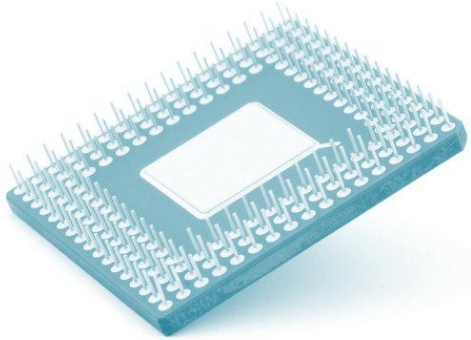

“redefining the limits of ultrasound”

Non-Contact Ultrasonic Inspection for Continuous Feedback in Manufacturing

JEC Europe
Paris

March 12, 2013

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

Topic Agenda

1	Non-Contact Ultrasound (NCU)	• Significant advancements in non-contact ultrasound now allow for analysis of composite and other materials in the early stages to final stags of their formation
2	Continuous Inspection in Production	• Continuous feedback in production has tremendous benefits for waste reduction, process enhancement, and product improvement
3	Correlation of NCU Amplitude to Material Properties	• A relationship can be established to correlate the material property of interest with ultrasonic measurements
4	Applying NCU for Continuous Inspection in Production	• 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

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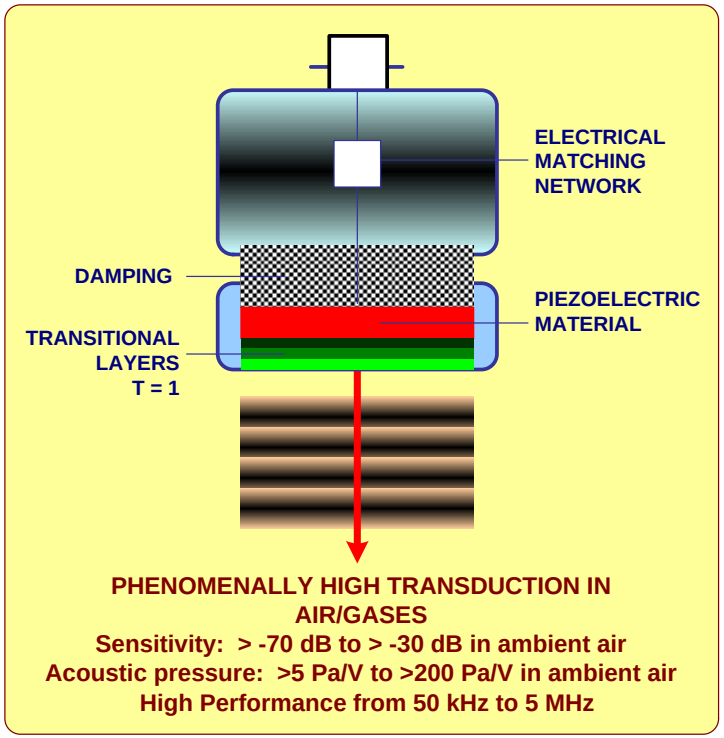
Significant advancements in non-contact ultrasound allow for high performance and widespread applicability

Elements of Non-Contact Transducers*



Features

- 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

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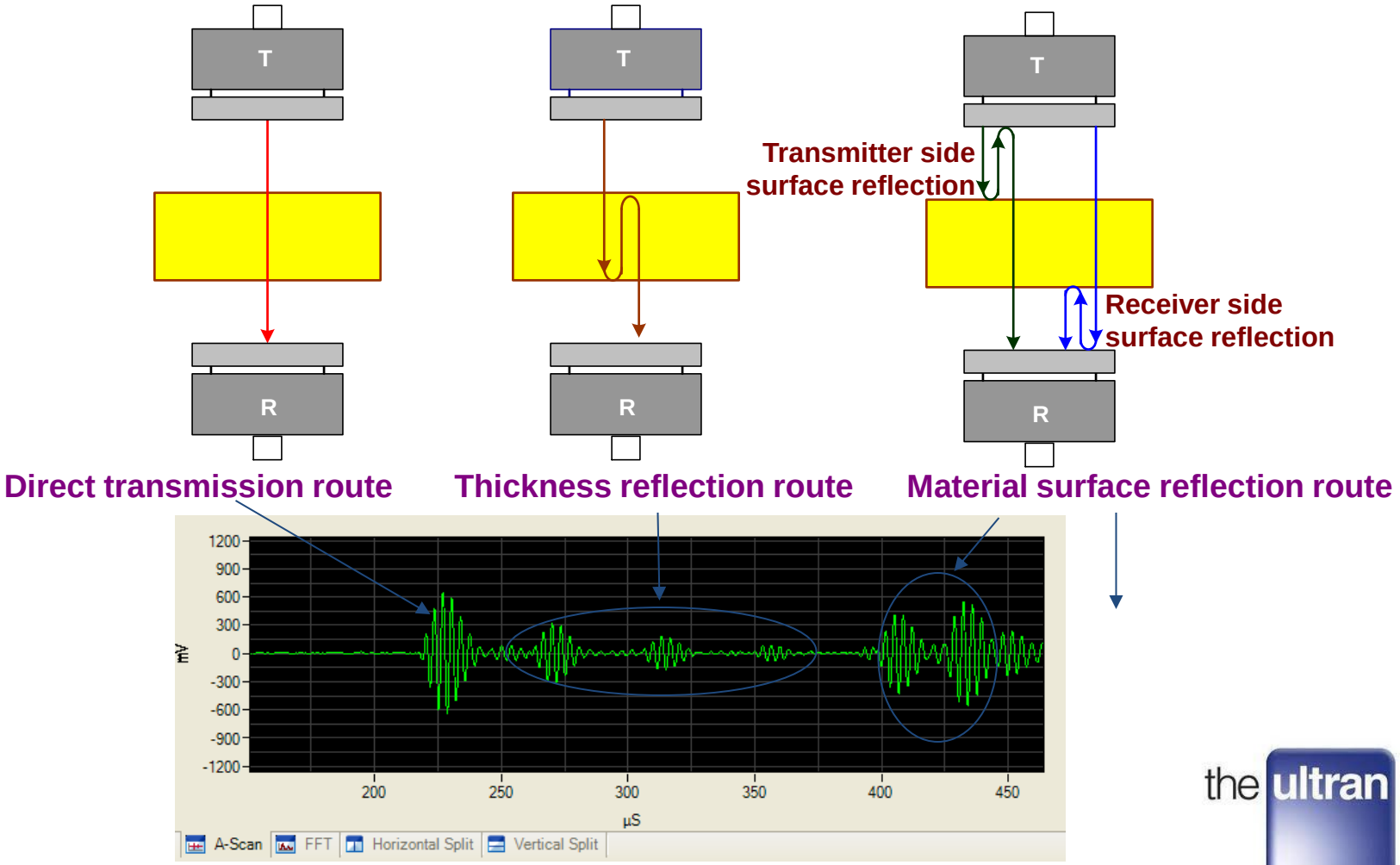
Through transmission is the most applicable and robust method of non-contact analysis



