Acoustic Characterization of Materials

Bernhard R. Tittmann
Group Leader
Acknowledgement

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  - J. SAKAMOTO, Visiting Grad. student, Aeronautical Institute, Brazil
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  - DR. M. KROPF, Research Associate, Penn State
Problem Statement

- Aircraft engine turbine and fan disk cracks have led to disk burst and catastrophic engine failures:
  - Air Florida Airlines 2198 – takeoff aborted

Part of the DC-10's fuselage after the crash.

Damaged Engine of N927DA
What are the Applications?

- Characterization of flaws is an important goal of ultrasonic NDE in aircraft
- Structural health monitoring to achieve retirement for cause.

- Aluminum wings/fuselage
- Composite components
- Turbines
- Steam pressure pipes/vessels
- Aircraft Disc brakes
OUTLINE

1. Intro
2. Detection of impact damage in fiber-reinforced composites
   - non-contact laser based ultrasound
   - hard and soft impacts
   - variety of composites
3. Detection of fatigue cracks in jet engine components.
   - in-situ high-temperature
   - sol-gel spray-on coatings
   - single crystals of transducers
4. Conclusion
Noncontact/remote NDE with Laser Based Ultrasound

- Lab system:
- Nd:YAG laser model Surelite I (Continuum) 1064 nm fundamental/2nd harmonic 532 nm.
- Mach-Zehnder Laser Interferometer (35 MHz)

**Critical Issues**

1. Control of Laser Power
2. Ultrasound beam profile
3. Damage to structure surface
4. Trigger timing for Signal Processing
Laser energy (34mJ-430mJ) as function of Q-switch delay.

\[ y = 0.0000000002799762073016x^6 - 0.00000004101850786783650x^5 + 0.00002366368033544640000x^4 - 0.00667252097642860000000x^3 + 0.90376561597524900000000x^2 - 45.60035294681510000000000x + 243.34249768786700000000000 \]
Set up with Nd-YAG Laser shutter, mirrors, Al target & Mach-Zehnder Interferometer.
Nd:YAG: 10 Hz rep. rate, Q-switch delay 117 µs, 200 mJ energy; pulse width ~15 ns. Laser beam unfocsd diam. $w = 3.42$ mm; area $S = 0.092$ cm$^2$. Laser fluence 2.18 J/cm$^2$; detection with Interferometer
LONGITUDINAL/SHEAR ARRIVALS VS LASER ENERGY.

![Ultrasound signal graph](image)

- Various laser energy levels (E) are shown, with different markers indicating different energy levels:
  - E = 29 mJ (dotted red)
  - E = 51 mJ (dotted purple)
  - E = 104 mJ (dotted black)
  - E = 154 mJ (dotted green)
  - E = 200 mJ (dotted blue)
  - E = 250 mJ (dotted cyan)
  - E = 301 mJ (dotted light green)
  - E = 349 mJ (dotted yellow)
  - E = 402 mJ (dotted light orange)
  - E = 445 mJ (dotted light red)

Graph parameters:
- Displacement [nm]
- Time [s] (labeled as 10^6 x 10^6)
Some ablation even at minimum Fluence

• Spot radius $w = 1.75 \text{ mm}$ and area $S = 0.096 \text{ cm}^2$

(A) Min Fluence= 0.34J/cm$^2$;  
(B) 0.45 J/cm$^2$;  
(C) 0.89 J/cm$^2$.

Close-up; Scale: >——— 2mm
LBU Evaluation

- Longit wave ampl. vs laser energy (top) vs fluence (bott)
Signal Processing

Delay: after Nd:YAG shot there is trigger delay of 103 ns until laser beam effectively impinges the sample.

To avoid this delay the trigger provided by the photo-detector was chosen as trigger source.

Signal processing:
- Short-Time Fourier Transform (STFT)
- Continuous Wavelet Transform (CWT)
- Noise reduction Stationary Wavelet Transform (SWT)
Soft Body Impact On PEEK Composites

- Specimens: AS4/PEEK (APC-2/AS4, ICI-Fiberite) and AS4/PEEK+IL
- Lay-ups: (0/+30/0/-30)s, (0/+60/0/-60)s, (0/+45/90/-45)s.

- Flat specimens were cut to 100 x 100 mm
- Thicknesses were approximately 3 mm.

