Contact-free porosity detection in composite parts by a pore resonance mechanism

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Acoustic resonance – an everyday phenomenon, useful for NDT?

- Can we use this for CFRP testing?

Outline

1. **Motivation**
2. Laser-excited Acoustics measurement system
3. Experimental results
4. Conclusion and Outlook

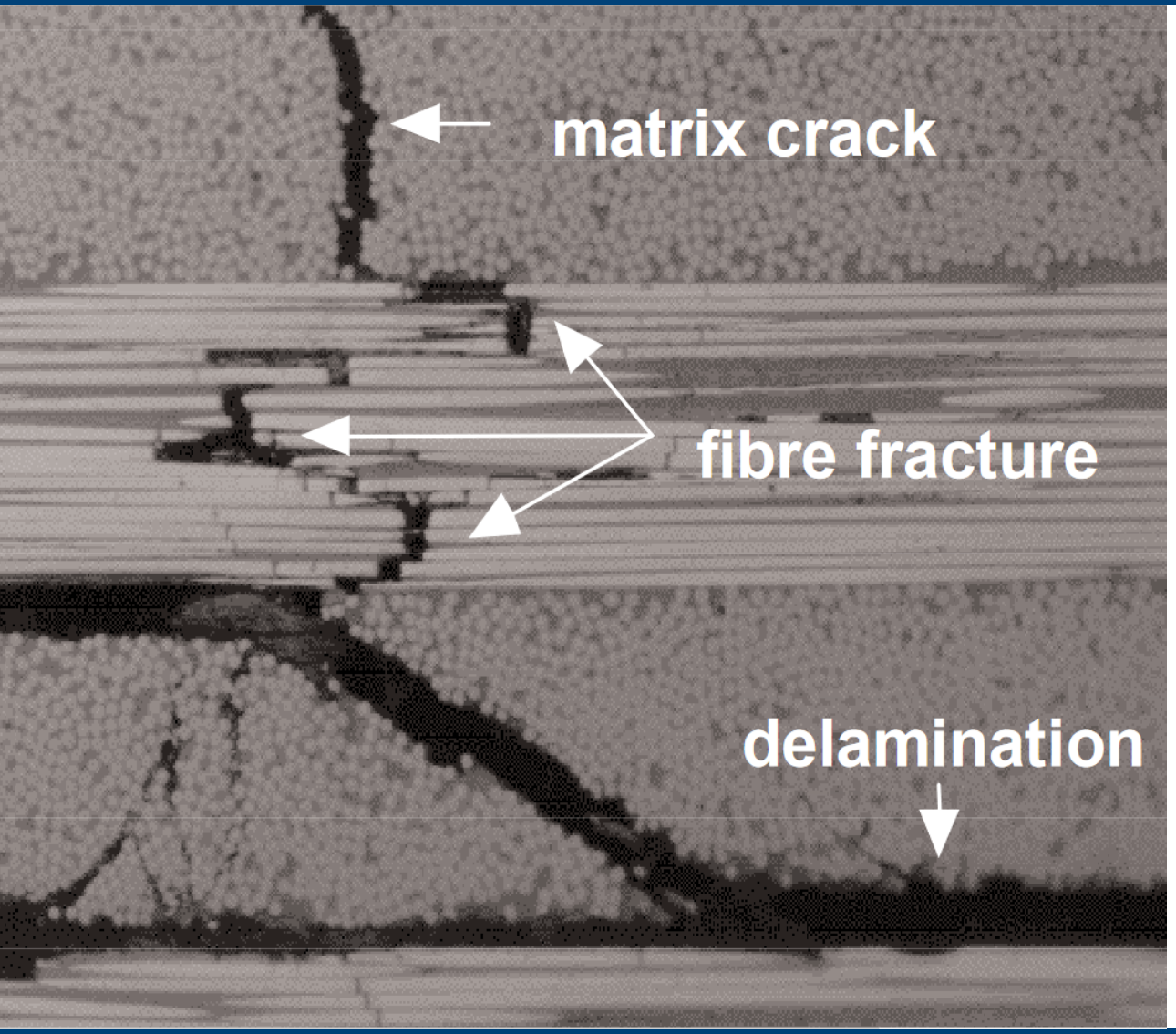
Why inspect finished CFRP parts?