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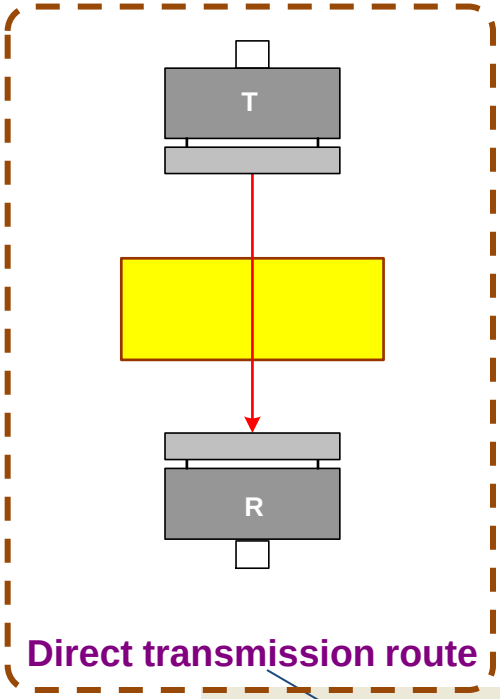
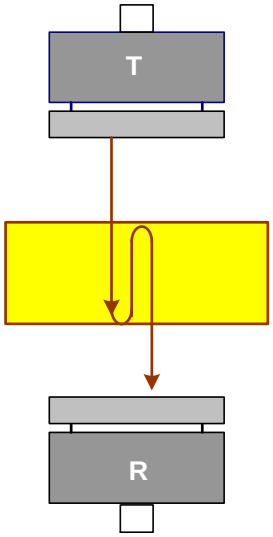
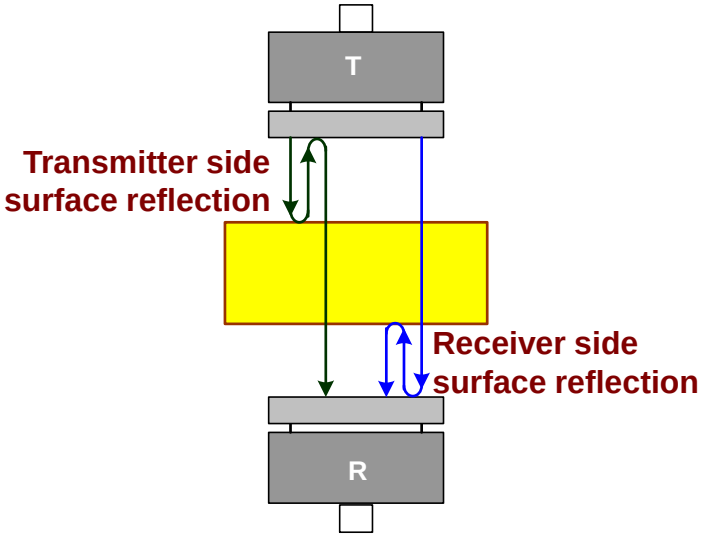
For most analyses in non-contact ultrasound, it is easiest to use the direct transmission route



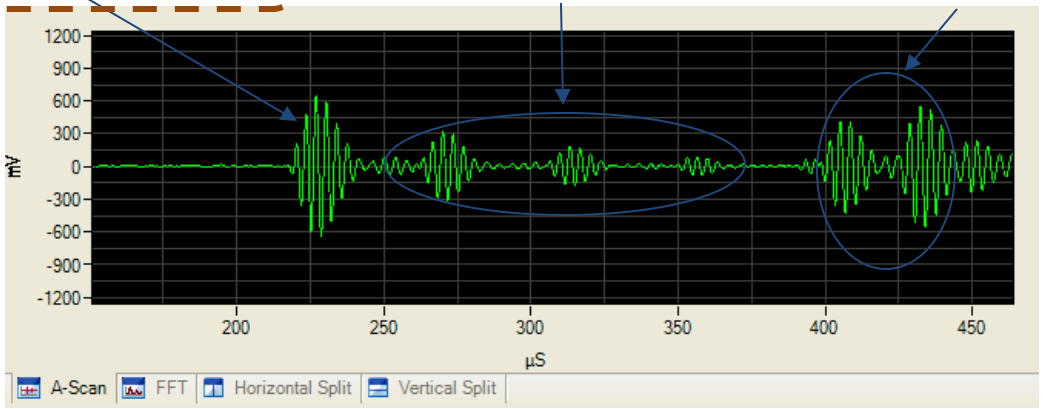




Direct transmission route

Thickness reflection route

Material surface reflection route



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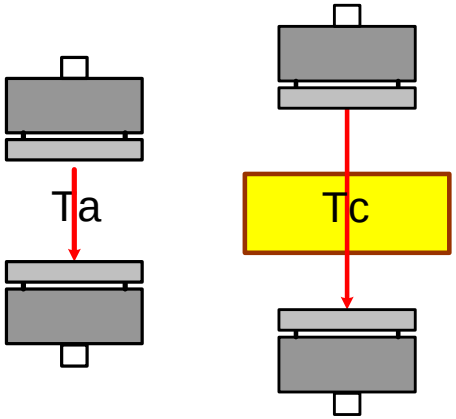
The key ultrasonic measurement through non-contact through transmission is attenuation or transmittance

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

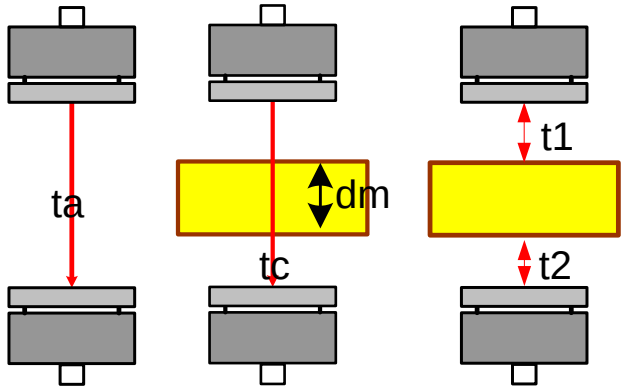
Material Velocity is often directly related to material density

Material Velocity, V_m when thickness is known

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

$$t_{am} = \frac{d_m}{V_a}$$

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



Material Velocity, V_m when thickness is unknown

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

$$d_m = V_a \times t_{am}$$

$$t_{am} = t_a - \left(\frac{t_1 + t_2}{2} \right)$$

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

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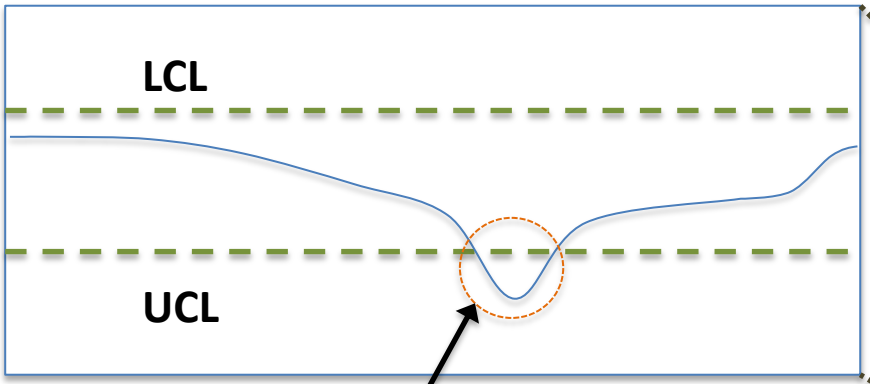
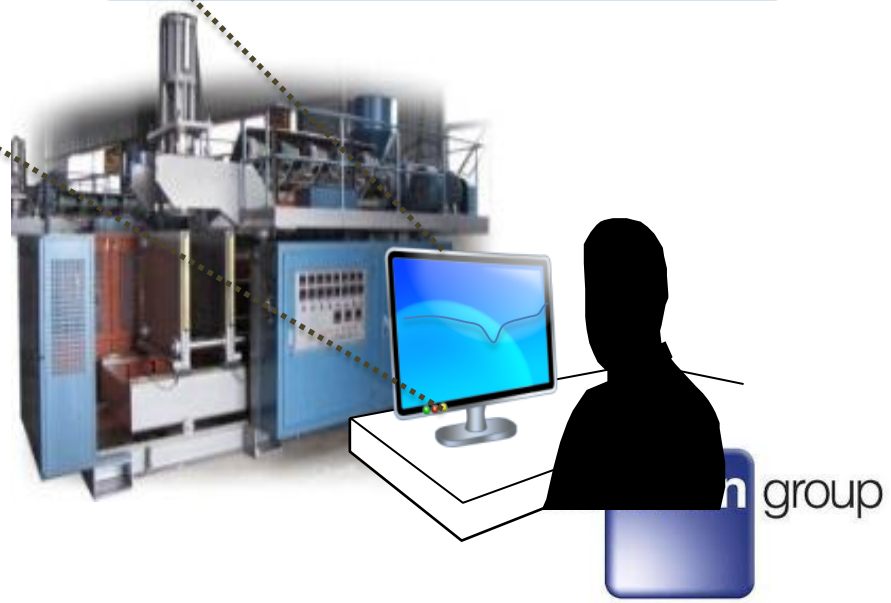
Closing the loop on a manufacturing process allows for instant feedback and process control

