“redefining the limits of ultrasound”

Non-Contact Ultrasonic Inspection for Continuous Feedback in Manufacturing

JEC Europe
Paris

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We will explore non-contact ultrasound (NCU), the advantages of continuous inspection and applicability of NCU to composite analysis

<table>
<thead>
<tr>
<th>Topic Agenda</th>
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<tbody>
<tr>
<td><strong>1. Non-Contact Ultrasound (NCU)</strong></td>
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<td>• Significant advancements in non-contact ultrasound now allow for analysis of composite and other materials in the early stages to final stages of their formation</td>
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<td><strong>2. Continuous Inspection in Production</strong></td>
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<td>• Continuous feedback in production has tremendous benefits for waste reduction, process enhancement, and product improvement</td>
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<td><strong>3. Correlation of NCU Amplitude to Material Properties</strong></td>
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<td>• A relationship can be established to correlate the material property of interest with ultrasonic measurements</td>
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<td><strong>4. Applying NCU for Continuous Inspection in Production</strong></td>
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<td>• Application of NCU to continuous production allows for a safe, reliable, and relatively inexpensive way to save money, improve manufacturing and performance, and gain competitive advantage</td>
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Significant advancements in non-contact ultrasound allow for high performance and widespread applicability

**Elements of Non-Contact Transducers***

- Transition layer and matching layers provide efficient transmission through air
- Optimized for frequencies between 50 kHz and 5 MHz
- Gas matrix piezoelectric (GMP)* composite allows for enhanced performance at frequencies between 50 kHz and 500 kHz
- High quality results achieved with many composite materials

*US and International Patents
Through transmission is the most applicable and robust method of non-contact analysis.

- Direct transmission route
- Thickness reflection route
- Material surface reflection route
- Transmitter side surface reflection
- Receiver side surface reflection
For most analyses in non-contact ultrasound, it is easiest to use the direct transmission route.
The key ultrasonic measurement through non-contact through transmission is attenuation or transmittance.

**Transmittance in Material, $T_m$ (dB)**

$$T_m = T_c - T_a$$

$T_c$ (dB) transmission in air + material
$T_a$ (dB) transmission in air column

Material Transmittance is related to material texture, Z, homogeneity, and other physical characteristics.
Material Velocity is often directly related to material density

**Material Velocity, \( V_m \) when thickness is known**

\[
V_m = \frac{d_m}{t_{am} - (t_a - t_c)}
\]

- \( d_m \): material thickness
- \( t_{am} \): tof in air corresponding to \( d_m \)
- \( t_a \): tof in air
- \( t_c \): tof in air + material
- \( V_a \): air ultrasound velocity

\[
t_{am} = \frac{d_m}{V_a}
\]

**Material Velocity, \( V_m \) when thickness is known**

\[
V_m = \frac{d_m}{t_{am} - (t_a - t_c)}
\]

\[
d_m = V_a \times t_{am}
\]

- \( t_1 \): round trip tof from transducer 1 to materials surface
- \( t_2 \): round trip tof from transducer 2 to material surface

**Material Velocity Equivalent, \( V_e \) when thickness is known**

\[
V_e = \frac{d_m}{\delta t}
\]

- \( \delta t = t_a - t_c \)

*Indirectly proportional to \( V_m \)

Easy to measure, does not require air/gas velocity
Closing the loop on a manufacturing process allows for instant feedback and process control

- Can make adjustments during process to remain within control limits
- Enables continuous process improvement
- Provides further product information and creates opportunity for product improvement
- Allows for 100% inspection of manufactured product
  - Identify regions of defective material
  - Certification of sold product
Non-Contact Ultrasound can measure key material properties in many composite materials

- **Prepreg**: Carbon Fiber, Glass Fiber, etc...
- **CFRP & GFRP**
- **Honeycomb Sandwich structures**
  - Nomex core and aluminum core with composite & Al skins
- **Carbon-Carbon composites**
  - Autoclave oven fixtures
  - Disk Brakes (aircraft and automobile)
- **Foam Core sandwich structures**
Using a bench-top C-Scan system, we can characterize various composite materials.