- Gun (H. Morita, Virginia Tech Univ)
- Gelatin and Al bullet
- Velocity 90-190 m/s

- Ultrasonic C-Scan system (ULTRAN NDC700).
- 10 MHz transducer with a focal length of 12 mm and diameter of 9.6 mm
- Focus on backsurface
C-Scan Images of Subsurface Gelatin Bullet Impact Damage (No visible mark on surface)

<table>
<thead>
<tr>
<th>Stacking Sequence</th>
<th>AS4/PEEK</th>
<th>AS4/PEEK + IL</th>
</tr>
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<tbody>
<tr>
<td>(0/30/0/-30)s</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>(32.1J, 146.1m/s)</td>
<td>(30.8J, 143.5m/s)</td>
</tr>
<tr>
<td>(0/60/0/-60)s</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
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<tr>
<td></td>
<td>(32.5J, 146.8m/s)</td>
<td>(34.5J, 151.1m/s)</td>
</tr>
<tr>
<td>(0/45/90/-45)s</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td></td>
<td>(40.4J, 163.2m/s)</td>
<td>(34.3J, 150.7m/s)</td>
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Scan Area = 80x80mm
0 deg
Comparison Damage Area versus Impact Energy: soft impact has lower damage threshold and slope than Al bullet impact.

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\(\Delta----: \text{High velocity impact} \quad \bullet----: \text{Gelatin impact} \)
Acoustic Microscope Image of C/C composite after Carbonization showing transverse cracks and delaminations
Acoustic Emission through long wire waveguides
The projected damage areas were measured with an ultrasonic C-scan system. 

- Heat-up of Carbon-Carbon in Autoclave with severe fracture at 200°C.
- AE detected remotely through wire waveguide.
Magnetostrictive Sensing

- **Joule Magnetostriction**
  - Pulsed current in coil = dynamic magnetic field (Solenoid)
  - Interaction with static magnetic field (marker)
  - Strain (ultrasonic waves) generated in waveguide

- **Wiedemann Effect Magnetostriction**
  - Pulsed current through waveguide (Circular magnetic field)
  - Interaction with static magnetic field (marker)
  - Strain (ultrasonic waves) generated in waveguide
Remote Temperature Sensing

- Due to guided wave principles, ultrasound can be sent over long distance through a wire waveguide

- Wave velocity is a function of temperature
  - Measure changes in time-of-flight to calculate temperature inside furnace

Material Comparison

![Experimental Results Molybdenum](image)

- Change in time (us)
- Temperature (°C)
- Runs 1, 2, 3

![Graphs showing temperature vs. run results](image)
Remote Temperature Sensing

- Hostile environments can restrict what type of sensors can be used
- Conventional transducers cannot be used at high temperatures

![Diagram showing various materials and their electromechanical properties](image)

- NBT: Na$_{0.5}$Bi$_{4.5}$Ti$_4$O$_{15}$
- CBT: CaBi$_4$Ti$_4$O$_{15}$
- LGS: La$_3$Ga$_5$Si$_4$O$_{14}$
- LGT: La$_3$Ga$_{5.5}$Ta$_{0.5}$O$_{14}$

(s) single crystal, (c) poly crystal, (tex) textured crystal, (f) film
Lithium Niobate crystal bonded to steel

Graph showing the temperature history of LiNbO3 with different bonds (B1, B2, B3). The graph plots temperature in degrees Celsius against time in hours, with a logarithmic scale for voltage in volts.
SAWs generated by removable transducer

- 6 mm thick titanium alloy (ASTM B-265) bar.
- Tone burst at 2.2 MHz, pulse width 7.94 μs,
- Travel distance: 183 mm.
High Temperature Transducers

- Aluminum Nitride Single Crystal Wafer
High Temperature Transducer

- Aluminum Nitride (AlN) candidate for high temperature transducers
  - Piezoelectric due to AlN’s crystal structure
  - Crystal structure stable to ≥ 1800°C
  - Produces strong, clean waveform over large T-range

- Carbon-carbon is an attractive candidate for backing material
  - High damping
  - High conductivity allows simplified electrical connections
Bismuth Titanate

- Chemical Formula: Bi$_4$Ti$_3$O$_{12}$
  - Ferroelectric material with a layered perovskite-like crystal structure
    - Am-1Bi$_2$MmO$_{3m+3}$ (m=3)
  - Originally fabricated through powder sintering
    - Starting powders: Bi$_2$O$_3$ and TiO$_2$
    - Sintered at around 800 – 900°C
  - Technique of Sol-gel spray deposition has recently been developed

- Measured $d_{33}$ of 12 pC/N
- Performance at $T>800$C
Sol-Gel Bismuth Titanate

Time Domain Signals: 550 - 600 C

Voltage (V) vs. Time (x 10^-5)

- 550 C
- 600 C
- 650 C
Spray-on sol-gel piezoelectric ultrasonic transducers for online health monitoring at high temperatures

Bismuth titanate-lithium niobate composite transducer voltage as a function of temperature

Functional spray-on bismuth titanate transducer on curved turbine blade fin
Conclusions

- Developed several approaches for ultrasonic damage detection in aircraft components for structural health monitoring

- Described 3 ultrasonic sensor techniques
  1. Laser ultrasound
  2. Wire waveguide for active and passive NDE
  3. High T piezoelectric transducers

- High temperature capability demonstrated to ~1000°C

- Preliminary results appear promising