- 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

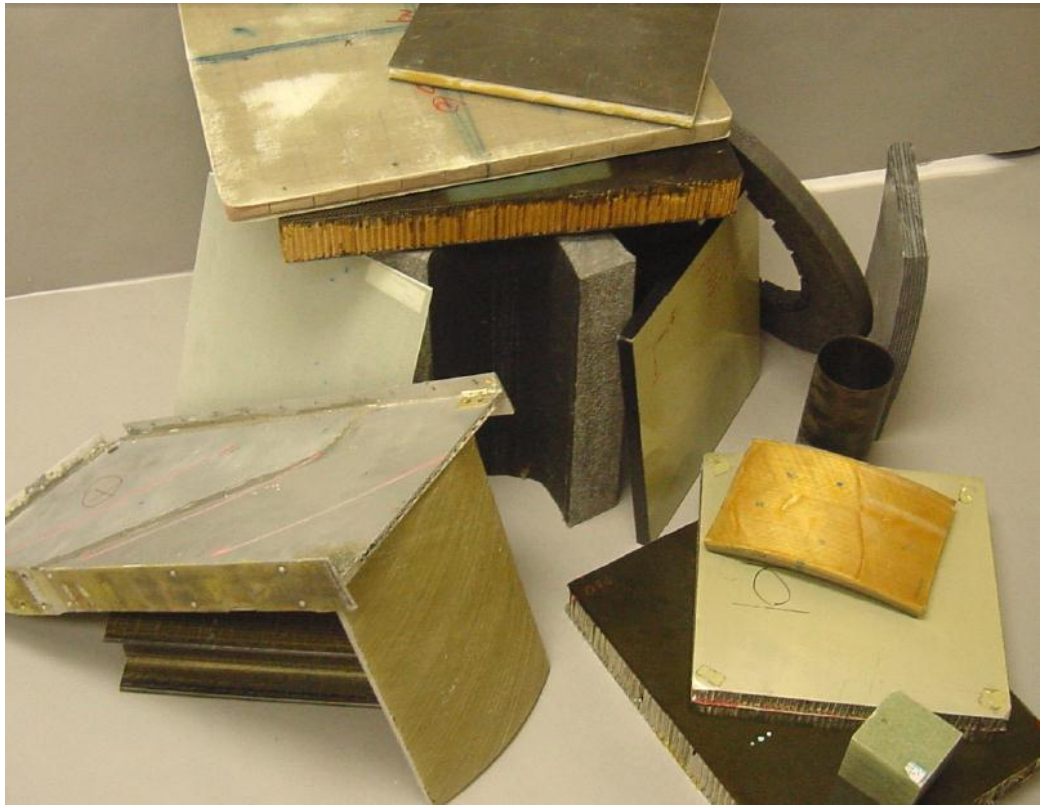


Process out of control



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**



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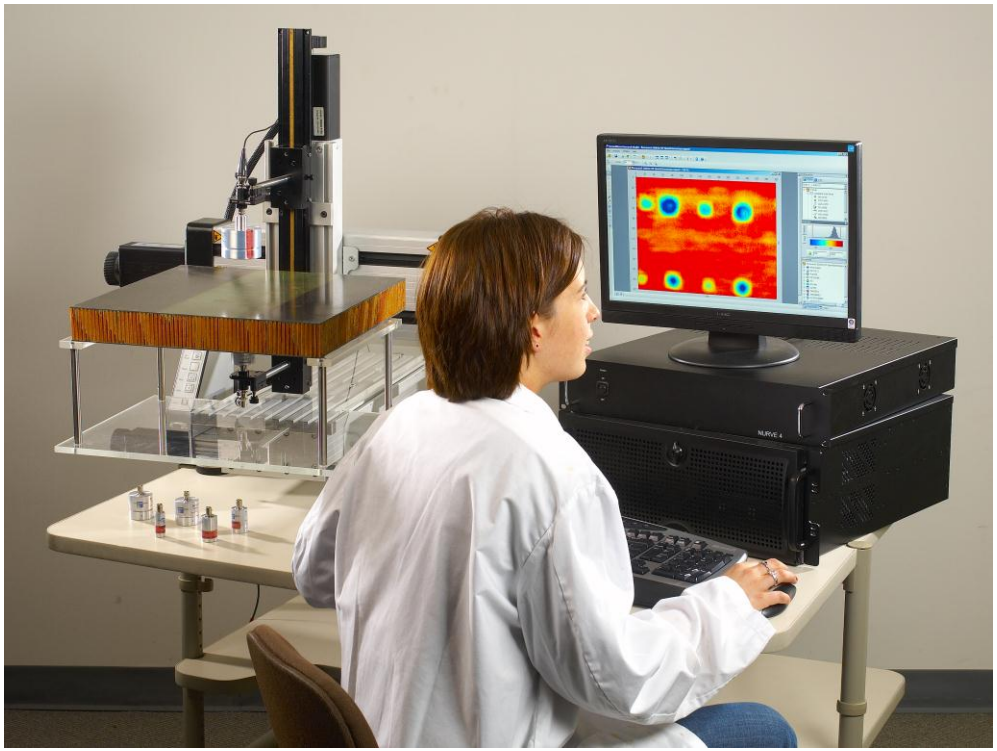
Using a bench-top C-Scan system, we can characterize various composite materials

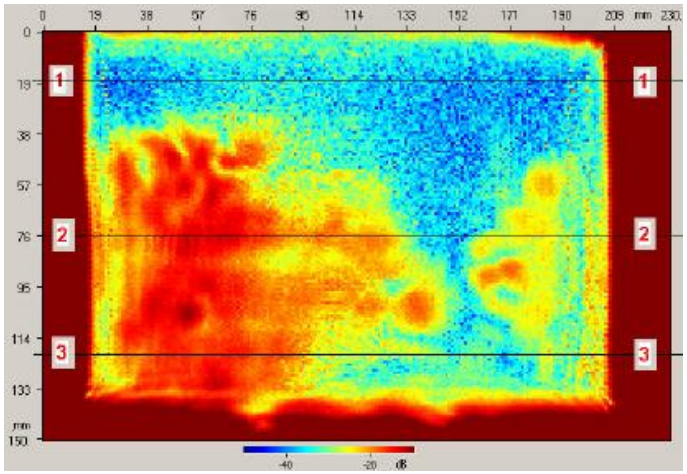


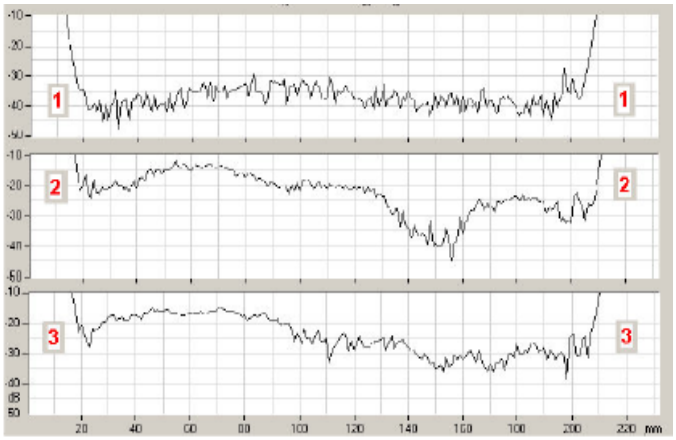
System Features

- 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)

