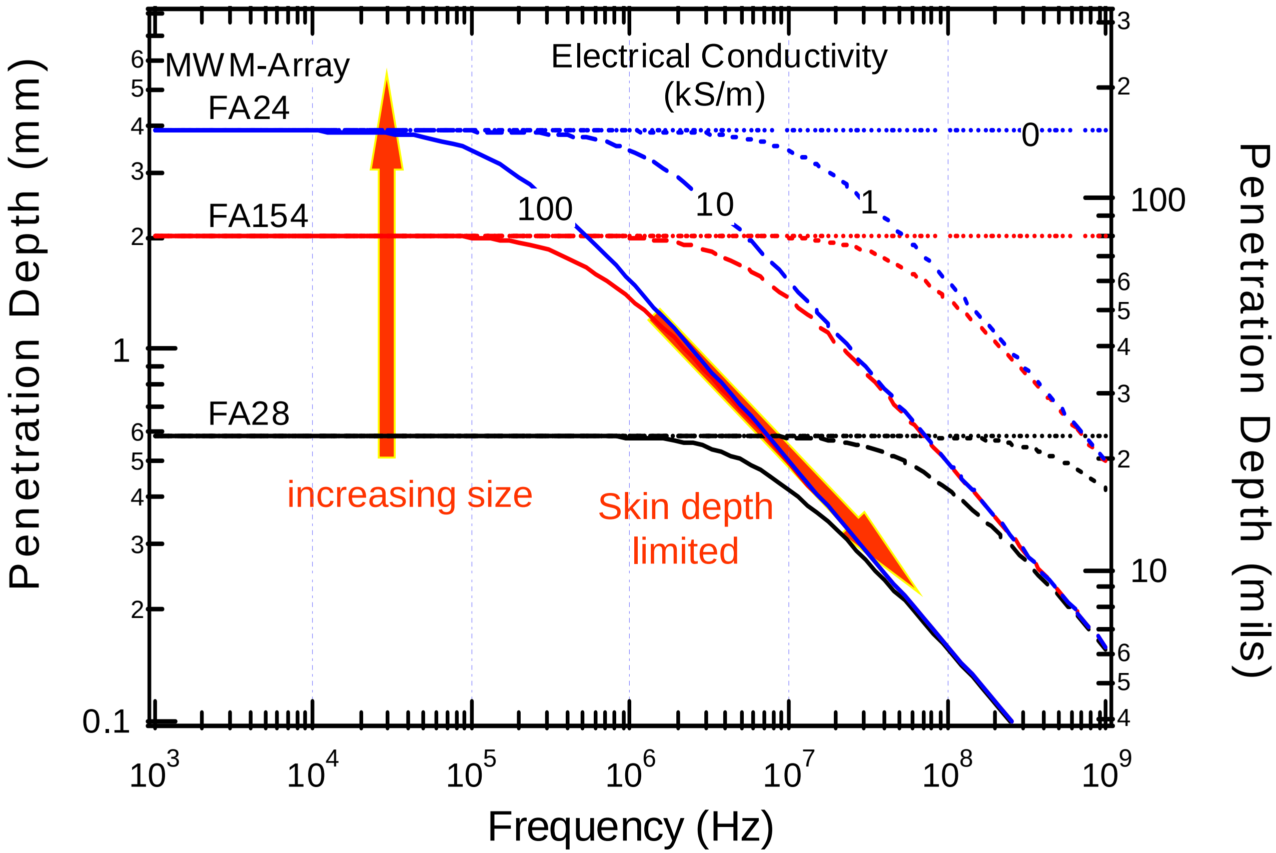


FA49
7 elements
several wavelengths



MWM-Array Sensor Selection

- Magnetic field decays exponentially with distance away from sensor
  - Decay rate determined by skin depth at high frequencies and sensor dimensions at low frequency

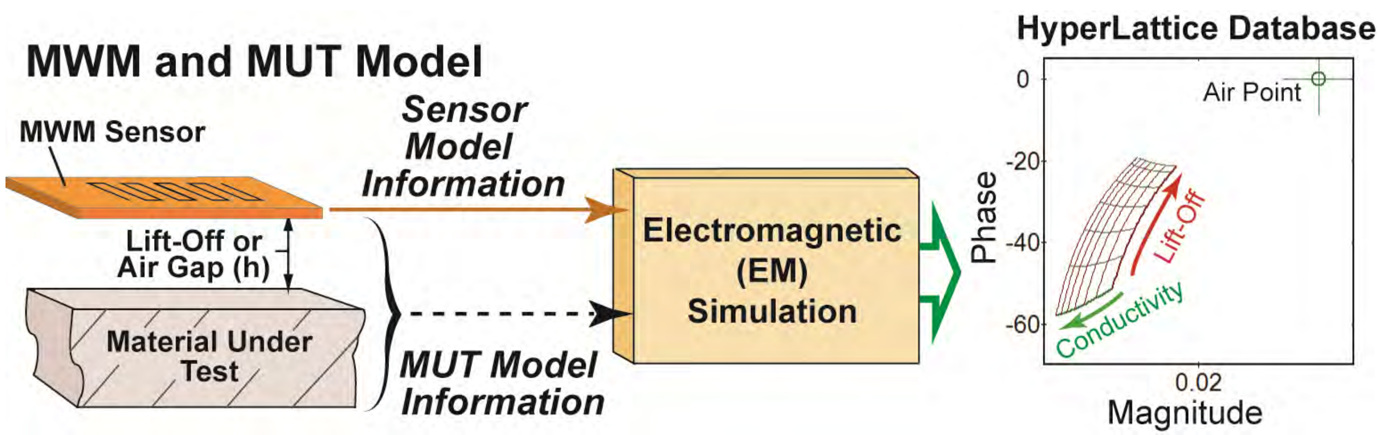


Spatial Fourier Mode Depth of Penetration = 1/Re(Γ_n)

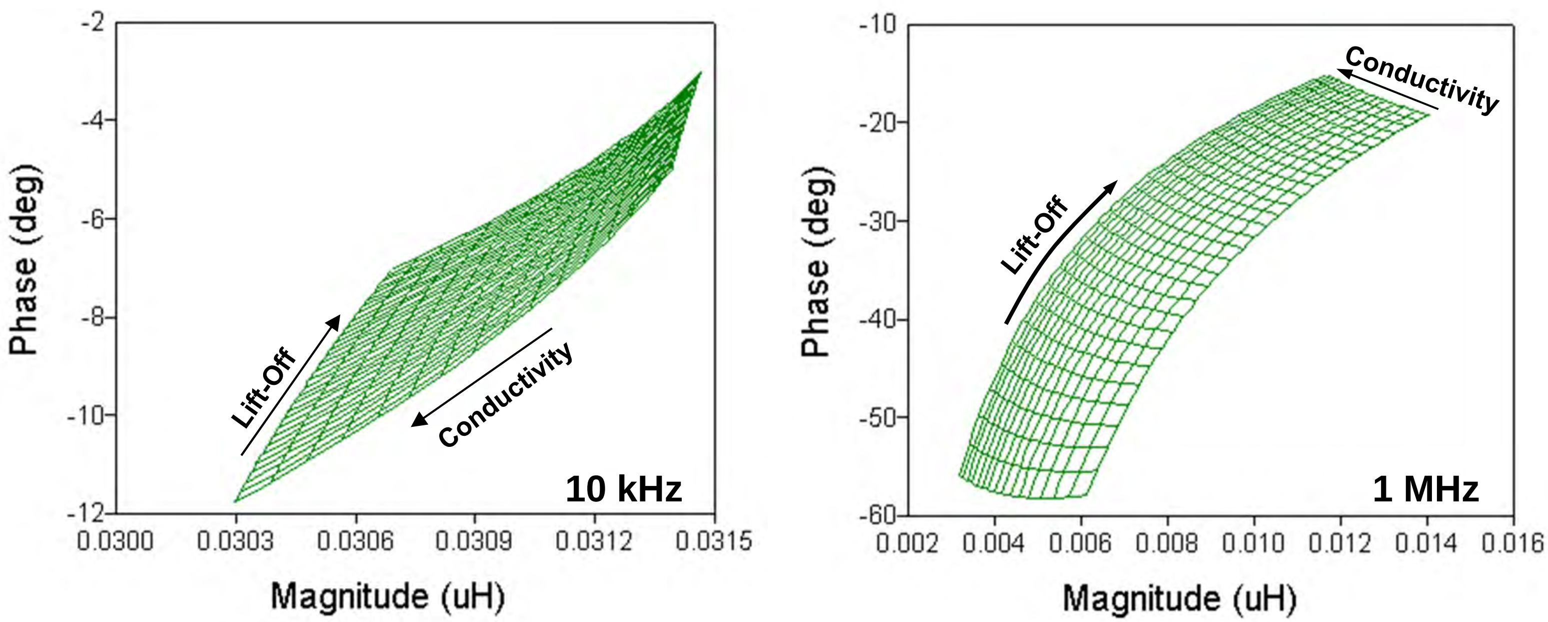
$$\Gamma_n = \sqrt{(2\pi n/\lambda)^2 + j2/\delta^2}$$

