Health Monitoring Methods for Joints in Rotorcraft Composite Structures

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http://www.sikorsky.com/
Pull bending test

(a) Debonding initiation

(b) Delamination propagation

(c) Final failure

Luo et al. (2012)

Push bending test

(b) Further matrix cracking in curved webs

(c) Matrix cracking and fibre fracture in bottom plate

(d) Final failure
• Material
  - Carbon-fiber-reinforced polymer, for example AS4/8552 [0\45\90\-45]_{s2}

• Structure configuration (cross-section)
Transmitted Energy for Incident Mode 1

Transmitted Energy for Incident Mode 3

Frequencies corresponding to poor transmission.
Structural Health Monitoring of Joints in Composites

Aaron Lesky, Kyle Salitrik, Cliff J Lissenden, Joseph L Rose

Farhad Mohammadi, Advanced Cerametrics Inc.

National Science Foundation, CMMI, Sensors and Sensing Systems
Monitoring microstructural evolution of Alloy 617 with nonlinear acoustics for remaining useful life prediction

Yang Liu, Vamshi Chillara, Xiaochu (Frank) Yao, Gloria Choi, Brett Corl, John Weigle, Cliff J Lissenden

Nuclear Energy Universities Program, DoE
Second harmonic generation is sensitive to microstructural features of the material.

In this example, Cantrell and Yost, 2001 [Int J Fat 23:S487-S490] showed a monotonic increase in $b$ with cycling that correlates well with increase in dislocation dipoles.

Variability in $b$ values suggests localization.

Other examples include precipitates and radiation embrittlement.
Cumulative second harmonics increase linearly with propagation distance.

\[ \sigma = E\varepsilon \left(1 + \frac{1}{2}\beta\varepsilon\right) \]

\[ u = u_1 + u_2 \]

\[ u_1 = A_1 \sin(kx - \omega t) \]

\[ u_2 = \frac{\beta}{8} (A_1 k)^2 x \cos(2(kx - \omega t)) \]

\[ A_2 = \frac{\beta}{8} (A_1 k)^2 x \]

The cumulative nature makes it possible to experimentally identify material nonlinearity from other sources of nonlinearities.
Weakly nonlinear material response deviates only slightly from linear elastic, but enables higher harmonic generation.

\[ T_{RR} = \lambda tr\{E\} I + 2\mu E + C(tr\{E\})^2 I + B tr\{E^2\} I + 2B tr\{E\} E + A E^2 \]

Strain energy function truncated after cubic term instead of after quadratic term: hyperelastic material model
Internal resonance points enable primary mode selection for Lamb and Shear-Horizontal waves in steel plates.

Internal resonance points are tabulated. Also important are mode excitability and group velocity matching.
Internal resonance points enable primary mode selection for Lamb and Shear-Horizontal waves in steel plates.

<table>
<thead>
<tr>
<th>Internal Resonance Point</th>
<th>Mode Pair</th>
<th>Frequency-Thickness (MHz-mm)</th>
<th>Phase Velocity (mm/ms)</th>
<th>Group Velocity (mm/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1/S2</td>
<td>3.85</td>
<td>5.96</td>
<td>4.88/4.86</td>
</tr>
<tr>
<td>2</td>
<td>S2/S4</td>
<td>7.70</td>
<td>5.96</td>
<td>4.86/4.98</td>
</tr>
<tr>
<td>3</td>
<td>SH0/S0</td>
<td>1.72</td>
<td>3.23</td>
<td>3.23/4.43</td>
</tr>
<tr>
<td>4</td>
<td>SH1/S1</td>
<td>1.92</td>
<td>5.96</td>
<td>1.74/4.86</td>
</tr>
<tr>
<td>5</td>
<td>SH2/S2</td>
<td>3.85</td>
<td>5.96</td>
<td>1.75/4.92</td>
</tr>
<tr>
<td>6</td>
<td>SH3/S3</td>
<td>5.78</td>
<td>5.96</td>
<td>1.74/5.09</td>
</tr>
<tr>
<td>7</td>
<td>SH3/S4</td>
<td>5.46</td>
<td>7.09</td>
<td>1.45/2.78</td>
</tr>
</tbody>
</table>

Power flux occurs through gradients in displacement field.

The number of Lamb wave internal resonance points is extremely limited. SH primary modes generate cumulative symmetric Lamb modes.
Internal resonance points enable primary mode selection for Longitudinal and Torsional waves in steel pipes.

Axisymmetric L and T modes in pipe approach Lamb and SH waves in plate in the asymptotic limit.

[Chillara and Lissenden, 2013, Ultrasonics]
Displacement profiles in pipes are not symmetric/anti-symmetric.

\[ f_d = 3.85 \text{ MHz-mm and } c_p = 5.96 \text{ mm/ms} \]

Parity analysis not possible, but the nature of L and T modes enables us to conclude that primary L and T modes can generate cumulative L, but not T, second harmonics. [Liu et al., 2013 in-press]
Internal resonance points enable primary mode selection for Longitudinal and Torsional waves in steel pipes.