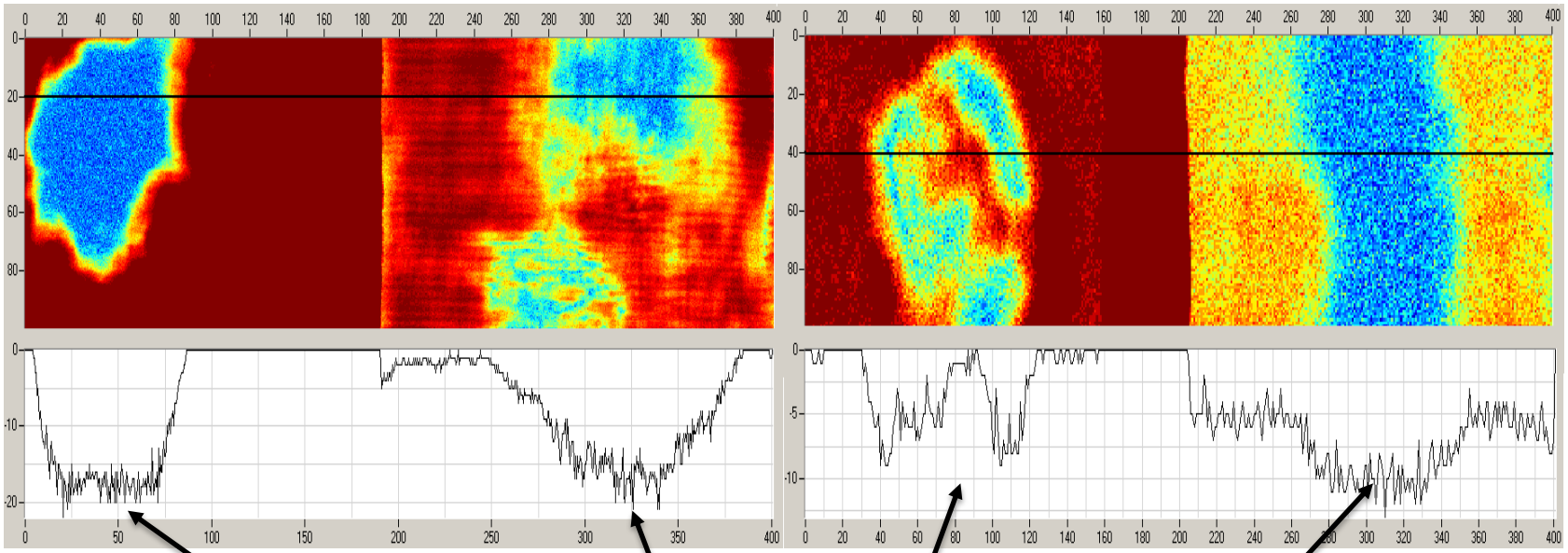




1. Complete disbond across top region of part
2. Well-bonded area on left side with disbonded region on right
3. Well-bonded area on left side with disbonded region on right

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

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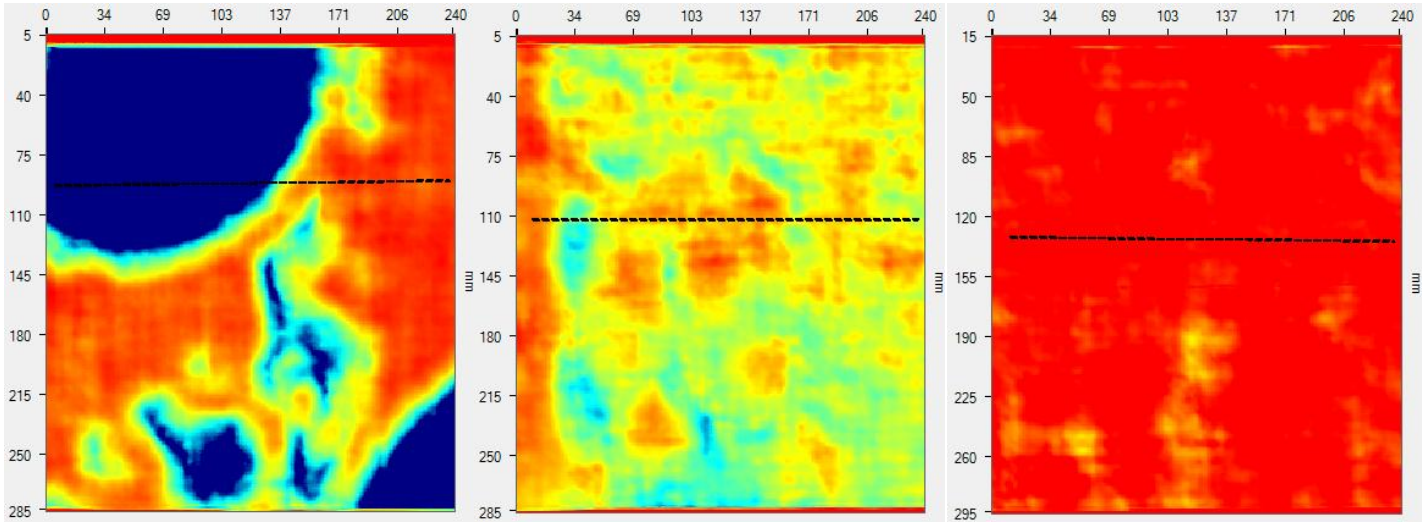
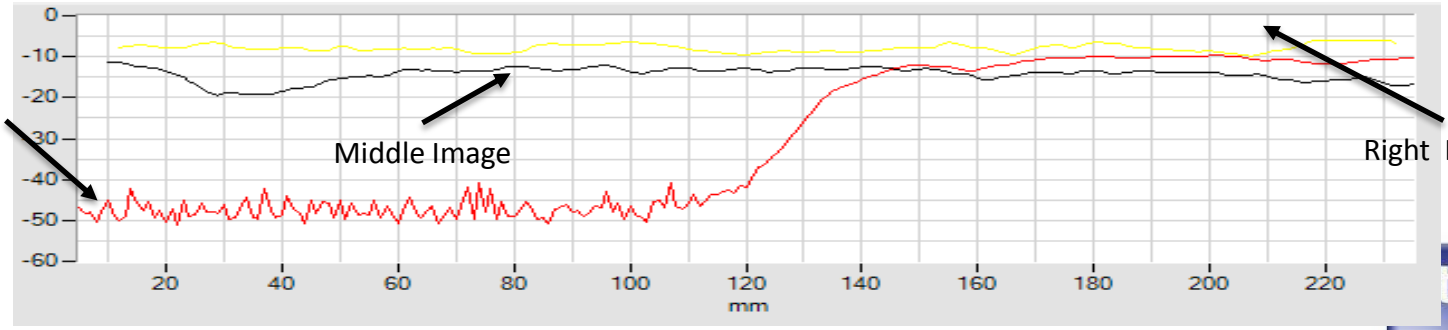
Delamination between layers for carbon-carbon plates can easily be detected using NCU

