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=IRutJfOsgI
Composite Damage/Defect Types

- X-ray CT data of microcrack damage
- Micrograph showing resin rich regions and fiber misalignment
- X-ray CT of PRSEUS Joint From NASA TM-2013-217799 by Patrick Johnston
- Voids
- Delams
- Micrograph showing porosity
- Micrograph showing resin rich regions and fiber misalignment
- X-ray CT data of delamination damage
- UT data of delamination damage
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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![ISAAC Automated fiber placement machine](image)

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

¼ in. tape prepreg
Defect samples

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- Waviness
- Misalignment
- Porosity
- Weak bonding
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

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

Fixed Polar Angle and Azimuthal Angle Scan X-Y
Delaminations and Transverse Cracks In Same Specimen

(Measured data, NASA: Johnston et al., 2012)

Scan Polar Angle and Azimuthal Angle
Fiber Direction at an X-Y Location

Quasi-Isotropic Lay-up

Quasi-Isotropic Lay-up with Misaligned Lamina

(Schematic data, after Declercq et al., 2006)
Array Approaches

Curved Linear Array

Distance from Array

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

Aperture:
4 Element
1 element steps
29 angles (2.9° incr.)

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

\[
\phi_{\text{layer}} = \frac{4\pi L}{\lambda}
\]

\[L \text{ is length of each layer, } \lambda \text{ is acoustic wavelength in each layer}\]

- Complex reflection coefficient of imperfect adhesive interface modelled as massless spring system*:

\[
R = \frac{Z_1 - Z_2 + i\omega Z_1 Z_2}{Z_1 + Z_2 + i\omega Z_1 Z_2} K
\]

\[Z \text{ is acoustic impedance of each interfacing layer, } \omega \text{ is angular frequency of ultrasonic wave, } K \text{ is effective spring constant of interface}\]

- Perfect interface: \( K \rightarrow \infty \)
- Complete disbond: \( K \rightarrow 0 \)

- 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)

![Propagation direction](image)

![Wavenumber analysis from LDV data](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


Can energy trapping be leveraged for multi-ply delamination characterization?

Simulation based study:
- 8 ply, IM7/8552 CFRP sample [(0/90)\textsubscript{2}]\textsubscript{5}, 0.92 mm thick
- 3 simple delamination cases: 1, 2, and 3 delaminations (+ pristine case)
- 300 kHz, 3 cycle Hann windowed sine wave
- \(dx=19\ \mu\text{m}, \ dt\text{ analysis } = 0.29\ \mu\text{s} \ (dt/200)\)
• Result for cases 2 and 3: wavefields visually appear the same from top surface

Pristine

Energy trapping clearly observable

Case 1

Case 2

Case 3
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, $15^\circ$ fiber wave $\rightarrow$ 4% change in velocity
- Study other processing approaches, use LDV to image wave behavior

From: Kugler and Moon 2002
doi: 10.1177/0021998302036012575

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?