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

Measurement Grids for Simplified Model



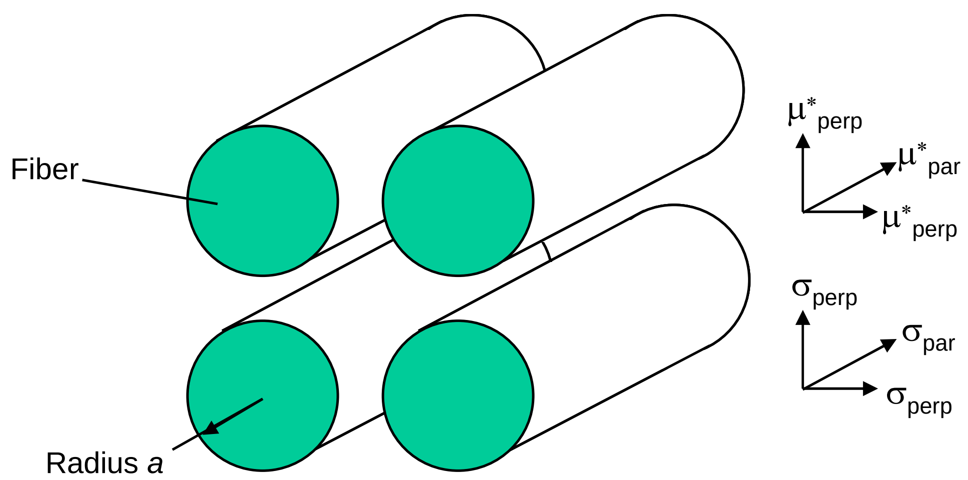
Example Grids for the MWM FS35 Sensor and Aluminum



Micromechanical Model: Eddy-Current Extension

- Model considers fiber bundles as an assemblage of parallel cylinders
  - Solve for field around a single fiber and extend to fiber bundle
  - Effective complex permeability and conductivity depend upon orientation with respect to fiber axis, fiber density and fiber contact
- For carbon fiber composites
  - Graphite fibers: ~7 μm diameter, nonmagnetic, ~20 kS/m (0.0344%IACS)
  - Radius << skin depth for typical eddy-current frequencies
- Indicates a strong orientation dependence of the properties
  - MWM-Arrays with linear drives can provide a measure of these orientation dependent responses

$\mu^*_{par} \approx \mu^*_{perp} \approx \mu_o$ $\sigma_{perp} \approx 0$ $\sigma_{par} \approx \sigma_f \nu_f$

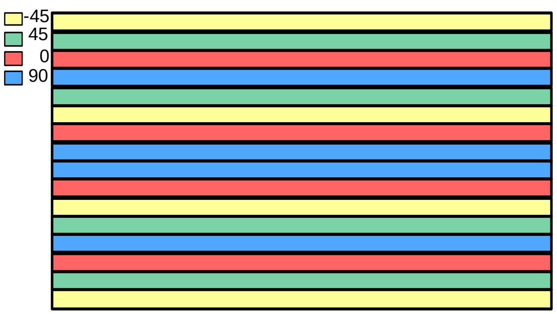


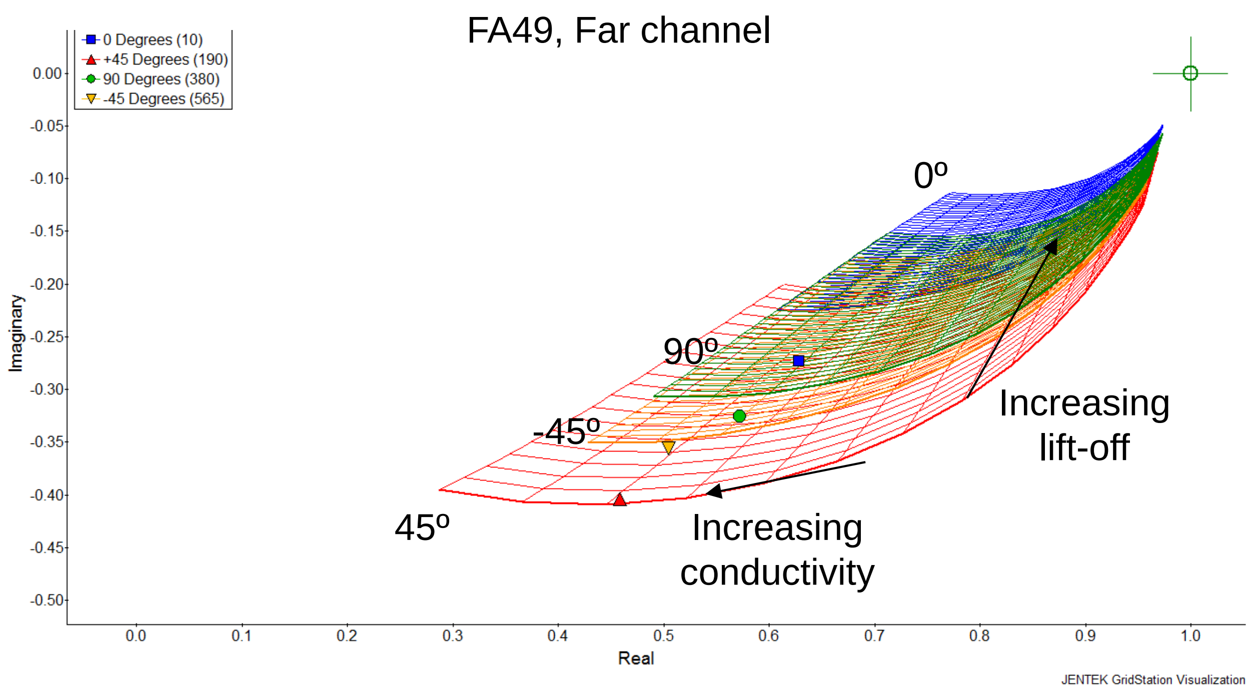
This first order model neglects interconnections (touching) between fibers