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



Major Delamination ***Uneven Resin Distribution*** ***Well Bonded Layers***



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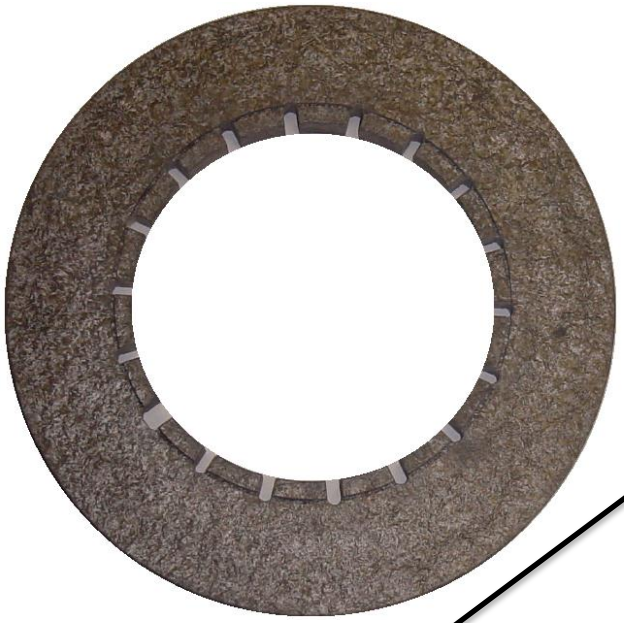
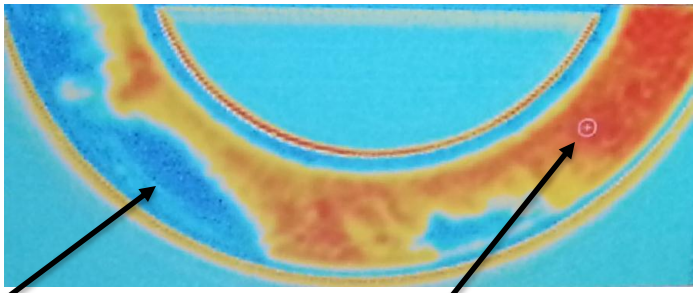
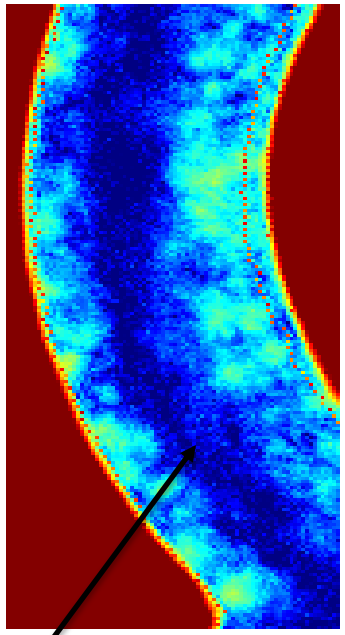
NCU can depict areas of delamination between layers of carbon-carbon disc brakes

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

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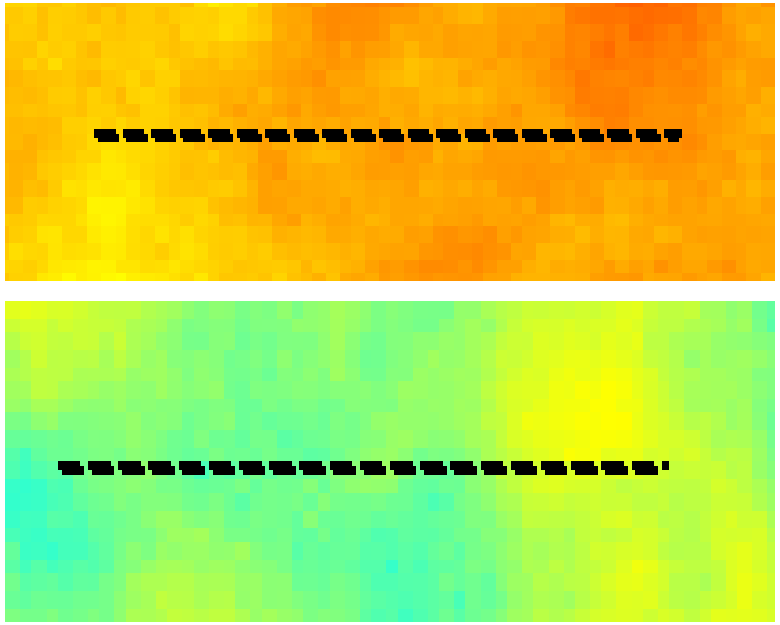
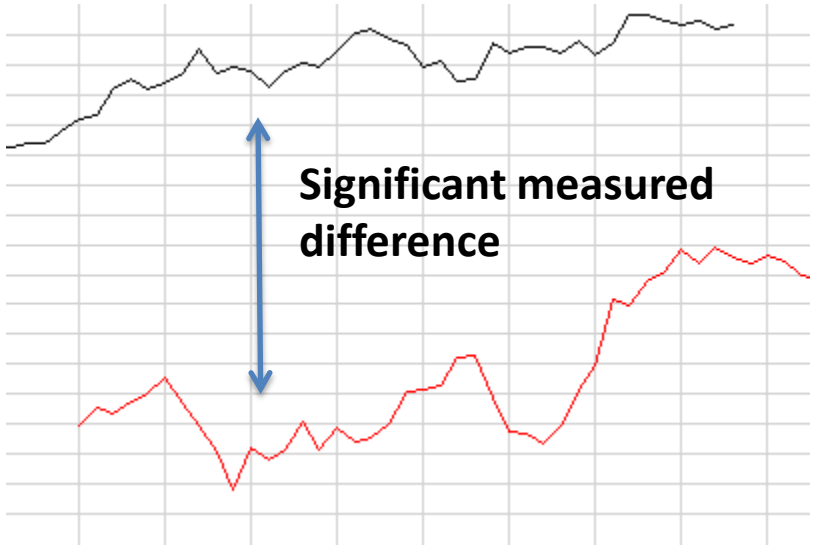
The wetness or porosity of carbon fiber prepreg can be directly correlated to ultrasonic signal amplitude in non-contact analysis

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

Higher Resin Content

Lower Resin Content





Subtle resin content differences demonstrate significant variation in ultrasonic amplitude level - can detect <1% change

