Non-destructive Evaluation Methods for Detecting Major Damage in Internal Composite Structures

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Participants

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• Other FAA Personnel Involved
  – Larry Ilcewicz

• Industry Participation
  – Boeing, Bombardier, UAL, Delta, DuPont, JC Halpin
**Motivation**

- High energy *blunt impact damage* (**BID**) of main interest
  - involves large contact area, multiple structural elements
    - GSE, FOD, railings/corners, hail ice, bird
    - internal damage (cracked shear tie, frame, stringer heel crack) can exist with *little/no exterior visibility*
- Damage to internal members not visible by typical one-sided NDE (e.g., UT scan)
- External-only NDE needed to find such damage
Ultrasonic Guided Waves: structure is a natural “waveguide”

Wave excitation

FEA wave propagation video (top view) – click to play

FEA wave propagation video (sectional view) – click to play
Non-Contact NDE Scanning Prototype

- Line scan approach with non-contact sensors on moving carriage
- Air-coupled piezocomposite transducers (170 kHz)
Non-Contact NDE Scanning Prototype

• Typical Signal:
  • Multi-mode: A0 & S0 in Skin/Stringer
  • Time of Arrival computed from Group Velocity obtained from analysis

Gating in 6 different exploitable packets to isolate different modes

Statistical (Outlier) Analysis
Non-Contact NDE Scanning Prototype

Statistical Analysis Results:

(Skin modes only)

Cracked skin
Disbonded stringer
Detached/cracked stringer

Excellent detection: 90% POD with 0% PFA
Excellent detection: 93% POD with 0% PFA
Ok detection: 90% POD with 20% PFA
Non-Contact NDE Scanning Prototype

Outlier Analysis Results:
(Skin + Stringer modes)

ROC curves for performance assessment

- Cracked Skin
- Detached/Cracked Stringer
- Disbonded Stringer

Perfect detection
Mini-Impactor (probes interior + portable)

- Frequency range up to 500 kHz and peak intensity at 42 kHz

Aluminum Tip – 0.56 mm thick
Uni-directional Carbon/Epoxy [0]_8 Layup; 0.56 mm thick

Impact Tip 5.1 mg FFT Plot

Amplitude (V)

Frequency (Hz) × 10^5

6.35 mm

102 mm
Mini Impactor on Built-up Panel

- Excitation and measurement (R15 contact transducer) on exterior skin-side
- S0 waves through skin path move faster (~150 kHz);
- A0 waves through C-frame path move slower (~50 kHz);
- Specimen with C-frame removed has only skin modes content
Mini Impactor on Built-up Panel

- Internal shear tie damage detection using mini-impactor excitation
GUIDED WAVE MODELING: S.A.F.E.

\[ u^{(c)}(x, y, z, t) = \sum_{j=1}^{n} N_j(y, z)U_{x_j} \]

Forced solution

\[ \mathbf{u}^{(c)}(x, y, z) = N(y, z)\mathbf{q}^{(c)}e^{i(\xi-x\omega t)} \]

Unforced solution

\[ \mathbf{A} - \xi \mathbf{B} \mathbf{Q} = 0, \]

Dispersion curves & mode shapes

Forced solution

\[ U(x_R) = -\frac{1}{2\pi} \sum_{m=1}^{2M} \left( \xi^m U_L^m \right)^T \frac{F_n U_R^m}{D_m} \int_{-\infty}^{\infty} \frac{1}{(\xi - \xi^m)} e^{i\xi(x_R-x_S)} d\xi \]
S.A.F.E. Results: CFRP skin + stringer

Stiffened Panel: Stringer Disbond Damage

- Wave propagation direction: 90° (across the stringer)
- Layup: 33 plies (Skin & Stringer)
- Lamina Properties: T800/3900-2 Unidirectional Tape

Dispersion Curve: New Panel, 33 layers, x=90°

 Laminate Properties: C reduced to 0.1 C for Plies 16, 17, 18
S.A.F.E. Results: CFRP skin+stringer

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- S0 modeshape
- A0 modeshape
Residual Strength Estimation: Wave Scattering

- Simple beam with through holes from 0.05 mm to 50 mm dia
- Mesh size = 1mm, Time step = 5e-8 sec, Exc = 2.5 cycle toneburst at 150 kHz
Empirically determine the exponential value $e$, and relate values to estimate residual strength

$$\text{Wave Amplitude} = (\text{Dam Size})^e \quad \Rightarrow \quad \frac{\sigma_{\text{crack}}}{\sigma_{\text{pristine}}} = \left(\frac{L_0}{\text{Dam Size}}\right)^m \quad \text{[Caprino]}$$