To prevent structural failure

non-destructive testing is **obligatory**

Image source: Robert Nichols / Picture Alliance

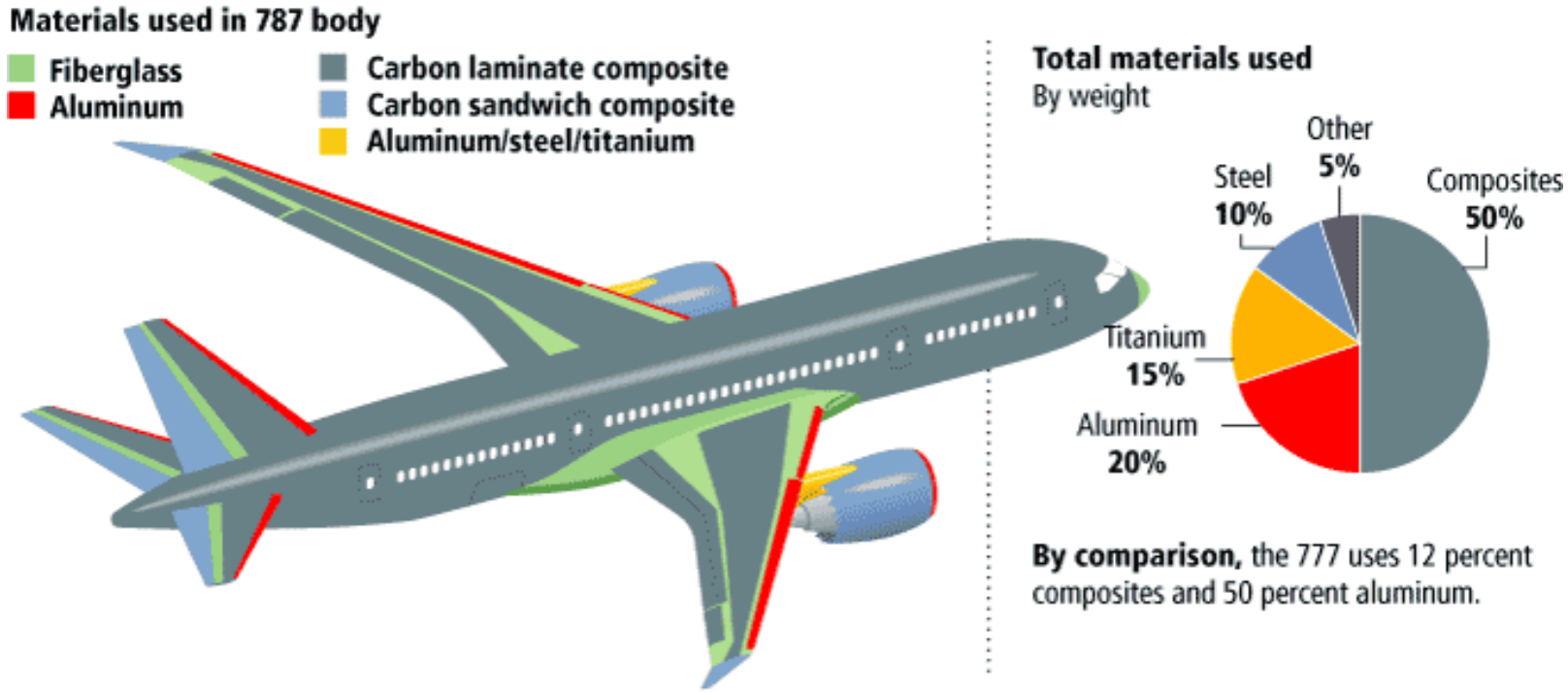
Why inspect finished CFRP parts?



Material damage can occur **in fabrication** or **during use**

Image source: Kreculj, D. & Rasuo, B. (2018). Impact damage modeling in laminated composite aircraft structures.

The widespread use of CFRP in the aerospace sector necessitates NDT



- CFRP makes up about 50% of the weight of modern aircraft
- **Low porosity levels** are essential for ensuring the performance of CFRP composite structures. [1]

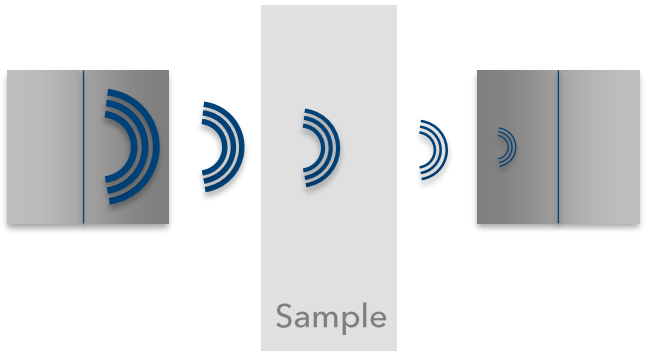
[1] Birt et al, 2004, "A review of NDE methods for porosity measurement in fibre-reinforced polymer composites." *Insight-Non-Destructive Testing and Condition Monitoring*, *46*(11), pp.681-686.

Image source: https://www.modernairliners.com/boeing-787

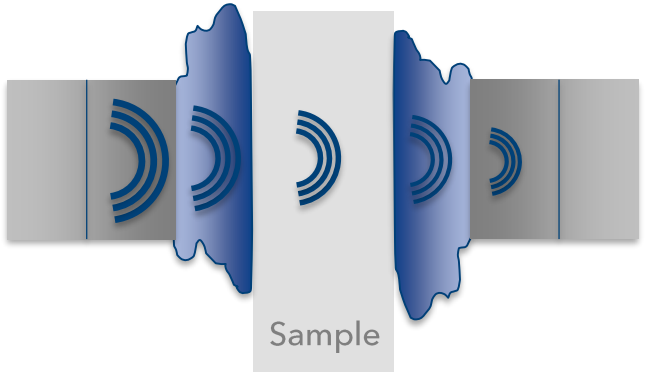
State of the art in Ultrasonic testing

- Ultrasound is a widespread technique for non-destructive testing CFRP parts
- Conventional air-coupled Ultrasound suffers from low resolutions
- Liquid-coupled ultrasound achieves high resolution, but is either impractical or even prohibited in many cases [2]
- Laser ultrasonic testing (with laser Doppler vibrometer) is highly dependent on sample surface reflectivity and roughness [3]
- Laser Excited Acoustics (LEA) is an alternative non-contact technique that is independent from surface properties! [4]