Composite Panel Grid Example

- Conductivity/lift-off measurement grids assuming quasi-isotropic layup
  - Non-zero conductivity only for aligned layers in each orientation
- Primarily observe response shift as effective lift-off changes with orientation
- General agreement of the model with measurement data in each orientation
  - Data is below the grids for the deep plies (0º and 90º), so other factors need to be considered

Quasi-isotropic Layup
(note that the angle here refers to the panel orientation)

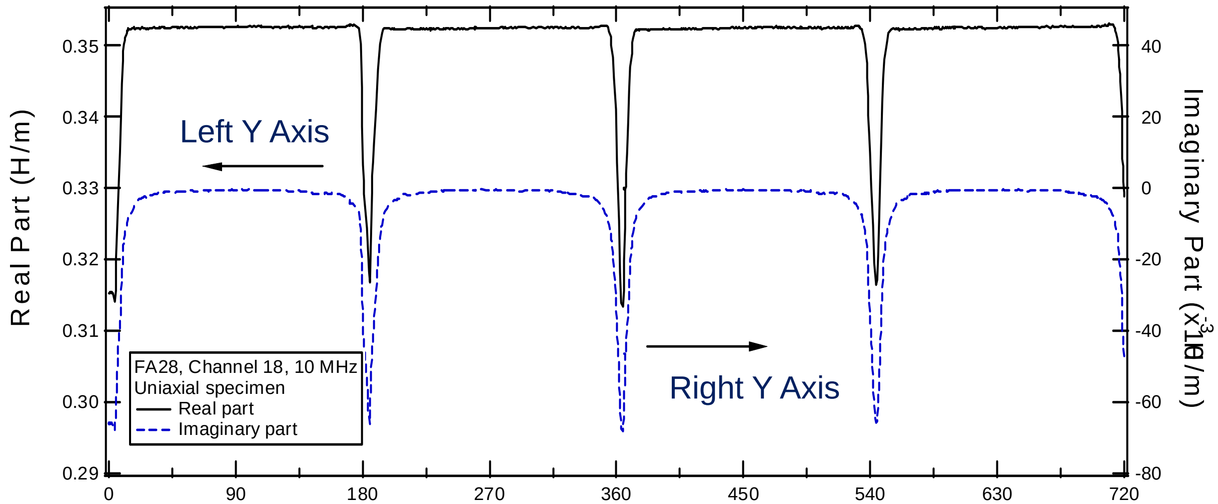




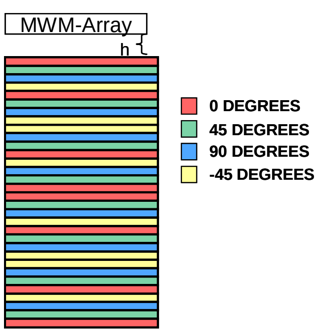
Composite Panel Measurements: Orientation Effect

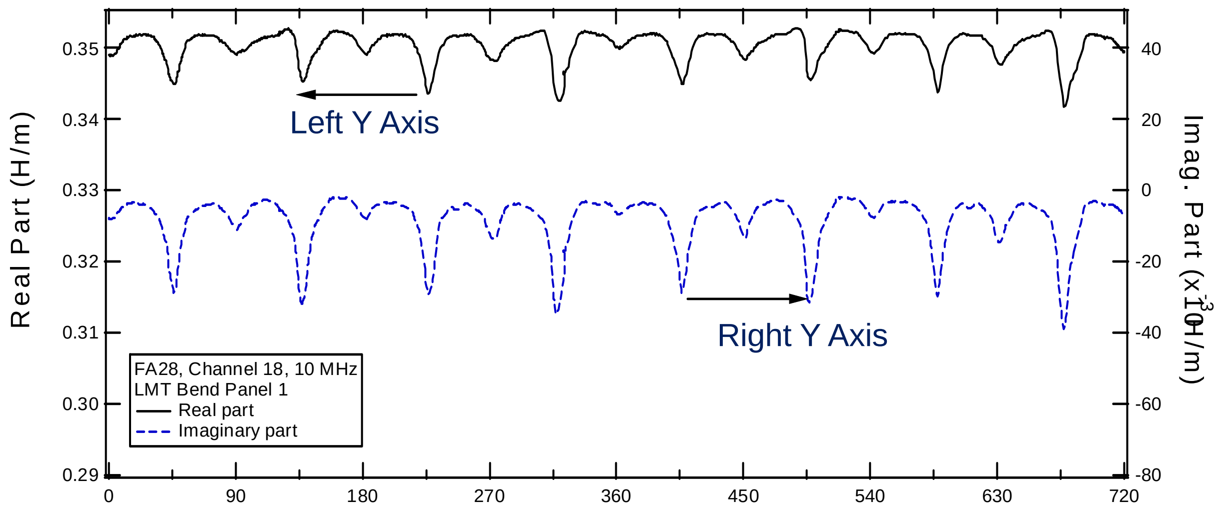
- Center element for FA28 MWM-Array
- Strong response when aligned with fibers in individual plies

Unidirectional Layup



Quasi-isotropic Layup (alternating layers at -45º, 0º, 45º, 90º)



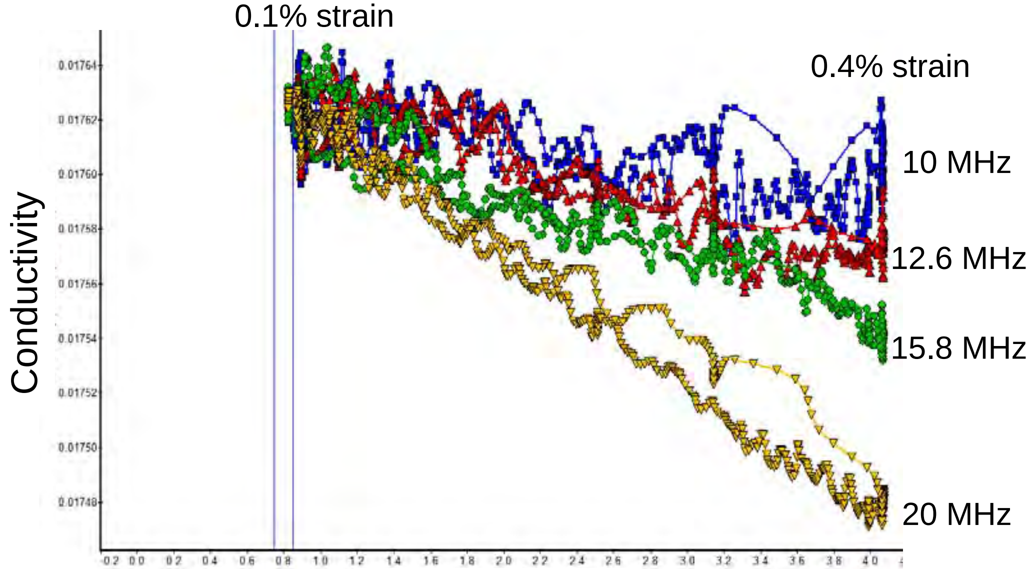


Composite Panel Stress Monitoring

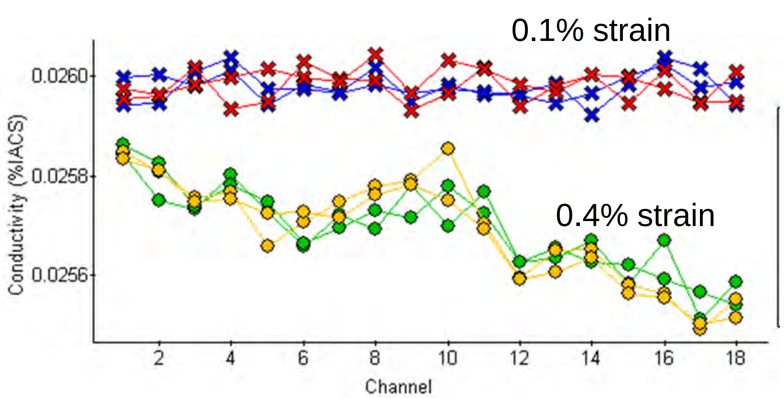
- 4-pt bending on uniaxial specimen
- MWM-Array placed on tensile side
- Observed decrease in effective conductivity with increasing tensile load
- Frequency and channel-to-channel variations are due to the simplified models (conductivity/lift-off) used for this analysis
- Care is taken to use mounting methods that minimize load transfer to the sensor