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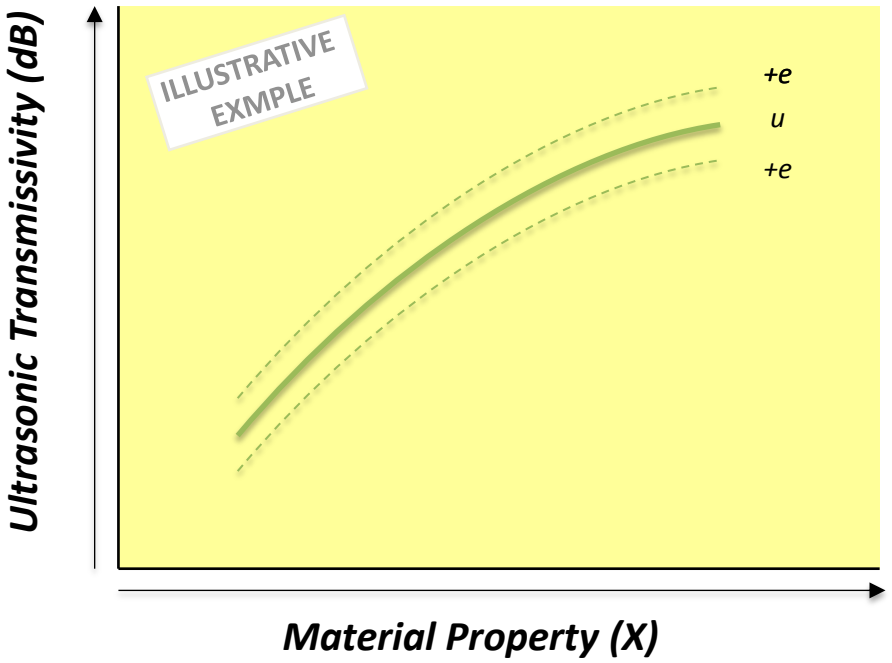
The relationship between the desired material property and ultrasonic amplitude can be formulated using statistical analysis on experimental results

Graphical Representation of Material Property vs. Ultrasonic Transmissivity



Correlation Function

- Transmissivity is expected to decrease as porosity increases or bond quality decreases
  - Low porosity (dryer material) and disbonded layers will have high attenuation and low transmissivity

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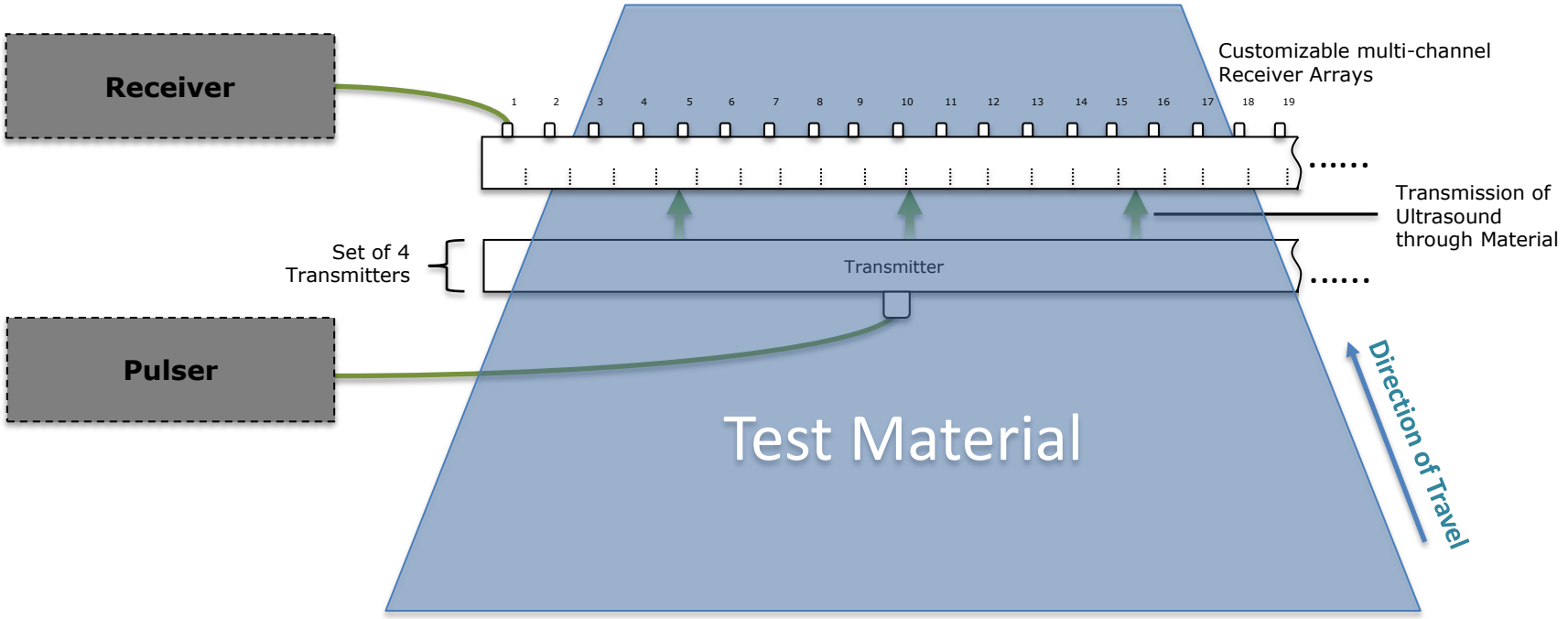
A multi-channel non-contact array can continuously analyze parts or web-lines in the downstream direction

Representation of Multi-Channel Array for Continuous Inspection



Transducer array can be arranged in a brick pattern for continuous cross-web coverage

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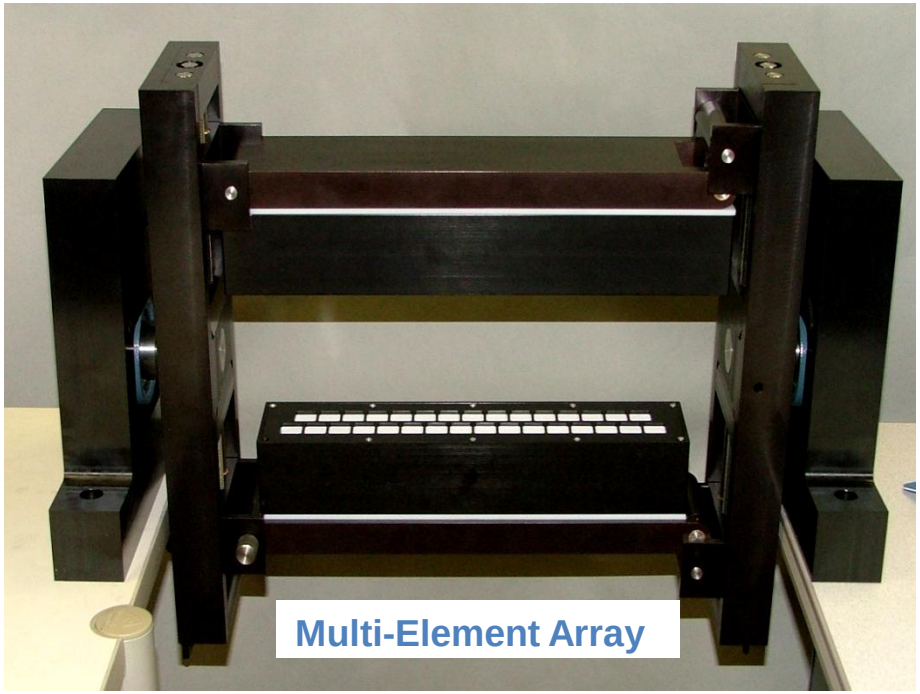
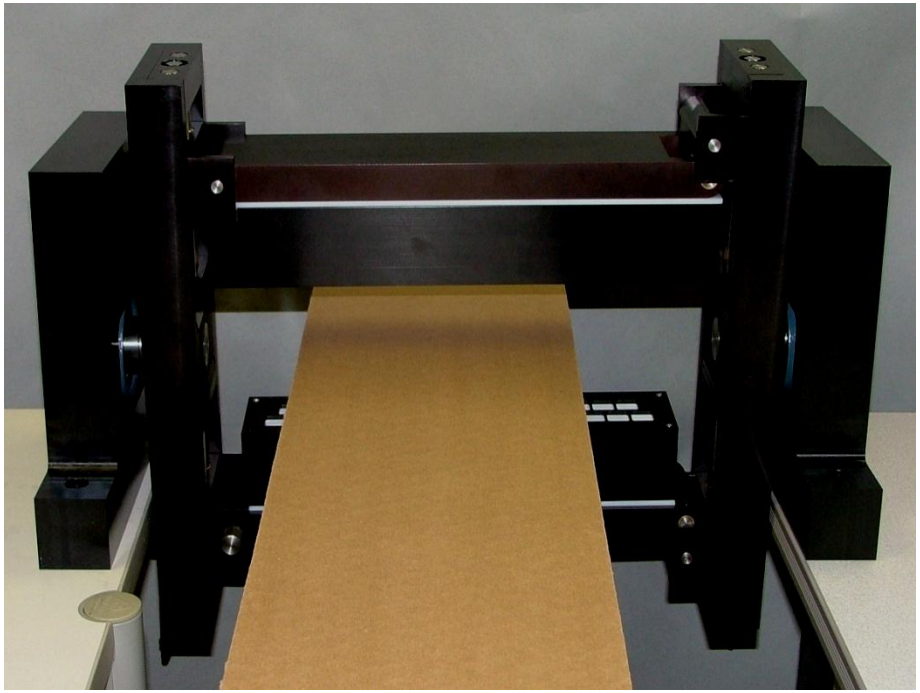
Application of non-contact ultrasound provides a safe and reliable method of continuous inspection