Air-coupled Ultrasound



Liquid-coupled Ultrasound



[2] Vanderheiden et al, 2018, "Transition to high rate aerospace NDI processes", AIP Conference Proceedings 1949, p. 020003
[3] Aguado et al, 2015, "Laser ultrasonic inspections of aero-nautical components validated by computed tomography" Proc. of 7th International Symposium on NDT in Aerospace
[4] Fischer et al., 2019, „Impact damage assessment in biocomposites by micro-CT and innovative air-coupled detection of laser-generated ultrasound", Composite Structures 210, pp. 922–931

Outline

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2. **Laser-excited Acoustics measurement system**
3. Experimental results
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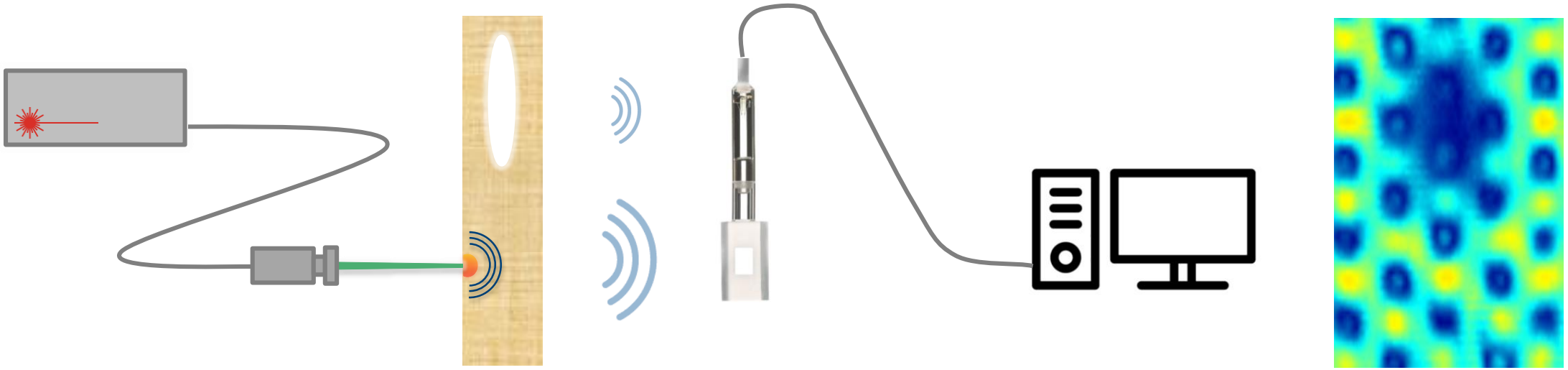
Operation principle of Laser-excited Acoustics (LEA)



Excitation laser (fiber-coupled)

Sample

Optical Microphone (fiber-coupled)

Data acquisition

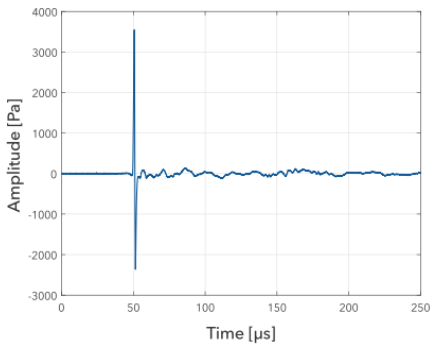
Scan result

Broadband excitation meets broadband detection

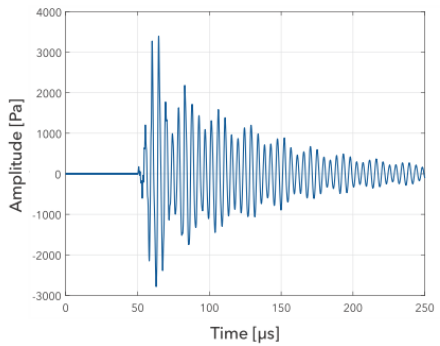
Broadband, non-contact excitation

- Excitation by short laser pulse (few ns)
- Short pulse width → broad frequency spectrum