Representative Specimen

FA154, mounted to surface

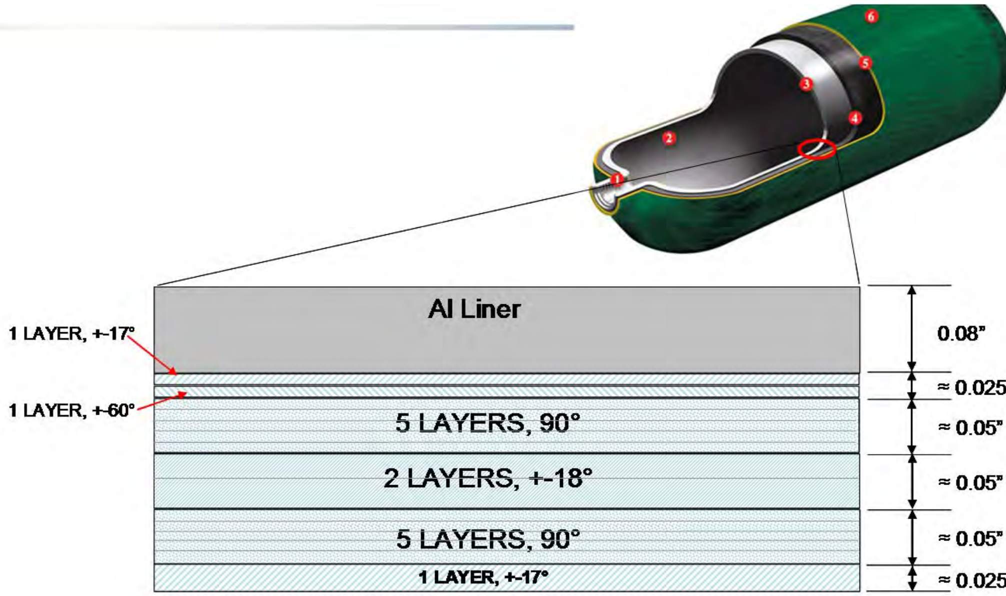


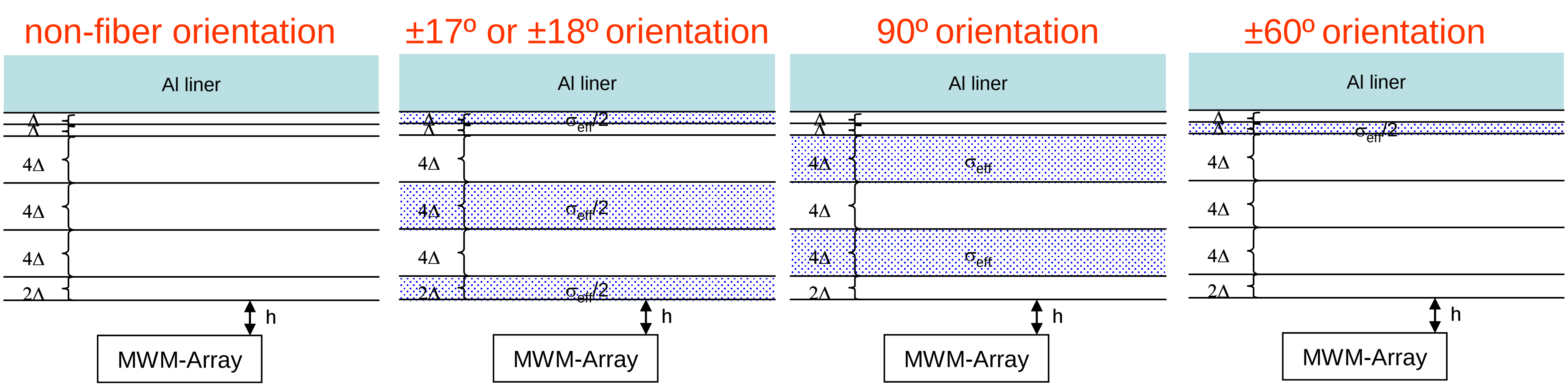
FA24, pick-and-place



Example COPV Layup

- Representative layup for composite overwrapped pressure vessels
- MWM-Array sensitive to composite layers with fibers oriented parallel to drive windings
- This indicates that the sensor orientation is important for assessing the fiber properties