Brick Pattern Array for Continuous Inspection Cross-web





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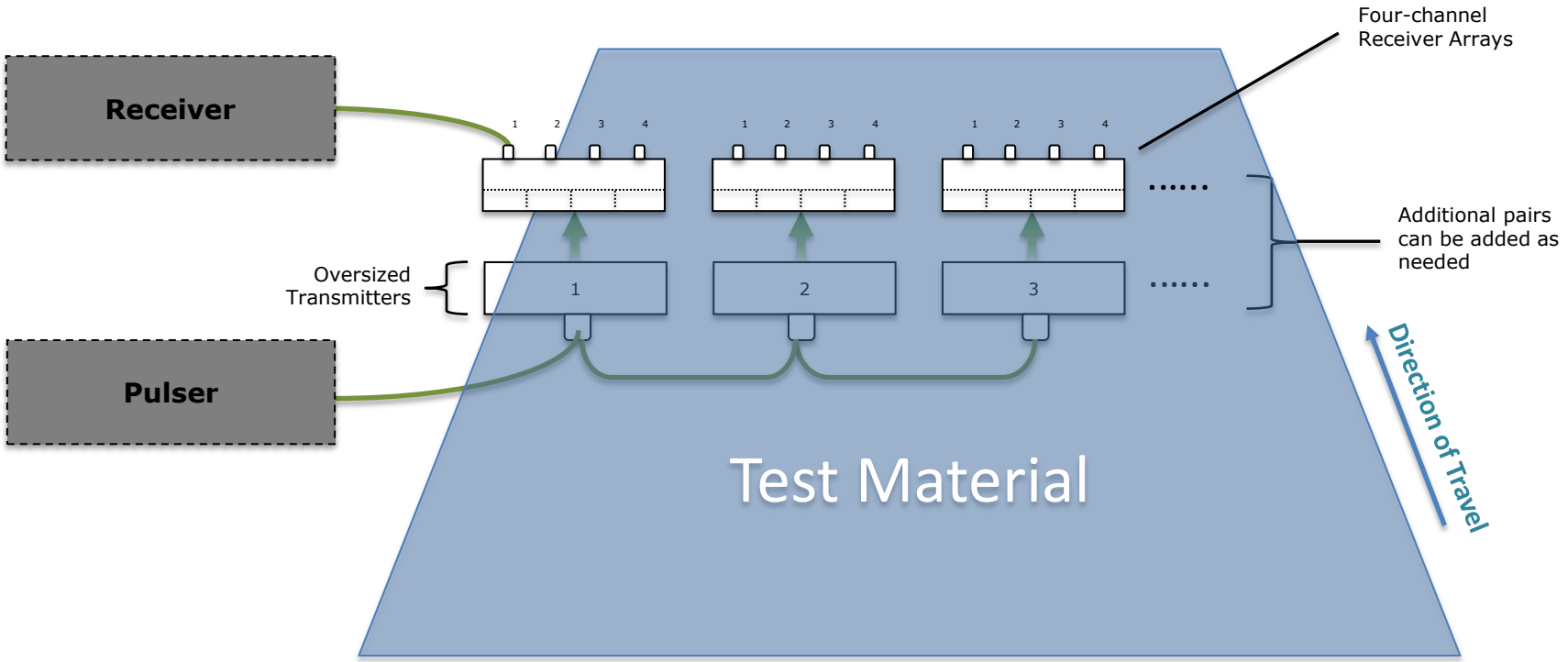
A multi-channel non-contact array can continuously analyze parts or web-lines in the downstream direction

Representation of Multi-Channel Linear Array for Continuous Inspection



Linear array pattern allows increased modularity across the web-line or test material

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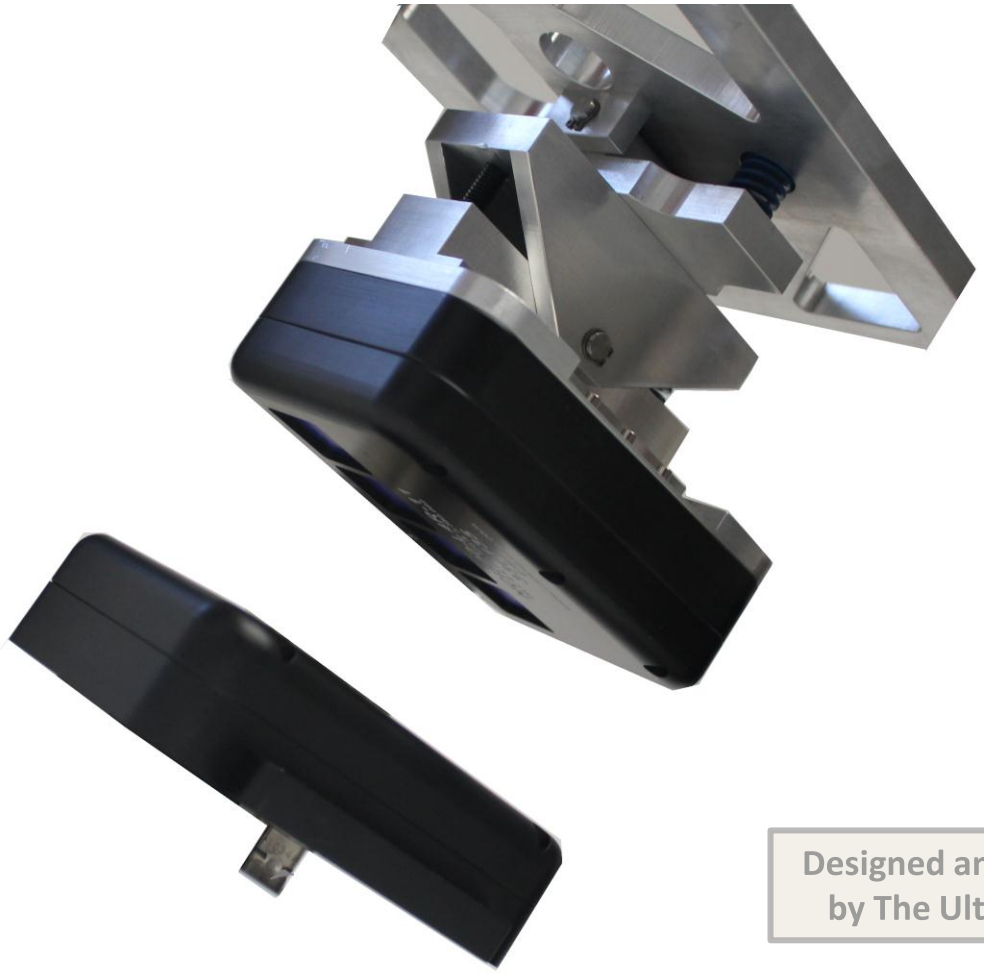
Our 4-channel array pair is fully modular and can be used with mechanism for alignment in rotational axes