<table>
<thead>
<tr>
<th>Internal Resonance Point</th>
<th>Mode Pair</th>
<th>Frequency-Thickness (MHz-mm)</th>
<th>Phase Velocity (mm/ms)</th>
<th>Group Velocity (mm/ms)</th>
<th>Normalized Power Flux Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>L(0,4)/L(0,5)</td>
<td>3.85</td>
<td>5.96</td>
<td>4.86/4.92</td>
<td>2.81×10^4</td>
</tr>
<tr>
<td>2</td>
<td>L(0,5)/L(0,9)</td>
<td>7.70</td>
<td>5.96</td>
<td>4.92/5.18</td>
<td>1.36×10^5</td>
</tr>
<tr>
<td>3</td>
<td>L(0,2)/L(0,3)</td>
<td>2.28</td>
<td>4.57</td>
<td>2.32/2.31</td>
<td>1.35×10^{-3}</td>
</tr>
<tr>
<td>4</td>
<td>L(0,3)/L(0,6)</td>
<td>4.56</td>
<td>4.57</td>
<td>2.31/2.34</td>
<td>2.18×10^{-2}</td>
</tr>
<tr>
<td>5</td>
<td>L(0,4)/L(0,8)</td>
<td>6.84</td>
<td>4.57</td>
<td>2.31/2.38</td>
<td>3.63×10^2</td>
</tr>
<tr>
<td>6</td>
<td>L(0,1)/L(0,1)</td>
<td>0.15</td>
<td>1.73</td>
<td>0.85/2.34</td>
<td>2.68×10^{-6}</td>
</tr>
<tr>
<td>7</td>
<td>T(0,1)/L(0,2)</td>
<td>1.72</td>
<td>3.23</td>
<td>3.23/4.43</td>
<td>1.29×10^2</td>
</tr>
<tr>
<td>8</td>
<td>T(0,2)/L(0,4)</td>
<td>1.92</td>
<td>5.96</td>
<td>1.74/4.86</td>
<td>4.10×10^3</td>
</tr>
<tr>
<td>9</td>
<td>T(0,3)/L(0,5)</td>
<td>3.85</td>
<td>5.96</td>
<td>1.75/4.92</td>
<td>1.27×10^4</td>
</tr>
<tr>
<td>10</td>
<td>T(0,4)/L(0,7)</td>
<td>5.78</td>
<td>5.96</td>
<td>1.74/5.09</td>
<td>5.47×10^4</td>
</tr>
<tr>
<td>11</td>
<td>T(0,2)/L(0,3)</td>
<td>2.28</td>
<td>4.57</td>
<td>2.27/2.31</td>
<td>1.23×10^1</td>
</tr>
<tr>
<td>12</td>
<td>T(0,3)/L(0,6)</td>
<td>4.56</td>
<td>4.57</td>
<td>2.27/2.31</td>
<td>2.36×10^2</td>
</tr>
<tr>
<td>13</td>
<td>T(0,1)/L(0,1)</td>
<td>0.06</td>
<td>3.23</td>
<td>3.23/4.97</td>
<td>1.62×10^{-6}</td>
</tr>
</tbody>
</table>

l= 116.2 GPa, m = 82.7 GPa, A = -325 GPa, B = -310 GPa, and C = -800 GPa
r = 7932 kg/m³
SH1/S1 mode pair is cumulative: transient dynamics finite element simulation.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>0</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>u_y</td>
<td>0</td>
<td>5 x 10^{-7}</td>
<td>0</td>
</tr>
<tr>
<td>u_z</td>
<td>0</td>
<td>1 x 10^{-9}</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>0</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>u'_y</td>
<td>0</td>
<td>1 x 10^{-7}</td>
<td>0</td>
</tr>
<tr>
<td>u'_z</td>
<td>0</td>
<td>1 x 10^{-10}</td>
<td>0</td>
</tr>
</tbody>
</table>

SH mode

Lamb mode

d = 1.5 mm
f_0 = 1.28 MHz
I.R. Point 5

receiver

IDT
T(0,2)/L(0,4) mode pair is cumulative: transient dynamics finite element simulation.

**IDT**

- Torsional mode
- Longitudinal mode

**Receiver**

\[ d = 1.5 \text{ mm} \]
\[ f_0 = 1.28 \text{ MHz} \]

I.R. Point 8
Finite element results demonstrate that both mode pairs SH1/S1 and T(0,2)/L(0,4) are internally resonant.

**PLATE:** SH1/S1 cumulative z-component of displacement

**PIPE:** T(0,2)/L(0,4) cumulative z-component of displacement

Propagation distance in simulation is limited by large number of DOFs in model.
Selection of primary modes is critical to generate cumulative secondary guided wave modes in plates and pipes.

• Internal resonance points were tabulated for both plates and pipes
• SH modes can generate cumulative symmetric Lamb modes
• Torsional modes can generate cumulative Longitudinal modes
• Finite element simulation demonstrates that the secondary modes are indeed cumulative

TO DO:
• Experimental verification
Experiments with magnetostrictive transducers are ongoing and have great potential.
High Temperature Transducers for Online Monitoring of Microstructural Evolution

Kyle Sinding, Brian Reinhardt, Alison Orr, Yang Liu, Cliff J Lissenden, Bernhard Tittmann

Nuclear Energy Universities Program, DoE
BT/LN sol gel processed spray-on piezoelectric transducer

Multi-element transducer from laser ablation to provide mode control for nonlinear ultrasonic guided waves