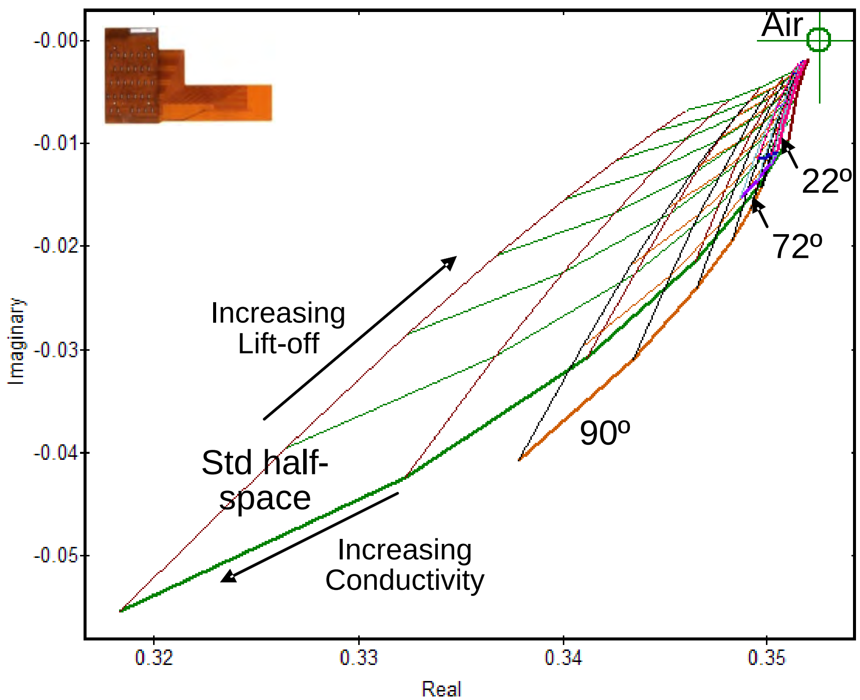




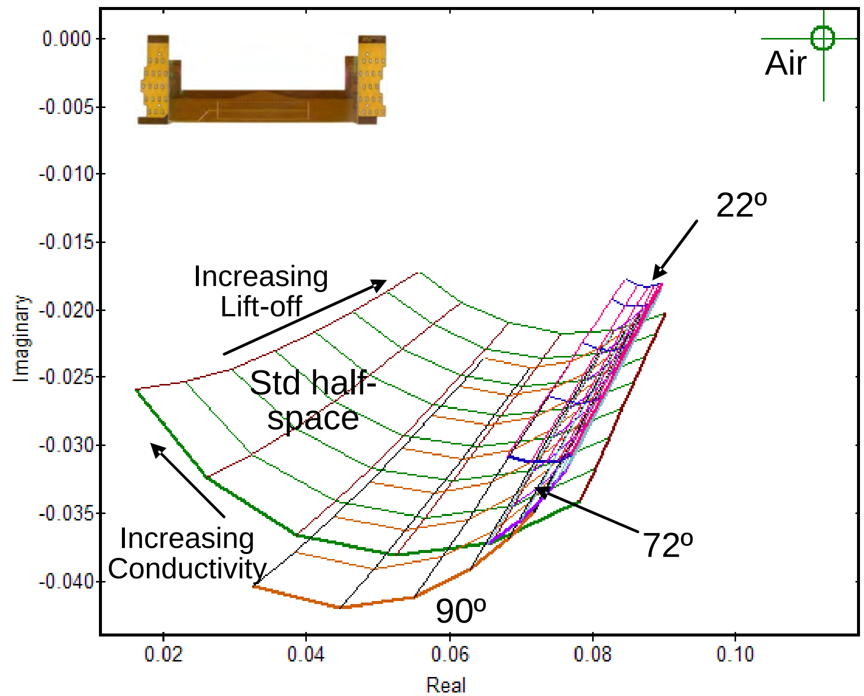
JENTEK Grids for MWM-Array on COPVs

- Representative grids for a composite overwrapped pressure vessel (COPV)
- Models account for layered geometry and orientation effects on properties within each layer
- Indicates that sensitivity to property variations in particular layers varies with fiber orientation, depth, and sensor selection

FA28

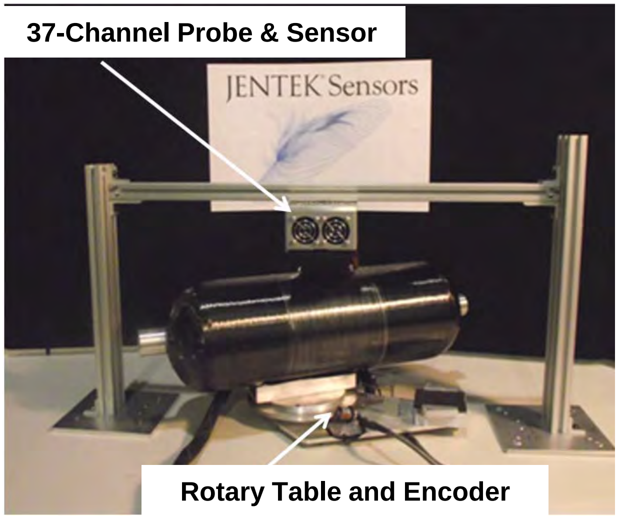


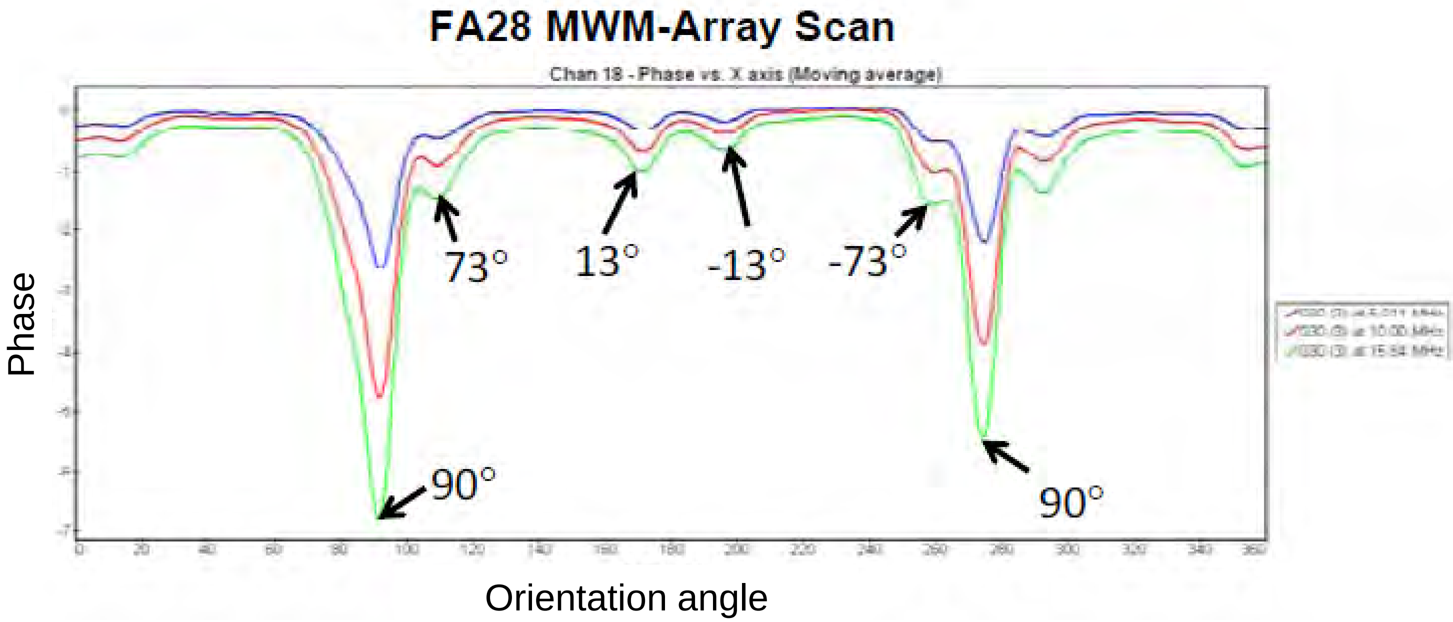
FA24



COPV Rotation Measurements

- Rotational measurements can be used to confirm fiber orientation in layup
- Indicates fibers oriented at approximately 13º, 73º, and 90º for this bottle