**System Features**

- Tone-burst pulser up to 375V, with frequency range from 50 kHz to 1 MHz
- 4-channel receiver up to 84 dB gain
- Software features:
  - Cross-sectional profiles for quantitative analysis
  - Absolute transmittance and reflectance measurements
  - Palette selection for easy accept-reject limits
  - Parametric correlation of acoustic vs. material characteristics
  - Statistical Quality Control
  - Numerous features for detailed localized region analysis
  - X-Y Scanning capability can be provided at customer request (various sizes available)
The below composite section demonstrates bonded and dis-bonded regions detected by NCU

**C-Scan and Line Scan Images of CFRP-GFRP Cylindrical composite section (19mm thick)**

1. Complete disbond across top region of part
2. Well-bonded area on left side with disbonded region on right
3. Well-bonded area on left side with disbonded region on right
Delamination can be detected within foam core structures

**C-Scan and Line Scan Images of GFRP Foam Core Sandwich Composites**

Areas of disbond between foam core and GFRP Skin
Delamination between layers for carbon-carbon plates can easily be detected using NCU

**Carbon-Carbon Plates for Oven Fixtures (~10mm thick)**

- **Major Delamination**
- **Uneven Resin Distribution**
- **Well Bonded Layers**
NCU can depict areas of delamination between layers of carbon-carbon disc brakes

**Carbon-Carbon Aircraft Disk Brakes**

- Blue regions depict disbond or delamination between layers
- Red areas indicate high quality bonding between layers
- Non-uniformity of bond quality between layers
The wetness or porosity of carbon fiber prepreg can be directly correlated to ultrasonic signal amplitude in non-contact analysis.

**C-Scan and Line Scan Images of two Carbon Fiber Prepreg Samples of Varying Resin Content**

Subtle resin content differences demonstrate significant variation in ultrasonic amplitude level - can detect <1% change.
The relationship between the desired material property and ultrasonic amplitude can be formulated using statistical analysis on experimental results.

**Correlation Function**

- Transmissivity is expected to decrease as porosity increases or bond quality decreases.
  - Low porosity (drier material) and disbonded layers will have high attenuation and low transmissivity.
A multi-channel non-contact array can continuously analyze parts or web-lines in the downstream direction.

**Representation of Multi-Channel Array for Continuous Inspection**

Transducer array can be arranged in a brick pattern for continuous cross-web coverage.
Application of non-contact ultrasound provides a safe and reliable method of continuous inspection.

**Brick Pattern Array for Continuous Inspection Cross-web**

Multi-Element Array

Designed and Produced by The Ultran Group
A multi-channel non-contact array can continuously analyze parts or web-lines in the downstream direction.

**Representation of Multi-Channel Linear Array for Continuous Inspection**

Linear array pattern allows increased modularity across the web-line or test material.
Our 4-channel array pair is fully modular and can be used with mechanism for alignment in rotational axes.

- 4-channel receiver array, can be built at frequencies between 50 kHz and 1 MHz
- Fully modular to allow for addition of increased number of channels
- Receiver alignment mechanism allows for adjustment in two axes of rotation
  - Alignment mechanism can be mounted to fixture across production line
At each channel we can continuously record the peak-to-peak amplitude across the product.

Peak to Peak value is Recorded at channel at specified time intervals.
Plotting the peak-to-peak values over time, we can continuously monitor materials and products via user-friendly software.

**Continuous Line Scans of Material**

- **Features**
  - Continuous line scan for up to 32 or more channels simultaneously
  - Adjustable upper and lower control limits
  - Alarm output if readings reach limits
  - Y-axis units can be converted to distance or other desired units
  - Y-axis units can be converted via a correlation function to directly measure desired material property

Designed and Produced by The Ultran Group
Non-Contact Ultrasound provides a safe and reliable method of measuring material properties during production

### Non-Contact Ultrasound

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<tr>
<th>Non-Contact Improvements</th>
<th>Correlation of NCU to Material of Interest</th>
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<td>• High performance between 50 kHz and 5 MHz</td>
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<td>• Capable of measuring properties of many composite materials</td>
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<td>• Very high signal to noise ratios obtained</td>
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<tr>
<td>• It is relatively simple to correlate NCU data with material properties</td>
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<td>– For Example: Change in porosity, delamination, air gap, etc...</td>
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### Continuous Inspection

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<th>Improve Process and Product</th>
<th>Waste Reduction</th>
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<td>• Obtain data earlier during manufacturing process</td>
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<td>• Improve process with immediate feedback</td>
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<td>• Can improve product performance with better knowledge of manufacturing process, gaining competitive advantage</td>
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<tr>
<td>• Locate specific areas with defects or poor performance</td>
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<tr>
<td>– Create product maps and product certifications</td>
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<td>• Eliminate destructive tests and need to discard untested product</td>
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### Close the Loop

- Multi-channel non-contact ultrasonic analysis is readily available
  – Products can be customized with relative ease for numerous applications
- NCU is robust, reliable, and relatively low cost
- Ultrasound is one of the safest technologies for inspection
Questions?