Ultrasonic Characterization of Aerospace Composites

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Advanced Composites Project

• 5 Year Project:
  – Reduce timeline for certification of composite structures
    • Currently takes ~20 years from material development to market use
  – Infuse advanced tools to accelerate regulatory acceptance of advanced composites
• Partnership: NASA, FAA, DoD, Industry, University
• NDE of composites will play a key role in all three technical challenge areas:
  1. Predictive capabilities (e.g., damage progression)
  2. Rapid Inspection
  3. Enhanced Manufacturing
Composites for Space

https://www.youtube.com/watch?v=IRutJfOsgI1

130 metric tons to orbit
Composite Damage/Defect Types

X-ray CT data of microcrack damage

Micrograph showing resin rich regions and fiber misalignment

Fiber waviness (in-plane), From Kugler and Moon 2002
doi: 10.1177/0021998302036012575

X-ray CT data of microcrack damage

Micrograph showing porosity

X-ray CT of PRSEUS Joint
From NASA TM-2013-217799 by Patrick Johnston

Micrograph showing resin rich regions and fiber misalignment

UT data of delamination damage

Micrograph showing porosity

2.5 mm
ACP NDE Research

- Carbon fiber reinforced polymer composites
- NDE focus areas:
  - Inspection of complex geometry components
  - Rapid large area inspection
  - Defect/damage characterization
  - Validation of detectability
- Of-interest defect/damage types include:
  - Microcracking, fiber waviness, delamination, porosity, manufacturing variability, etc
- Experiment:
  - Thermography, ultrasound
- Simulation:
  - Enables model based inspection prediction/validation
  - Custom code, 3D simulation
Defect samples

- Delamination
- Cracking
- Overlap
- Gaps
- Waviness
- Misalignment
- Porosity
- Weak bonding
Defect samples

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Overlaps and gaps on order of 1/8” to 1/2”
Defect samples

- Delamination
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- Misalignment
- Porosity
- Weak bonding

ACC Partners
Ultrasonic approaches

• Polar scattering
  • Cracking, fiber waviness, fiber misalignment, porosity

• Phase sensitive methods
  • Weak bonding

• Guided waves
  • Delamination, fiber waviness, porosity
Polar Scattering Applications

Polar Backscatter Geometry

Fixed Polar Angle, Scan Azimuthal Angle

*Low Volume-Fraction Porosity*

Scan Polar Angle and Azimuthal Angle

*Fiber Direction at an X-Y Location*

Delaminations and Transverse Cracks
*In Same Specimen*

(Schematic data, after Declercq, et al, 2006)

(0, 0)


(20, -45)

(Schematic data, after Declercq, et al, 2006)

Quasi-Isotropic Lay-up

Quasi-Isotropic Lay-up with Misaligned Lamina

Fixed Polar Angle and Azimuthal Angle

Scan X-Y

(Fiber Orientation

(20, -45)

(Schematic data, after Bar Cohen and Crane, 1982, and others)
Array Approaches

**Curved Linear Array**

- Array: 5 MHz
- 32 Element
- 25 mm radius
- 1.3 mm pitch

**Spherical Shell 2-Dim Array**

- 2-Dimensional array can scan polar and azimuthal angles to interrogate a location to obtain data on fiber orientation, and presence of flaws such as porosity, transverse matrix cracks, in addition to delaminations

**Goals:**
- More quantitative data improves characterization of composite
- Efficiency is gained by gathering multiple scans worth of information during a single scan using one probe
Planned Work: Characterization of Fiber Waviness

- Previous work has demonstrated the principle of polar backscatter and wide-angle scattering measurements

- Work planned under ACP:
  - Understand the interdependence of ultrasonic, measurement, and composite material variables:
    - **Ultrasonic**: F-number, focal length, beam width, center frequency, bandwidth
    - **Measurement**: Polar angle, azimuthal angle, Z-offset, scattering angle, time-gating
    - **Composite material**:
      - Stacking sequence, lamina thickness, fiber and matrix material
      - Lamina depth, lamina thickness, separation of parallel lamina, surface roughness
      - Fiber waviness, micro-cracking, porosity, delamination, transverse cracks
  - Develop verified design parameters for wide-angle, curved, 2-D array probe to optimize measurement performance
  - Design, fabricate, and demonstrate 2-D array probe
  - Involves theory, experiment, and modeling and simulation
Phase based methods for quantitative adhesive bond strength measurement

