MATERIALS CHARACTERIZATION USING LASER ULTRASONIC GUIDED WAVES

NDCM XII VA Tech
June 19 to 24, 2011

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Maryland, USA

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COMPOSITES HAVE A LONG HISTORY*

The composite bow.

The ancient Egyptians used several different types of bows. The two most common varieties were the self bow, made of one piece of wood, and the laminated composite bow.

The composite bow was introduced to Egypt from Western Asia probably around 1700 BC. It was made of layers of different materials, such as wood, horn and sinew. It was superior to the self bow and could hit a target at a distance of some 250 m. The bow had a characteristic double-curve shape which became triangular when strung (the ends were bent back when the bow was being strung).

The photograph shows a self bow (top) and five composite bows from the tomb of Tutankhamun. H. Burton photo. 484. © Griffith Institute, Ashmolean Museum, Oxford.

* www.griffith.ox.ac.uk
Hooke’s law: stress $\sigma$ is applied

$\varepsilon = s \sigma$, where $s$ is compliance

strain $\varepsilon$ is imposed

$\sigma = c \varepsilon$, where $c$ is stiffness

More generally for composite:

all of the tensor components of strain or stress are applied

$$\varepsilon_{ij} = S_{ijkl} \sigma_{kl}$$

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl}$$

$S_{ijkl}$ and $C_{ijkl}$ matrix contains $9 \times 9 = 81$ components.
Issues with Structural Materials Diagnostic

MATERIAL DAMAGE DIAGRAM

NDT REQUIREMENTS PREDICTION PATH:
Model material damage from micro to macro to structural effects.

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Laser Ultrasonic Guided Wave Test Setup

Guided wave source
(Time 0)

Test panel

Formed laser source

Test “Gage” Length

Laser or contact detector

Amplifier

Traveling wave

Nd:YAG pulsed Laser

Data acquisition and signal processing

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Stress-waves are mechanical phenomena, in NDE stress-waves can directly sense the mechanical state of the materials.
Sensing Transducer Performance

PIN Transducer

MINIATURE Transducer

40 Degree Conventional Wedge

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SIGNAL METAL, Al 7075-T6 (0.063 in, 1.63 mm thick)
SIGNAL METAL, Al 2024-T3 (0.123 in, 3.16 mm thick)
Laser Ultrasonic Guided Waves

Five Laser Impulses

Time 5.6 µs

Composite Plate

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LASER ULTRASONIC GUIDED WAVE TESTING OF COMPOSITES

**Materials Properties Measurements**

**TEST ASSUMPTIONS:**

• **SOUND VELOCITY** $V_{xy}$ **RELATES TO COMPOSITE DIRECTIONAL MODULUS VIA**

$$E_{xy} = k \times V_{xy}^2$$

where $k$ is specific materials constant

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**Measuring $V_{xy}^2$ Enables Direct Sensing of the Composite Material Elastic Modulus**

• Depending on “Guided Wave” modes, different material parameters control $V_{xy}$.

• The test sample measurements' are examples of fiber and overall average plate material dominated properties.
Elastic Modulus:

Homogeneous, Isotropic:

\[ E = \rho V_L^2 \left[ \frac{(1+\nu)(1-2\nu)}{(1-\nu)} \right] \]
\[ G = \rho V_s^2 \]

Homogeneous, Orthotropic (Plane Strain):

\[ E_1 = \rho V_L^2 (1-\nu_{12}\nu_{21}) \]
\[ G_{13} = \rho V_s^2 \]
### Performance estimates for the guided wave composite characterization

<table>
<thead>
<tr>
<th>GAUGE PATH, FLAT SURFACE</th>
<th>PATH ERROR</th>
<th>PATH ERROR</th>
<th>TIME INTERVAL $\Delta T$ in $\mu$s</th>
<th>DIGITIZER ERROR</th>
<th>FIRST ARRIVAL</th>
<th>PEAK ARRIVAL</th>
<th>ZERO CROSSING</th>
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<tbody>
<tr>
<td>mm</td>
<td>+ / - mm</td>
<td>%</td>
<td>ASSUMED $V = 10$ mm/$\mu$s</td>
<td>+ / - 4 ns</td>
<td>+ / - 50 ns</td>
<td>%</td>
<td>+ / - 4 ns</td>
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<td>0.10 %</td>
<td>0.04 %</td>
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<td>15,000</td>
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<td>0.33 %</td>
<td>0.13 %</td>
<td>0.053 %</td>
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<tr>
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<td>0.1 %</td>
<td>10,000</td>
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<td>0.20 %</td>
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<tr>
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<td>5,000</td>
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<td>0.40 %</td>
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<tr>
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<td>0.05</td>
<td>0.4 %</td>
<td>2,500</td>
<td>0.32 %</td>
<td>2.0 %</td>
<td>0.80 %</td>
<td>0.32 %</td>
</tr>
</tbody>
</table>

### WAVEFORM ANALYSIS TIME TEST POINTS

- Zero crossing most reproducible
- Measurements capable of resolving changes as small as $1\text{in}10^3$ to $1\text{in}10^4$
- Bi-static transmit/receive configuration
- Conventional methods cannot achieve such accuracy

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Direct Sensing of the Composite Materials Elastic Modulus
Plot of first arrival velocity square vs measured modulus for samples D, E, F and G
Direct Sensing of the Composite Materials
Elastic Modulus

Directional change of V in unidirectional composite materials
Kevlar Composite tape UT Guided Wave Velocity Tests

KEVLAR STRIP IN THE TENSILE LOAD FRAME

Plot of sound speed as function of strain for the two test runs.

1 in grips were used to hold 1½ in wide strip of Kevlar material.

The overall strip length between grips was 38 cm.

Ultrasonic guided wave test path was 57.99 mm between laser source and receiving transducer roughly in the middle section of the sample.
Velocity maps on the fatigued bottles. Bottle No 61 is considered a virgin sample.
Ultrasonic measurements are in materials plane \((x/y\) axis\) of the composite and not in thickness \((z\) axis\) direction.

Measurements utilize unconventional transducers:
- **laser** ultrasonic wave source
- air coupled receivers
- miniature sub-wavelength transducers receivers.

Tests from one side, on surface, capture full ultrasonic signatures.

Ultrasonic signals are complex guided waves:
- separated into material dependent
- geometry dependent
- structure \((\text{path})\) dependent components.

Signal amplitude and signal time resolution significantly improved over conventional ultrasonic, captured and analyzed with recently available digitizing capabilities, processed via new signal analysis methodology.

The measurements reported are new and cannot be reproduced using conventional ultrasonic methodology.
SUMMARY

• Ultrasonic in-plane guided wave propagation is complex process (especially in composites) but it can enable in-plane material properties characterization.

• Ultrasonic transduction process is critical for validity and quality of the in-plane test measurements.

• A reproducible and robust laser-generation and sub-wavelength transducer sensing methodology/technology has been developed for the sensing of the materials properties.

• Laser ultrasonic guided waves tools enable one sided surface access measurements for the materials characterization. (Very useful)

• In-plane guided waves can measure mechanical modulus of the materials.

• Experimental test confirm the utility of the methodology for the materials properties sensing.
Conclusions

New and improved transduction methodologies have enabled better guided wave control and more accurate sensing options.

Computers have enabled better data collection at higher frequencies with friendlier user interface.

New test modalities and remote sensing provides significant advantages over conventional ultrasonic NDC methods.

THE IMPACT

We can sense and measure materials information that was considered inaccessible.