Residual Strength Estimation: Validation

- Three new stringer panels fabricated
  - T800/3900-2 uni-directional tape plies. Skin thickness = 3.175mm
  - Panel dimensions: 1m x 1.3m
  - Five stringers with 0.26m spacing
  - Various impact energy levels

Impact Locations

A (stringer flange)

B (stringer cap)
Thermography for Independent Damage Survey

Thermography (TSR): ground truth of damage for quantitative damage survey

Dent 1:
Energy Level = 30 J

Dent 2:
Energy Level = 50 J
Ongoing/Future Work

• Package mini-impactor into scanning system to probe interior structure for damage (shear ties and C-frames)

• Continue S.A.F.E. modeling of guided waves to select specific mode-frequency combinations highly sensitive to specific damage

• Conduct additional FE analyses of wave scattering through relevant damage types/severity for residual strength estimation from the guided wave measurements

• Validate residual strength predictions from wave measurements through failure tests of impacted panels
EXTRA SLIDES
Statistical Analysis

- Outlier Analysis:
- Multivariate
- Multi-mode

Super-Vector for mode compounding

Baseline Signal
(six possible time gates)

Test Signal
(six possible time gates)

Feature Super-Vector

\[ \chi = \left\{ \begin{array}{l}
\text{Max Ampl} \\
\text{Max Ind} \\
\text{Variance} \\
\text{Kurtosis} \\
\vdots \\
\text{Max Ampl} \\
\text{Max Ind} \\
\text{Variance} \\
\text{Kurtosis} \\
\vdots \\
\text{Max Ampl} \\
\text{Max Ind} \\
\text{Variance} \\
\text{Kurtosis} \\
\end{array} \right\}_{m_1}
\]

Baseline Vector
Average, Covariance
\[ \bar{x}, C \]

Known Undamaged Region:
Any Location

Test Vector
\[ \chi \]
Any Location

Damage Index (DI) :
(Mahalanobis Squared Distance)

\[ (x - \bar{x}) + C^{-1} + (x - \bar{x})^T \]

threshold

Sample number

If DI > threshold \( \Rightarrow \) DEFECT
New Stringer Panel Response Study

- Green’s Function Approach
  - To extract structural behavior/response
  - To apply inversion methods for damage and structure characterization
    - residual strength estimation
  - Semi Analytical Finite Element (SAFE) Method
    - FE discretization and problem formulation (material & geometry)
    - Normal mode decomposition of guided waves (eigenvalue problem)
    - Analytical solution of wave propagation in space and time

Forced Solution: arbitrary force (in space and time)

\[
\hat{F} = \int_{-\infty}^{\infty} F(x) e^{-i\xi x} dx, \quad \hat{U} = \int_{-\infty}^{\infty} U(x) e^{-i\xi x} dx
\]

\[
U(x_R) = -\frac{1}{2\pi} \sum_{m=1}^{2^M} \left( \xi^m L_u^m \right)^T F_n U_R^m \int_{-\infty}^{\infty} \frac{1}{D_0} \int_{-\infty}^{\infty} \frac{1}{(\xi - \xi^m)} e^{i\xi(x_R-x_s)} d\xi
\]

\[
U(x_R, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} U(x_R) e^{i\omega t} d\omega
\]

Panel Complexity Testing: External v. Internal UGW Transmission

- Wave transmission energy comparison between internal path (shear tie & C-frame) vs skin path shows 50 kHz wave energy is better transmitted internally compared to the exterior skin transmitted wave energy relative to 150 kHz.
Mini Impactor on Composite Panel

- Gating of time signal important for capturing different modes of interest – specifically those passing through frame.
- FFT shows clear sensitivity to disrupted path (C-frame detached at bolts to represent being fully cut)

Panel Exterior View

Skin Path

Skin + Stringer Path

Shear Tie + C-Frame Path

Panel Underside View

Disrupted path through C-Frame shows clearly in ~50 kHz range.
SAFE Results: CFRP skin

Stiffened Panel: Skin Surface Damage
- Wave propagation direction: 90° (across the stringer)
- Layup: 16 plies (Skin only)
- Lamina Properties: T800/3900-2 Unidirectional Tape

Dispersion Curves: New Panel, 16 plies, x=90°
Laminate Properties: C reduced to 0.1 C for Plies 1,2,3
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A0 modeshape

S0 modeshape
Residual Strength Estimation: Wave Attenuation Based

- Amplified out-of-plane displacement to observe A0 wave mode propagation around the hole notch
- Notch diameter = 30 mm
Flat Stringer Panel Impact Plan

- Stringer cap impacted portion will be trimmed into 0.3m specimens for compression w/o buckling
- Stringer flange impacted portion will be trimmed into 0.48m specimens for compression w/ buckling