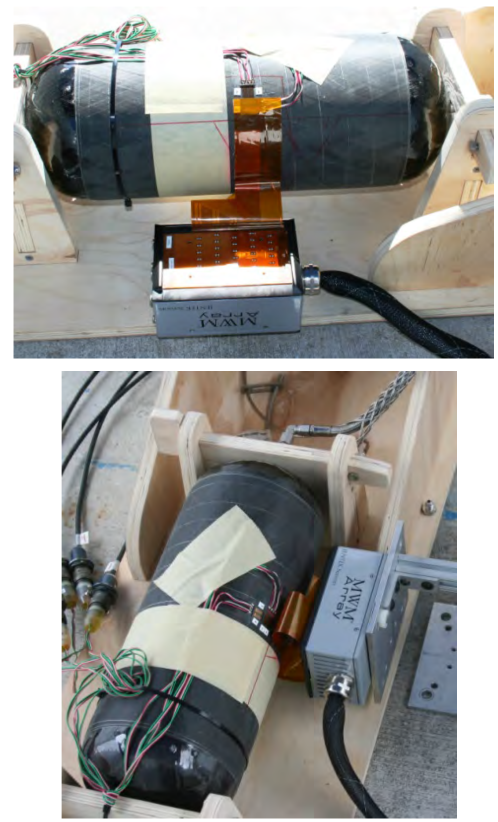




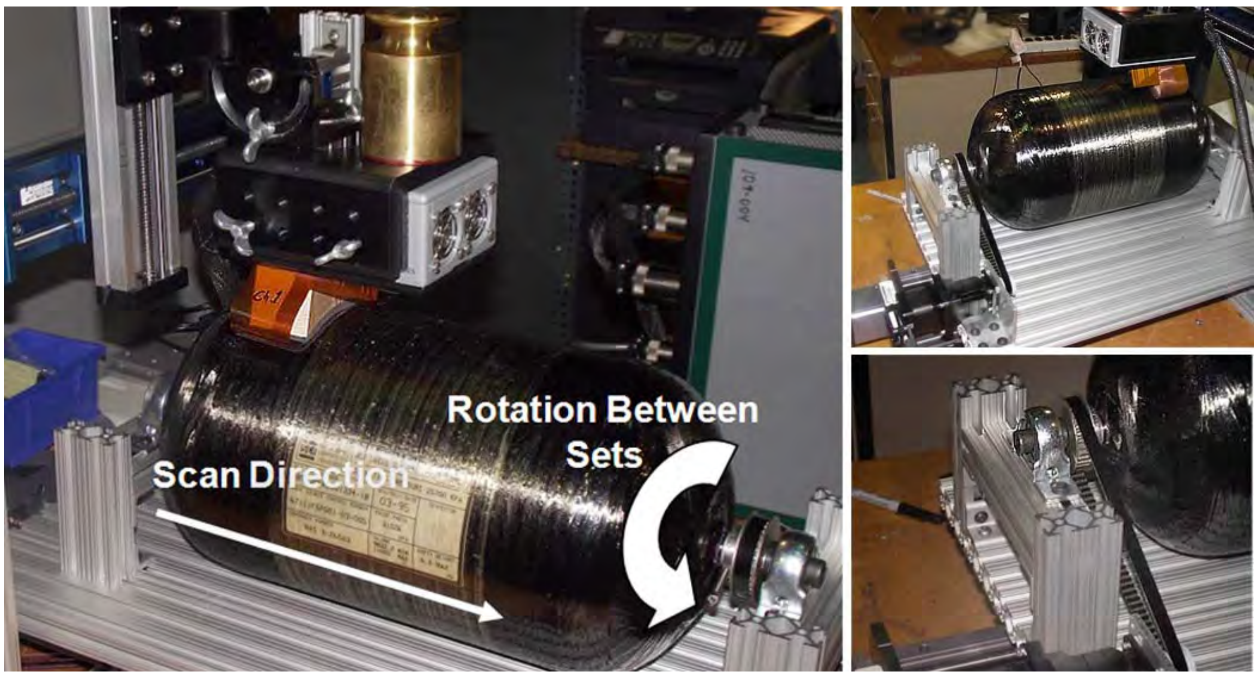
COPV Inspection and Monitoring

- Eddy current scans imaged both liner and composite properties
- Potential for manufacturing quality control both before and after overwrap is applied
- Surface mounted arrays provide information about COPV condition (e.g., stress)