Short pulse

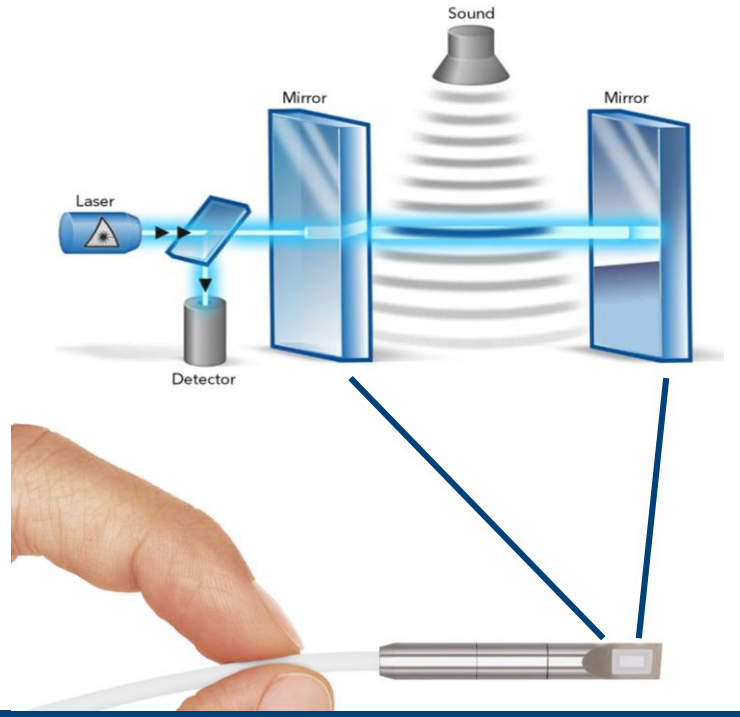


Compare: Piezo excitation

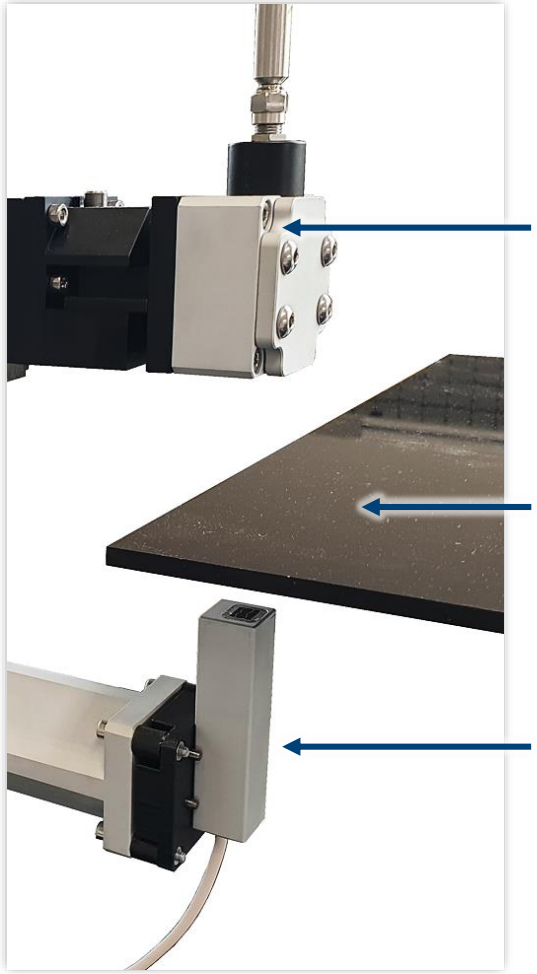


Broadband, non-contact detection

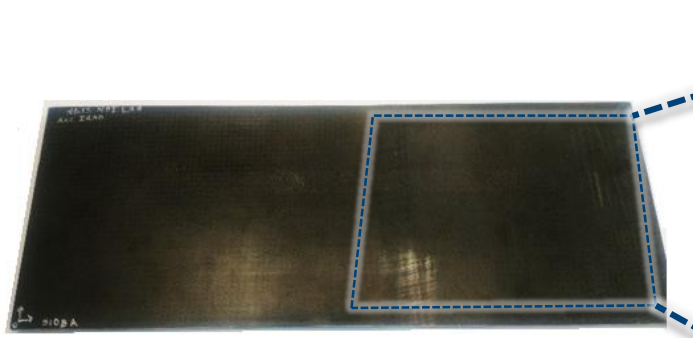
- Optical Microphone serves as broadband ultrasound detector (10 Hz – 2MHz)

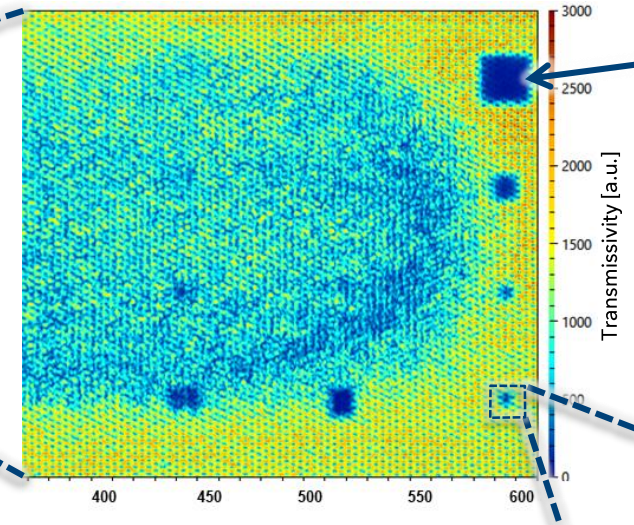


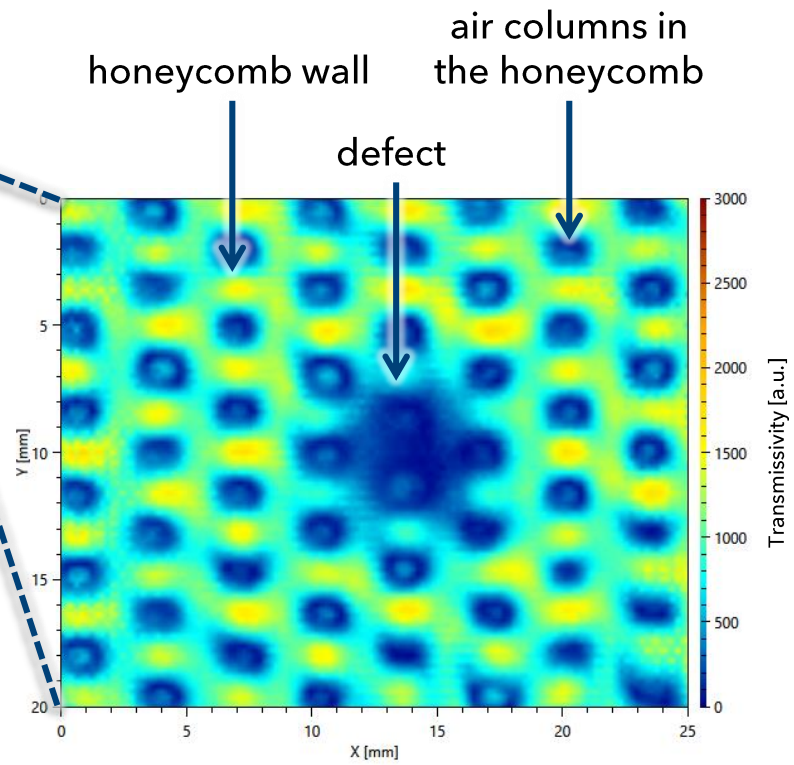
XARION Laser-acoustics measurement system for Composite NDT



