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=IRutJfOsgII

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

Micrograph showing resin rich regions and fiber misalignment

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

Voids

Delams

UT data of delamination damage

Fiber waviness (in-plane), From Kugler and Moon 2002
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Micrograph showing porosity

Micrograph showing resin rich regions and fiber misalignment

X-ray CT data of microcrack damage

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

- ISAAC Automated fiber placement machine
- Complex geometry
- Large area inspection
- Delamination
- ~2m ~3m
Defect samples

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

- Delamination
- Cracking
- Overlap
- Gaps
- Waviness
- Misaligning
- Porosity
- Weak bonding

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

¾ in. tape prepreg
Defect samples

• Delamination
• Cracking
• Overlap
• Gaps
• 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

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

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)


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

Curved Linear Array

Distance from Array

0°

-27°

27°

Polar Backscatter

Normal Incidence

Front

Glass

-30°

0°

30°

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

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

- Phase shift due to each layer:
  - \( L \) is length of each layer, \( \lambda \) is acoustic wavelength in each layer
- Complex reflection coefficient of imperfect adhesive interface modelled as massless spring system*:
  \[ R = \frac{Z_1 - Z_2 + i\omega Z_1 Z_2}{K} \frac{Z_1 + Z_2 + i\omega Z_1 Z_2}{K} \]
  - \( Z \) 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)

Propagation direction

Wavenumber analysis from LDV data
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


Tian, Composite, single delam

Michaels, Composite, simulated single delam

Energy Trapping Study

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

- Simulation based study:
  - 8 ply, IM7/8552 CFRP sample [(0/90)$_2$]$_3$, 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 μm, dt analysis = 0.29 μs (dt/200)
Results

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

Energy trapping clearly observable.

Pristine 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\(^1\), 15° fiber wave → 4% change velocity (†)
- 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?