NDT and SHM of Carbon Fiber Composites using Linear Drive MWM®-Arrays

3 April 2013

Andrew Washabaugh, Christopher Martin, Robert Lyons, David Grundy, Neil Goldfine
JENTEK Sensors, Inc., Waltham, MA 02453-7013
Phone: 781-642-9666; Email: jentek@jentekensors.com

Richard Russell
NASA Kennedy Space Center
Phone: 321-861-8618; Email: richard.w.russell@nasa.gov

Russell Wincheski
NASA Langley Research Center
Phone: 757-864-4798; Email: russell.a.wincheski@nasa.gov

MWM sensors and MWM-Arrays are covered by many issued and pending patents, including (but not limited to): 8,237,433, 8,222,897, 8,050,883, 7,994,781, 7,876,094, 7,812,601, 7,696,748, 7,589,526, 7,533,575, 7,526,964, 7,528,568, 7,516,864, 7,467,057, 7,451,857, 7,451,839, 7,411,390, 7,385,392, 7,348,771, 7,289,913, 7,280,940, 7,280,940, 7,230,421, 7,188,532, 7,163,764, 7,161,351, 7,161,350, 7,108,055, 7,095,224, 7,049,811, 6,995,557, 6,992,482, 6,992,095, 6,784,862, 6,781,387, 6,737,691, 6,657,673, 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 (other US/foreign patents issued and pending).
Presentation Outline

- Background
  - Development program goals
  - MWM-Array technology
  - Depth of penetration of sensing fields
  - Eddy-current extension of micromechanical model

- Example applications
  - Rotational measurements – verifying fiber orientations
  - Imaging impact damage
  - Volumetric imaging of damage
  - Stress monitoring of composites
  - Composite Overwrapped Pressure Vessel inspection and monitoring

- Summary
Development Program Approach

- **Goals**
  - Develop model-based methods for (primarily) carbon fiber composite NDT
  - Demonstrate high resolution damage and condition imaging for composites
  - Develop volumetric stress sensing magnetic stress gages for composites

- **Approach**
  - Focus on eddy current methods and sensor designs that are readily modeled.
  - MWM-Arrays uses a linear drive eddy current sensor array construct
    - Can induce eddy currents in the linear fibers of carbon fiber composites
    - In addition to using multiple frequencies, use winding geometry changes to alter penetration depth and assess material condition (e.g., damage and stress)

- **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 Instruments: GS-Durable and GS-HandHeld
Example MWM-Arrays

- 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

Slide 5

Copyright © 2013 JENTEK Sensors
All Rights Reserved.
Measurement Grids for Simplified Model

Example Grids for the MWM FS35 Sensor and Aluminum

- Phase (deg)
- Magnitude (uH)

- 10 kHz
- 1 MHz

Conductivity

Lift-Off

JENTEK Sensors, Inc.
MWM-Array Depth of Penetration

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

![Graph showing depth of penetration vs frequency and electrical conductivity.](image)

Spatial Fourier Mode Depth of Penetration = $1/\text{Re}(\Gamma_n)$

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

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

$$\mu_{\text{par}} \approx \mu_{\text{perp}} \approx \mu_0 \quad \sigma_{\text{perp}} \approx 0 \quad \sigma_{\text{par}} \approx \sigma_f v_f$$

This first order model neglects interconnections (touching) between fibers.
Composite 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 -45°, 0°, 45°, 90°)
Simple layered-Media Composite Representation

- Layup for quasi-isotropic test panel
  - Uniaxial properties for each layer
- MWM-Array sensitive to composite layers with fibers oriented parallel to drive windings
- Composite layer appeared insulating if the drive windings are NOT within several degrees of fibers
- This visualization indicates that each sensor orientation is only sensitive to a subset of plies at varying depths within the composite.

(note that the angle is relative to the fibers at the surface)
Layered-Media Composite 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 (0° and 90°), so other factors need to be considered
Volumetric Property Imaging Approach

- Combination of sensor orientation and geometry can isolate depth and region of damage
  - sensor orientation determines plies
  - sensor geometry determines depth of sensitivity
  - spatial extent of damage determined from scan image
Volumetric Imaging of Composite Impact Damage

Sample provided courtesy of Lockheed Martin

Representative MWM-Array Scan Image
Representative Quasi-isotropic Panel Scan Images

Before Impact  After Impact  Subtracted  Subtracted and Smoothed

5 MHz

Before Impact  After Impact  Subtracted  Subtracted and Smoothed

10 MHz

Before Impact  After Impact  Subtracted  Subtracted and Smoothed

15.8 MHz

Copyright © 2013 JENTEK Sensors
All Rights Reserved.
Summary of Scans

- Individual scans combined together to create composite cross-sectional view.
Cross Sectional Images: Panel 1, Low Impact Level

MWM-Array FA28 Data for 0.085-in. thick panels

Cross Sectional View along X-axis

Cross Sectional View along Y-axis

JENTEKSensors, Inc. -- - - - - - - -
Copyright © 2013 JENTEK Sensors
All Rights Reserved.
Cross Sectional Images: Panel 2, Medium Impact Level

MWM-Array FA28 Data for 0.085-in. thick panels

Cross Sectional View along X-axis

Cross Sectional View along Y-axis
Cross Sectional Images: Panel 3, High Impact Level

MWM-Array FA28 Data for 0.085-in. thick panels

Cross Sectional View along X-axis

Cross Sectional View along Y-axis
Stress Monitoring

- 4-pt bending on uniaxial specimen
- MWM-Array placed on tensile side
- Observe decrease in effective conductivity with increasing tensile load
- Frequency and channel-to-channel variations are attributed to the simplified models (conductivity/lift-off) used for this analysis

FA154, mounted to surface

Representative Specimen

FA24, pick-and-place

JEN TEK Sensors, Inc.
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.

Images:
- FA28
- FA24
COPV Rotation Measurements

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

- Eddy current scans can image both liner and composite properties
- Potential for manufacturing quality control both before and after overwrap is applied
- Surface mounted arrays can 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

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

Before Impact Damage: Angular and Axial Views

After Impact Damage: Angular and Axial Views

Baseline Subtracted:
- 30 ft-lbs ~46 mils
- 20 ft-lbs ~26 mils
- 15 ft-lbs ~22 mils
- 10 ft-lbs ~6 mils

Preliminary Filtering: Angular and Axial Views
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**
- The conductivity images show significant spatial variations in the overwrap properties
- Changes in the effective conductivity images highlight the damage

Before Impact Damage

After Impact Damage

Baseline Subtracted

Preliminary Filtering
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 and conductivity.*
Summary

- An eddy current extension to a micromechanical model has been developed for conducting fiber composites.
- Layered-media models have been developed to account for anisotropic properties in composite plies.
- Eddy current sensor arrays with linear drives have shown a capability to determine fiber orientation and image fiber density variations in the composite.
- Data fusion with scans in various orientations and/or sensor geometries can be used to develop volumetric images of damage conditions.
- Stress monitoring of composites, for use in COPVs, has been demonstrated and is under development.