Sample inspection result of CFRP honeycomb sandwich with LEA technology





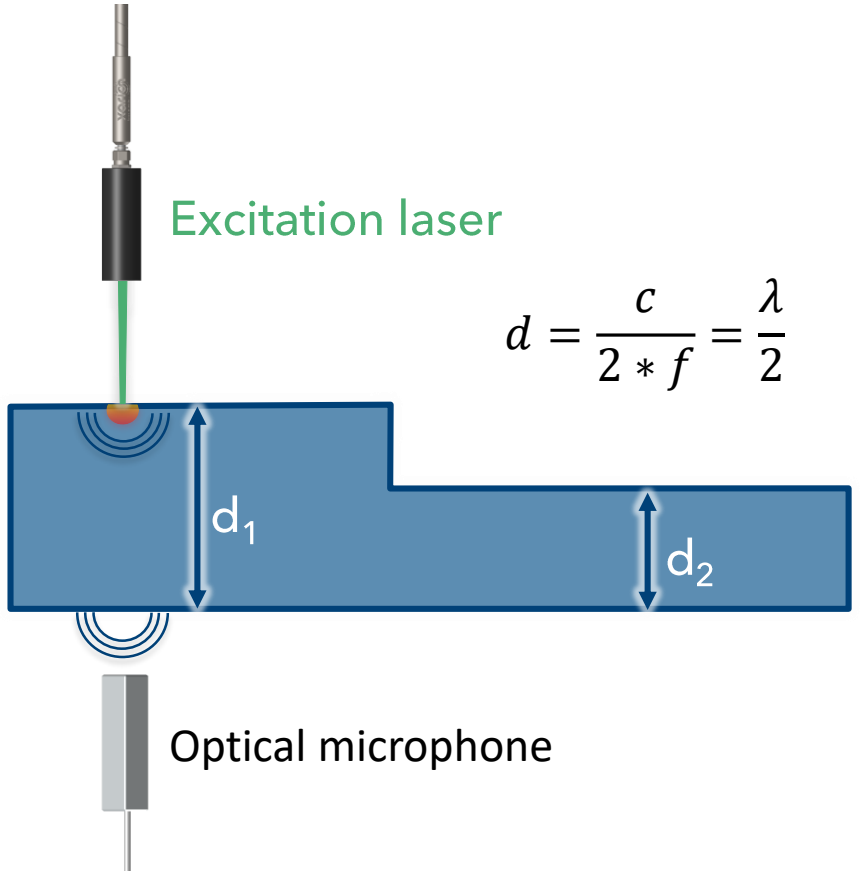


- Speed and resolution better than squirter ultrasound testing
- Completely contact-free, no liquid used
- No water management needed (maintenance, pre-treatment, waste disposal)

Brauns et al, 2021, "Laser-Excited Acoustics for Contact-Free Inspection of Aerospace Composites." *Materials Evaluation* 79, no. 1 (2021): 28-37.

Broadband capabilities enable detection of **local resonances**

- When ultrasound propagates through a sample, the spectrum of the initial waveform changes, e.g. due to
  - Sample thickness resonance [5] or
  - Local defect resonance [6]
- The resonance frequencies depend on the speed of sound in the material:
  - E.g. thickness resonance in steel (c = 5000 m/s)
  - Sound wave with f = 2 MHz:
    → wavelength 2.5 mm, thickness resonance for 1.25 mm
  - E.g. resonance of air bubble (c=340 m/s)
  - Sound wave with f = 500 kHz:
    → wavelength 680 µm, thickness resonance 340 µm



[5] Solodov et al, 2011"A local defect resonance to enhance acoustic wave-defect interaction in ultrasonic nondestructive evaluation, Appl. Phys. Lett. 99, p. 211911,
[6] Rus et al, 2021, "Thickness measurement via local ultrasonic resonance spectroscopy", Ultrasonics 1 09, p. 106261