• Important method of joining composite parts is through adhesive bonding
• Currently no proven method for measuring absolute bond strength
• Bonded repair currently only approved for certain factory conditions
• Quantitative bond strength measurement could allow:
  • Bond quality to be known at any point in bonded structures life
  • Detection of degraded bonds that have proved undetectable with current NDE
  • Inspection and improvement of bonding processes without needing destructive tests
Adhesive Bond Strength Monitor

- Developing an interferometric, phase-based ultrasonic technique for measuring bond strength
- Quality of adhesive bond will affect the amount of phase shift
- Received wave is compared to reference wave to determine phase shift in bonded specimen
- Much more sensitive than conventional ultrasonic measurement techniques
- Attempting to quantitatively measure adhesive bond strength

![Ultrasonic Wave Diagram]

- Phase shift due to each layer:
  - \( \phi_{\text{layer}} = \frac{4\pi L}{\lambda} \)
  - \( L \) is length of each layer, \( \lambda \) is acoustic wavelength in each layer
- Complex reflection coefficient of imperfect adhesive interface modelled as massless spring system*:
  - \( R = \frac{Z_1 - Z_2 + i\omega Z_1 Z_2}{Z_1 + Z_2 + i\omega Z_1 Z_2} \)
  - \( Z \) is acoustic impedance of each interfacing layer, \( \omega \) is angular frequency of ultrasonic wave, \( K \) is effective spring constant of interface
- Perfect interface: \( K \to \infty \)
- Complete disbond: \( K \to 0 \)
- Total phase response will be combination of phase shift in each layer and phase shift induced by imperfect interface

Guided waves

- Laser Doppler Vibrometry measurement

- Later in this session:
  - Characterizing delamination size, shape, and depth with guided wave methods (contactless measurement)

![Guided waves diagram](image)
Guided Wave Energy Trapping

- Studied previously by several authors via LDV and simple simulations
  - Prior studies focused on single layer delamination
- Current NDE methods (Cscan etc) allow for single-sided delamination sizing
  - But not single sided multi-layer damage characterization


3 Tian, Composite, single delam


6 Michaels, J; Dawson, A ; Michaels, T ; Ruzzene, M. Proc. SPIE 9064, (2014); doi:10.1117/12.2045172.
Energy Trapping Study

- Can energy trapping be leveraged for multi-ply delamination characterization?
- Simulation based study:
  - 8 ply, IM7/8552 CFRP sample \([(0/90)_2]_5\), 0.92 mm thick
  - 3 simple delamination cases: 1, 2, and 3 delaminations (+ pristine case)
  - 300 kHz, 3 cycle Hann windowed sine wave
  - \(dx=19 \, \mu\text{m}, \text{dt analysis} = 0.29 \, \mu\text{s} \ (\text{dt/200})\)
Results

• Result for cases 2 and 3: wavefields visually appear the same from top surface

Energy trapping clearly observable
Results

• Study difference in cumulative energy (KE) between cases, experimental work underway

\[ E_i(x, y, z, t) = \int_{t_1}^{t_2} \frac{1}{2} v_i^2 dt \]
Guided waves: Fiber waviness

- Plans to study methods for guided wave based techniques to detect fiber waviness
- Literature reports changes in group velocity\(^1\), 15° fiber wave → 4% change velocity (\(\square\))
- Study other processing approaches, use LDV to image wave behavior

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Conclusion

• Characterization of composite defects, degradation, and damage is of interest to NASA for aeronautics and space missions

• Advanced composites project currently focused on quantitative methods for aeronautics manufacturing and in-service defects

• LaRC NESB is performing and planning upcoming research into various ultrasonic composite characterization methods
Questions?