Surface-Mounted Setups

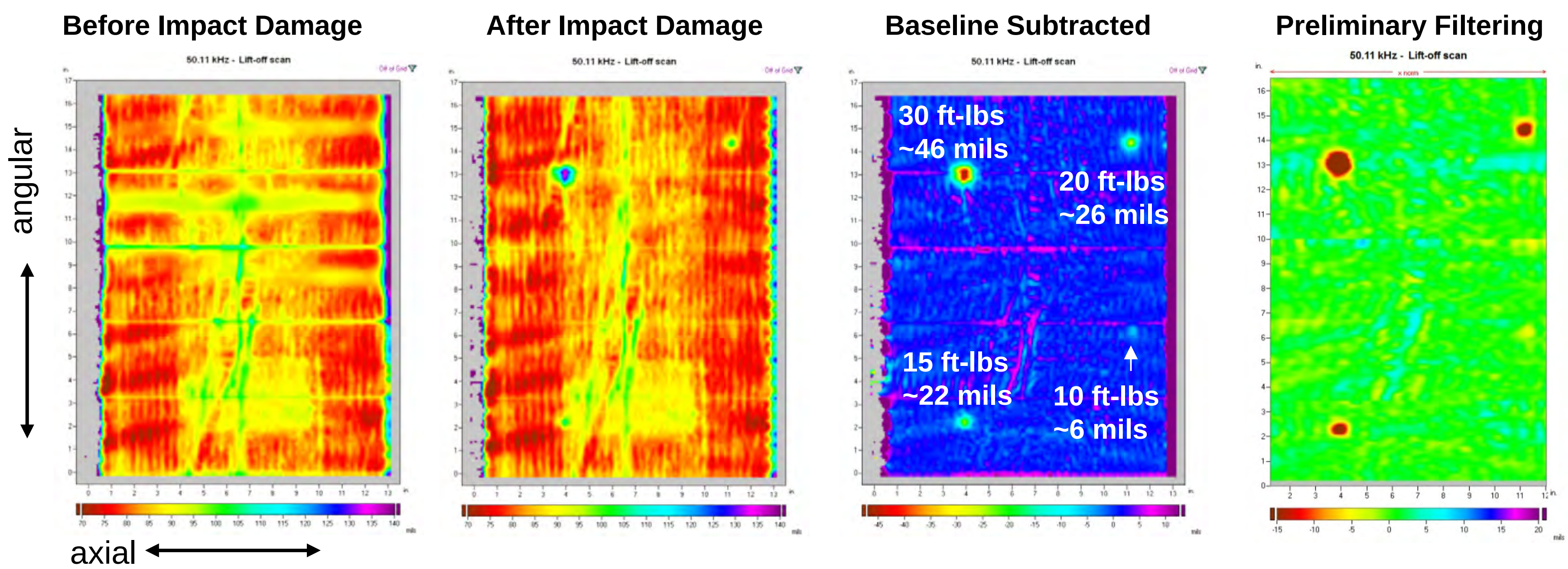


Bottle Scanning Setup



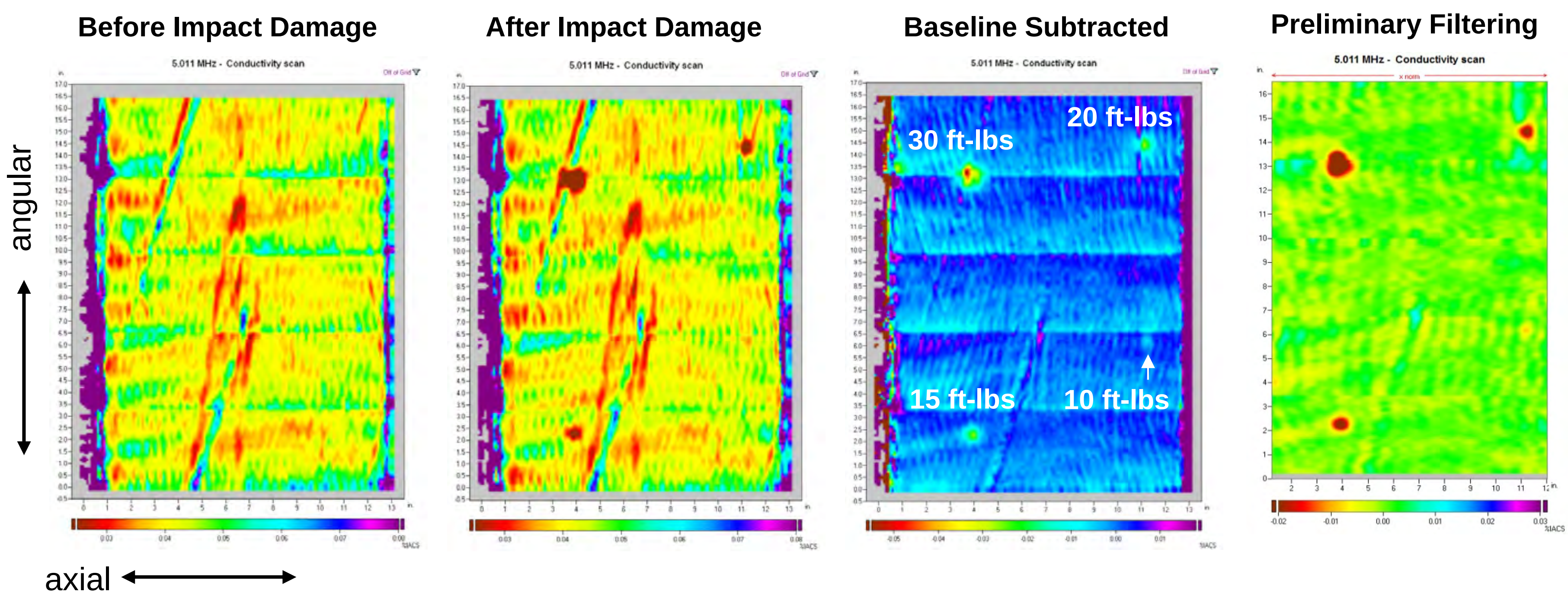
COPV: Low-Frequency Inspection

- 50 kHz
- 90° drive orientation with 0.066-in. thick overwrap
- At this frequency the sensor responds primarily to the liner
- Effective lift-off images show dents in liner
- Higher impact energy results in larger dents in the aluminum liner

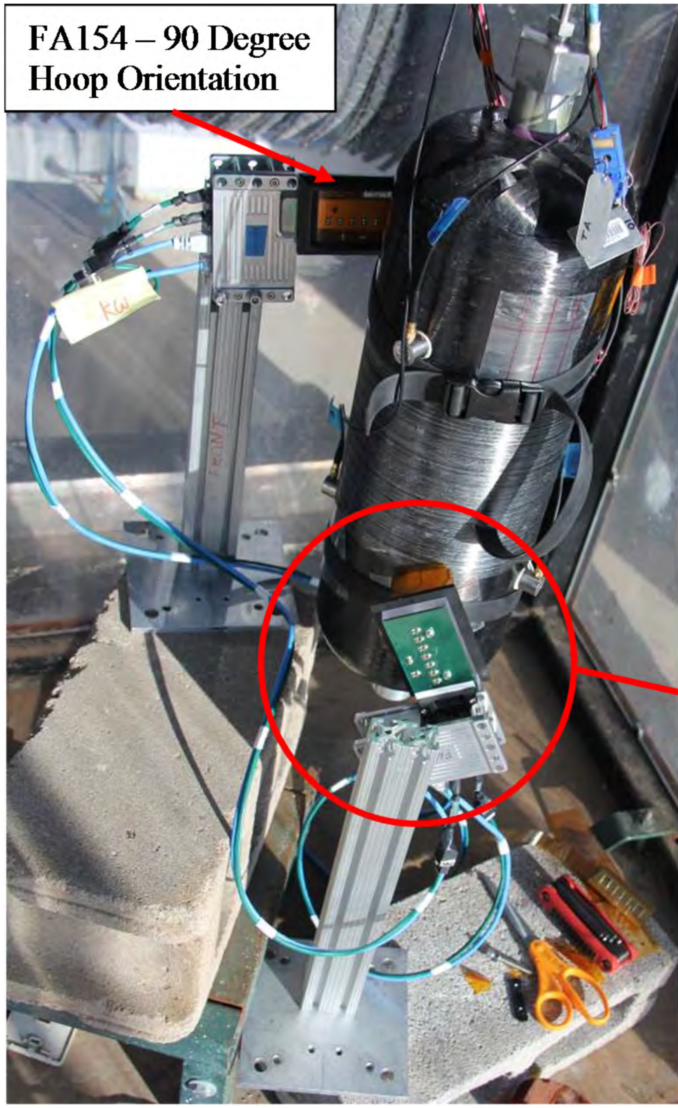


COPV: High-Frequency Inspection

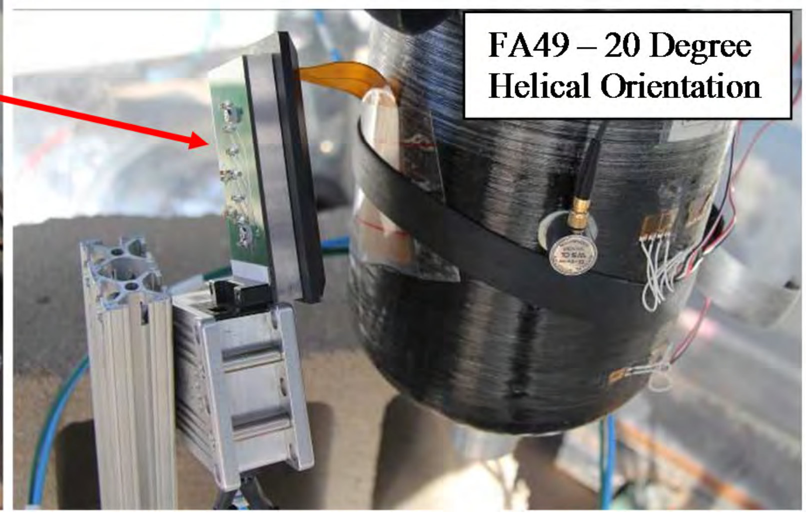
- 5 MHz
  - At this frequency more of the signal related to the composite overwrap properties
- 90° drive orientation with 0.066-in. thick overwrap
- Conductivity images show significant spatial variations in the overwrap properties
- Changes in the effective conductivity images **highlight the damage**