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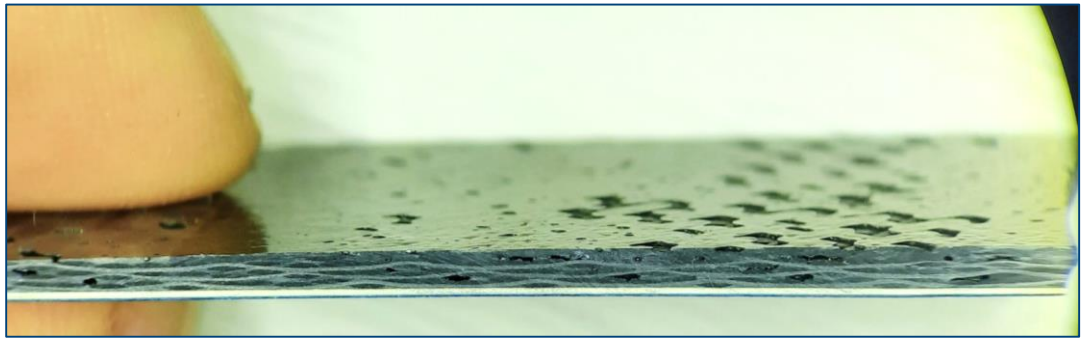
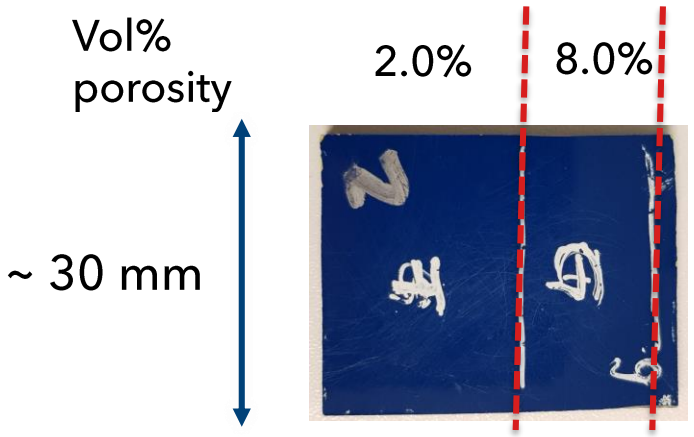
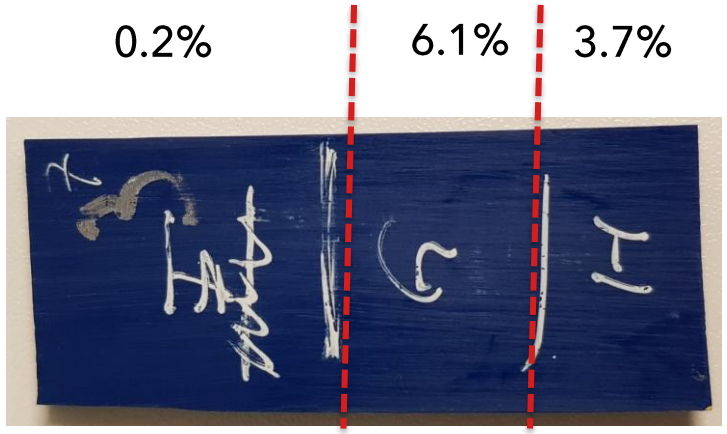
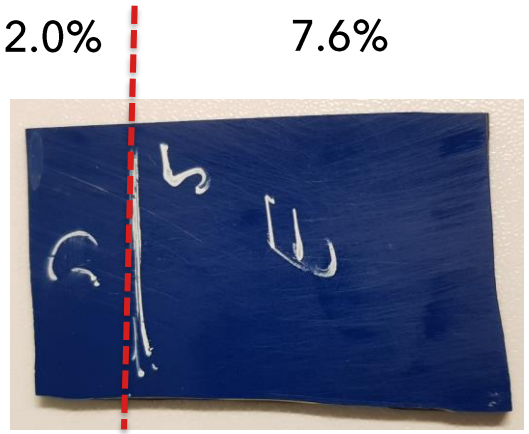
Experiments – samples

- CFRP samples with regions of varying porosity
- Porosity percentages verified with micro-CT and conventional UT







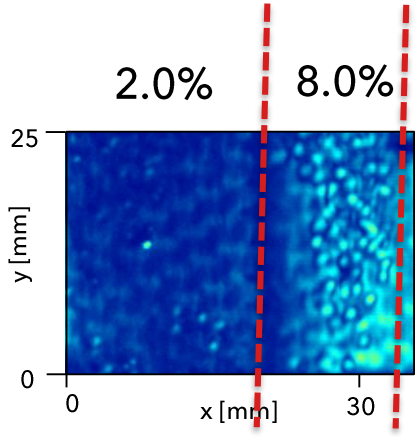


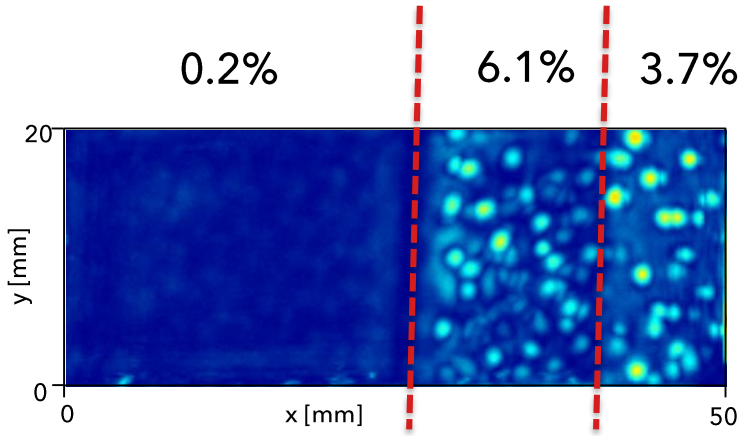
Results – XARION LEA C-scan images of samples