- 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

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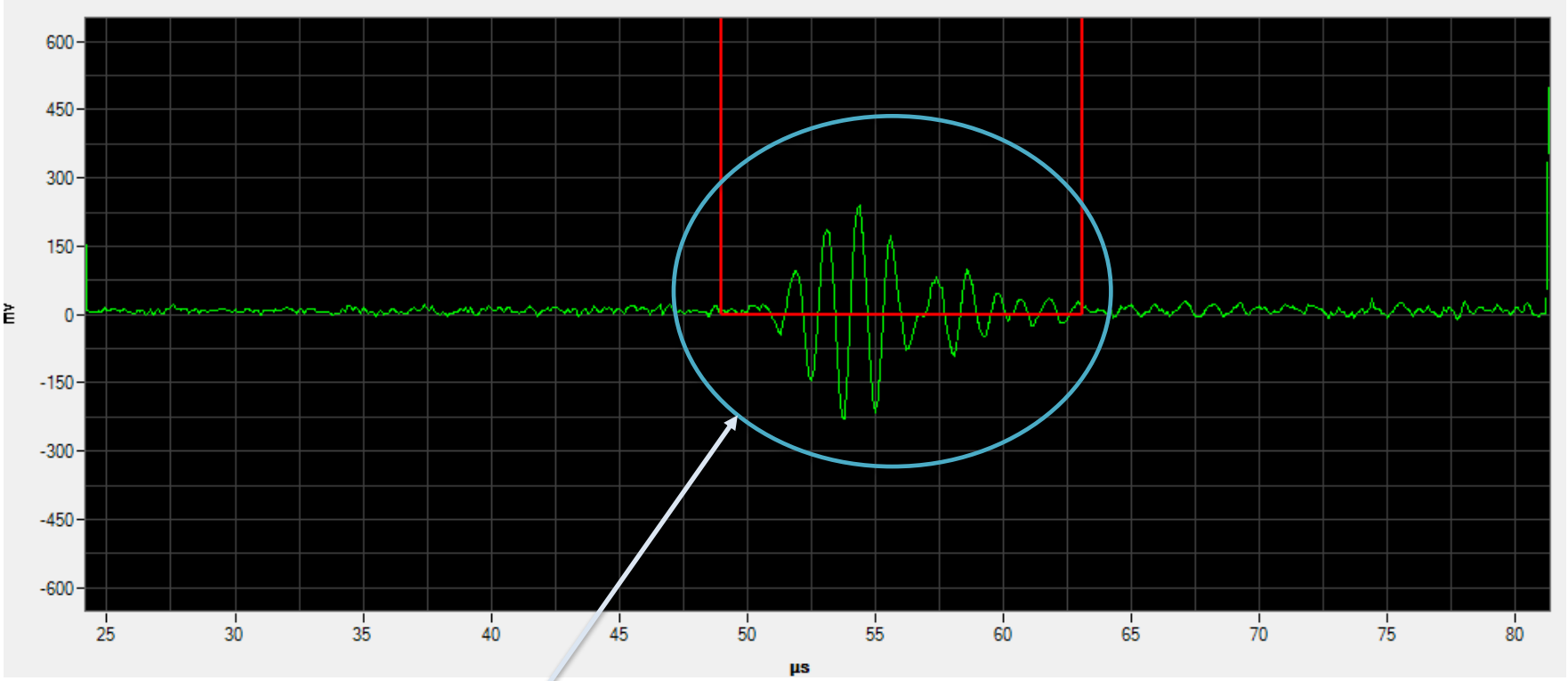
At each channel we can continuously record the peak-to-peak amplitude across the product



Peak to Peak value is Recorded at channel at specified time intervals

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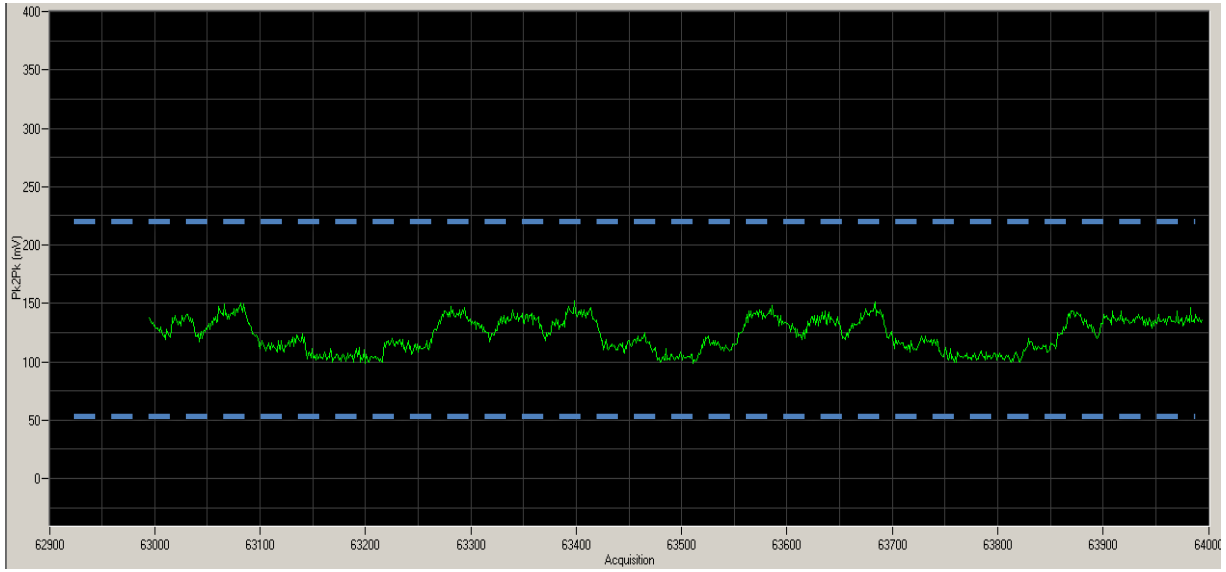
Plotting the peak-to-peak values over time, we can continuously monitor materials and products via user-friendly software

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

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Non-Contact Ultrasound provides a safe and reliable method of measuring material properties during production

Non-Contact Ultrasound

Non-Contact Improvements

- High performance between 50 kHz and 5 MHz
- Capable of measuring properties of many composite materials
- Very high signal to noise ratios obtained

Correlation of NCU to Material of Interest

- It is relatively simple to correlate NCU data with material properties
  - For Example: Change in porosity, delamination, air gap, etc…

Continuous Inspection

Improve Process and Product

- Obtain data earlier during manufacturing process
- Improve process with immediate feedback
- Can improve product performance with better knowledge of manufacturing process, gaining competitive advantage

Waste Reduction

- Locate specific areas with defects or poor performance
  - Create product maps and product certifications
- Eliminate destructive tests and need to discard untested product

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

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Questions?

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