COPV: Typical Mounting Configurations

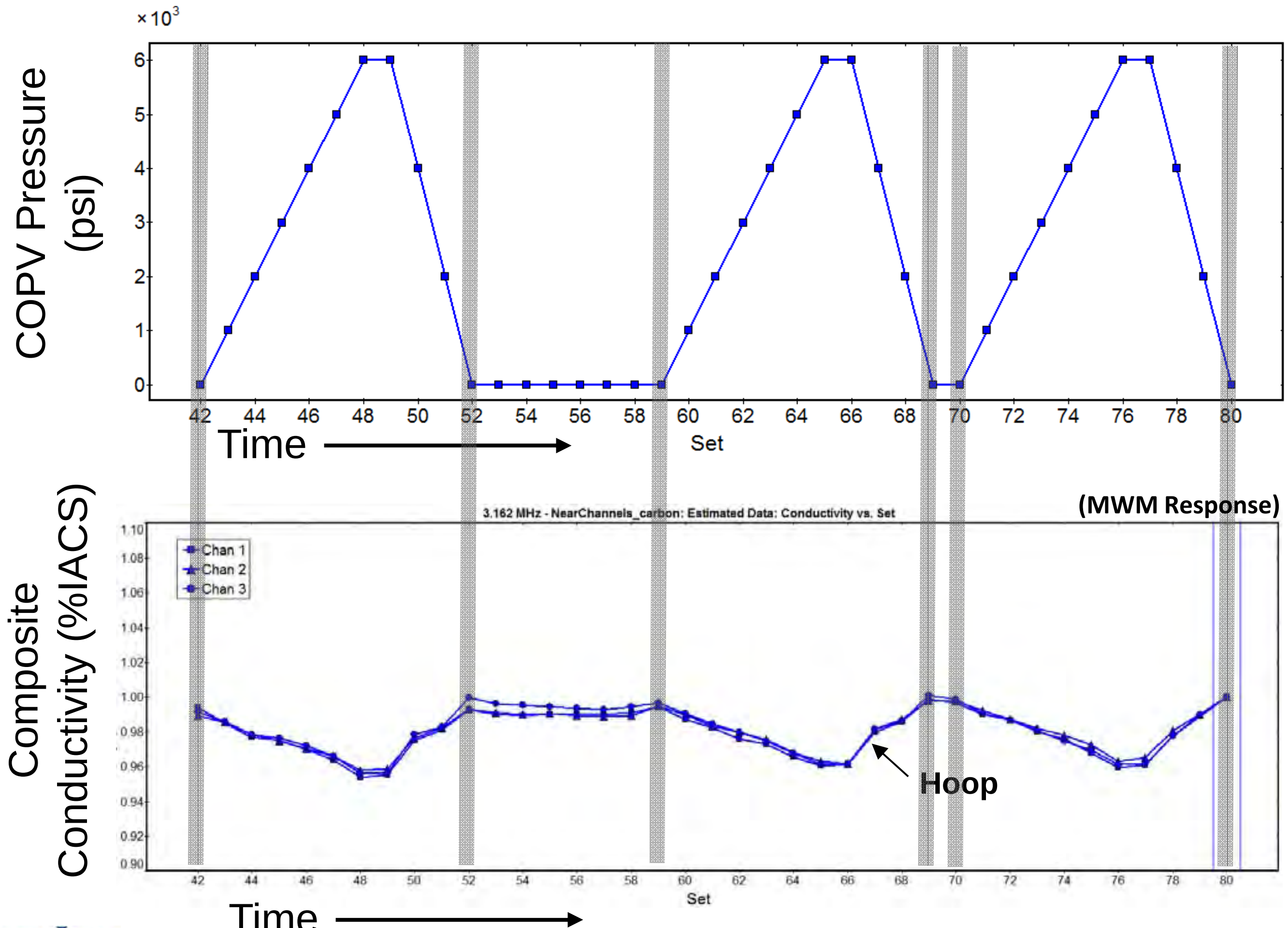


- Configuration used for basic feasibility tests
- MWM-Arrays mounted on bottle in two of the fiber orientations
- Measurements taken at multiple frequencies
  - A low frequency (50-300 kHz) to have sensitivity to liner properties
  - A high frequency (2-10 MHz) to enhance sensitivity to overwrap properties
- Similar configuration for long term test at NASA White Sands Facility



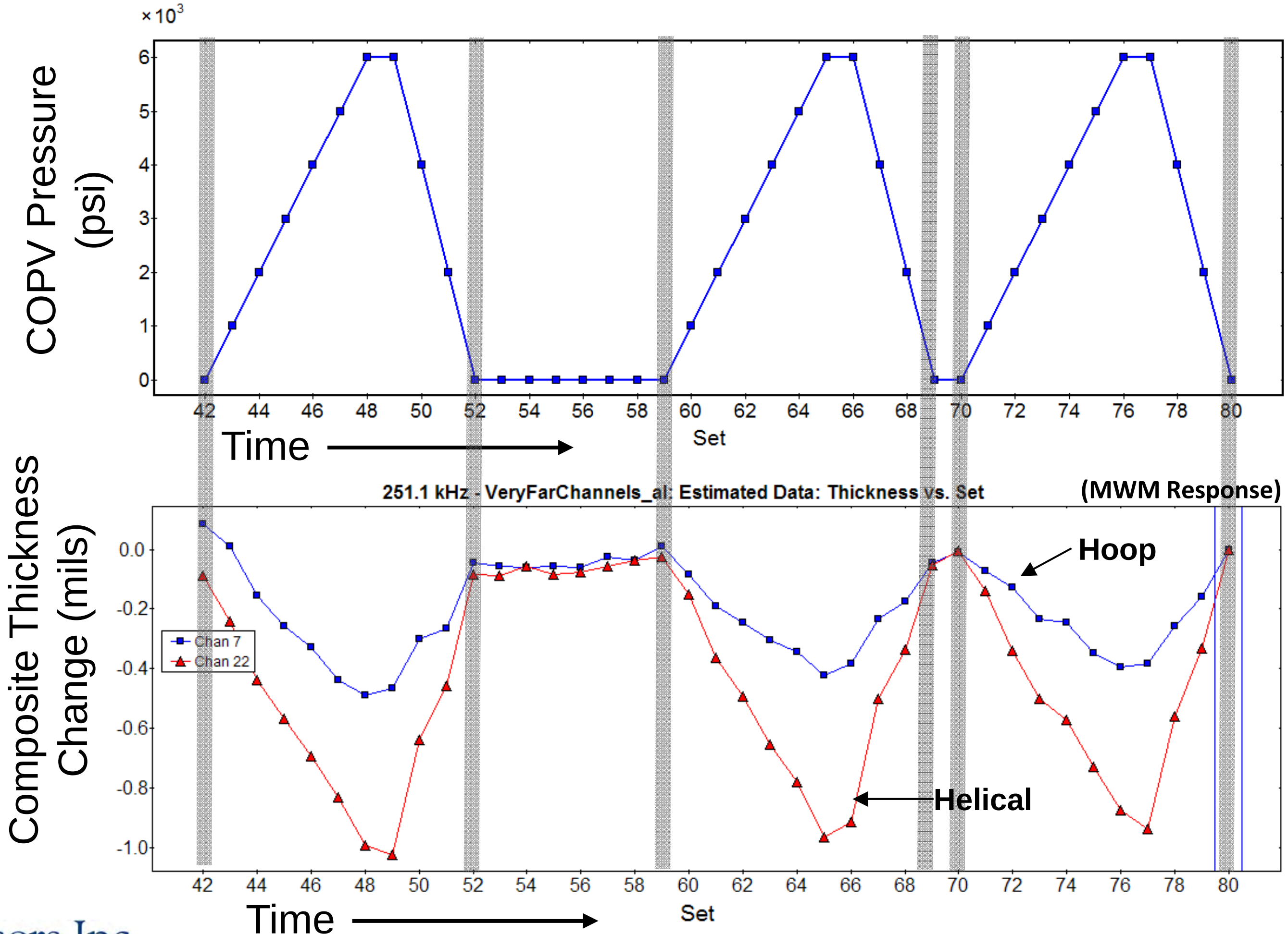
COPV: High Frequency Monitoring

- COPV hydrostatically pressurized for several cycles
- Near channels of FA49 used with the drive oriented parallel to the hoop fibers
  - For this configuration, these sense elements are only sensitive to the composite properties
- Modest reduction in conductivity consistent with tensile strain and 4-pt bend test results



COPV: Low Frequency Monitoring

- "Very-far" FA49 channels used with the drives oriented parallel to the hoop or helical fibers
  - For this configuration, these sense elements are primarily sensitive to the composite thickness.
- Composite thickness is reduced with pressurization
- ***The same array can be used to monitor both composite thickness <u>and</u> conductivity***



Summary

- Eddy current methods can be used for the inspection and montoring of composites containing conducting materials
- Eddy current sensor arrays with linear drives have shown a capability to determine fiber orientation and image fiber density variations in the composite
- Feasibility for stress monitoring of composites, particularly for use in COPVs, has been demonstrated
- A long duration test has been performed to establish instrument stability; ongoing work is aimed at analyzing results from this test

Questions?

The views and opinions expressed in this presentation are those of the authors and do not necessarily represent official policy or position of JENTEK Sensors, Inc., NASA, or any Department of the U.S. Government.

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