- Signal is bandpass-filtered from 200-700 kHz, acoustic energy is displayed
- Individual pores can be visualized

Vol% porosity

C-scan XARION





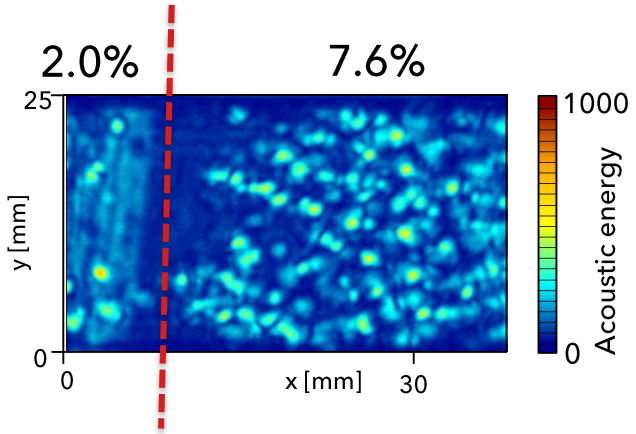
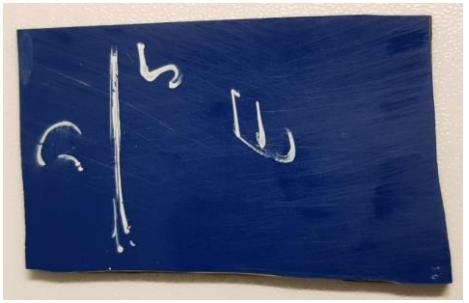
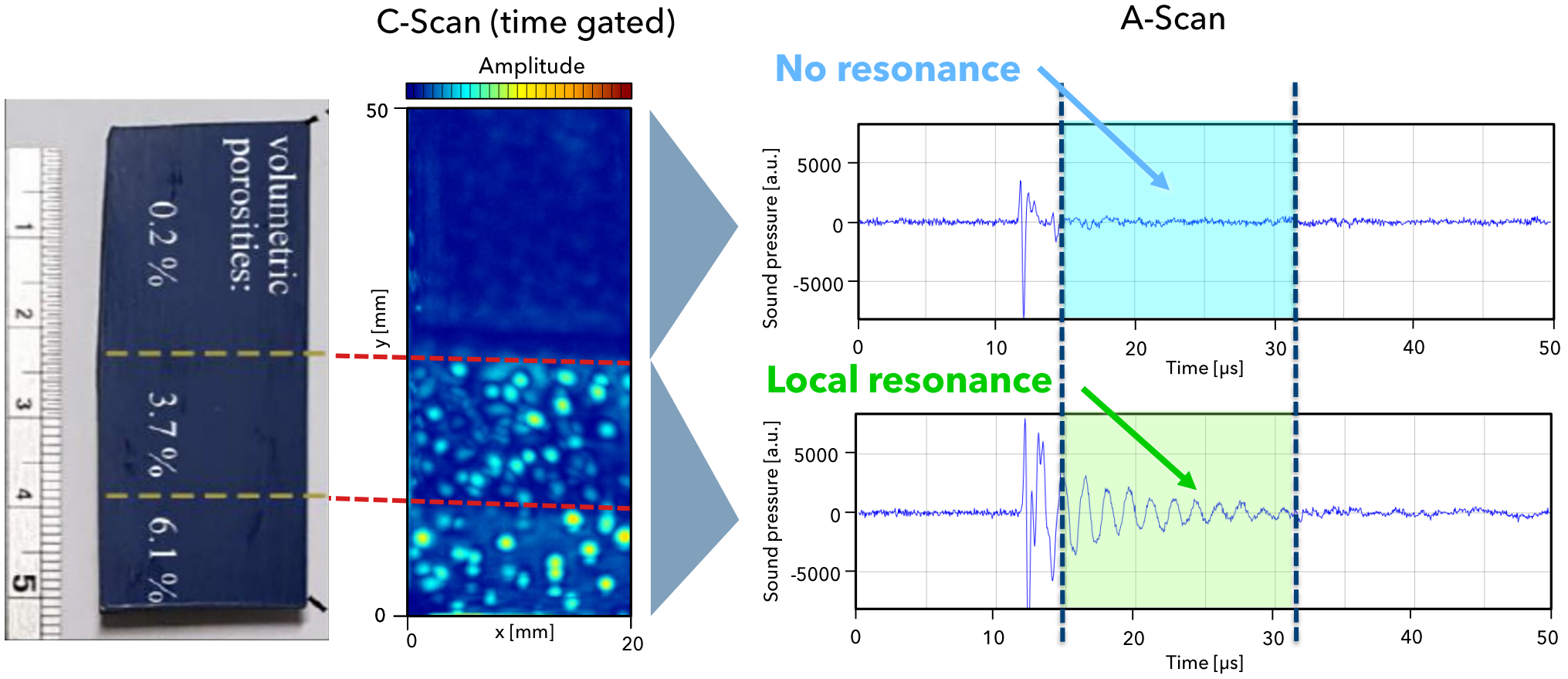


Photo of sample



Results – Pores exhibit resonance, which can be seen in A-Scans

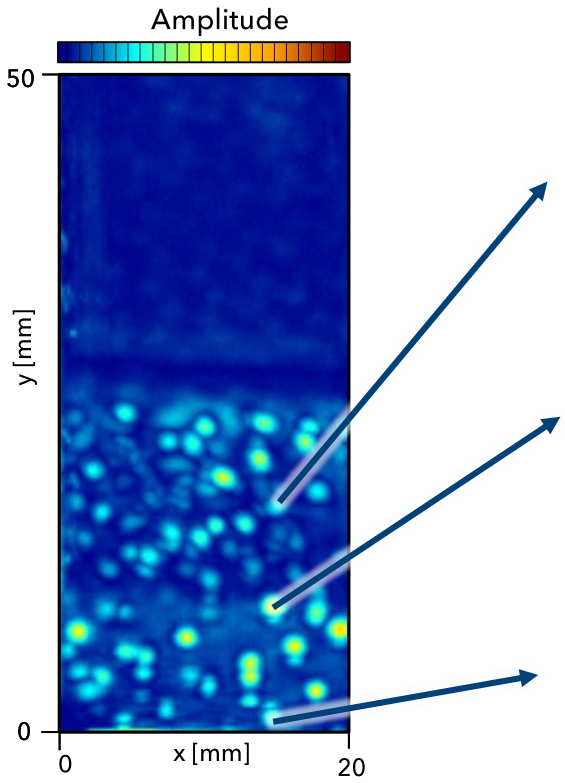


Frequency analysis reveals size of pores!

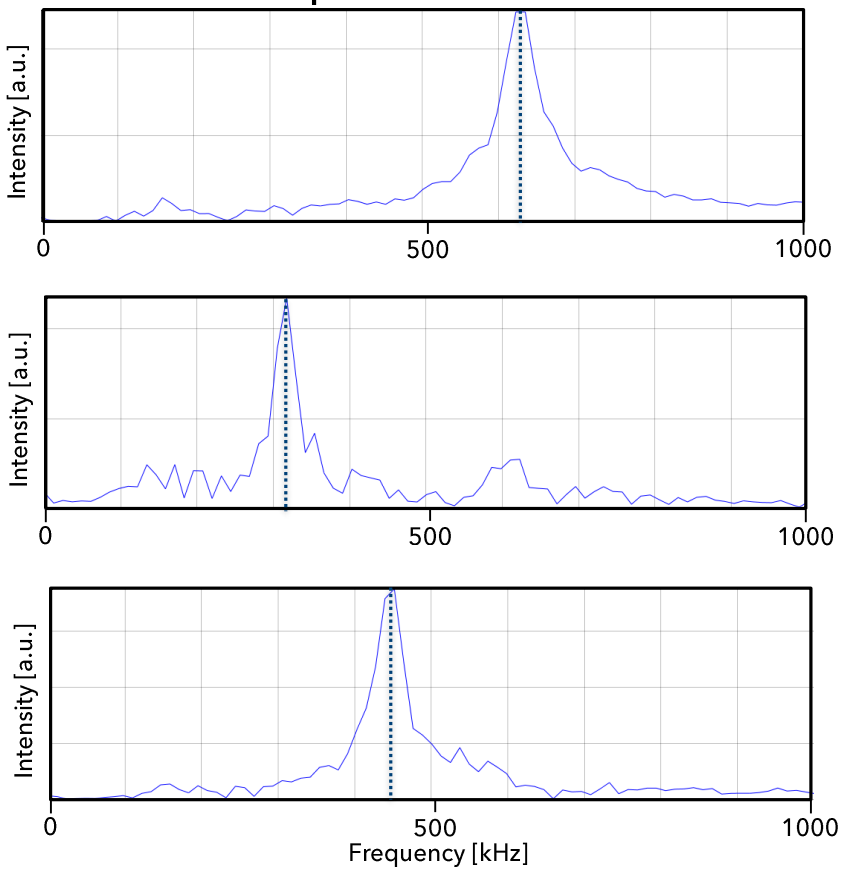
Pores as "thickness resonators"

$$d = \frac{c}{2 * f_0}$$

C-Scan (time gated)



Spectral A-Scan



$f_0 \approx 630$ kHz

d ≈ 270 µm

$f_0 \approx 320$ kHz

d ≈ 530 µm

$f_0 \approx 440$ kHz

d ≈ 380 µm

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Conclusion

- Laser-excited acoustics enables NDT of aerospace composites with
  - no contact
  - no water or coupling liquid
- Regions of **different porosity** can be **clearly distinguished**
- **Individual pores** can be resolved through a pore **resonance** mechanism
- **Spectral analysis** allows the estimation of individual **pore size**
- Calculated pore sizes match typical CFRP pores

LEAsys turnkey system

… and Outlook

https://www.youtube.com/watch?v=m-o7C7s02E4

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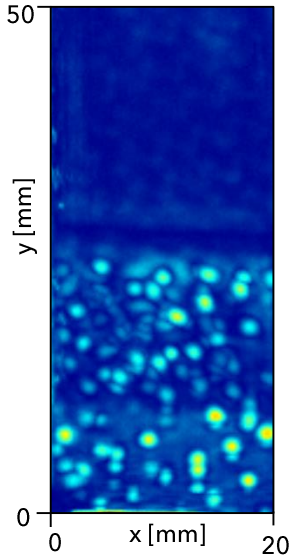
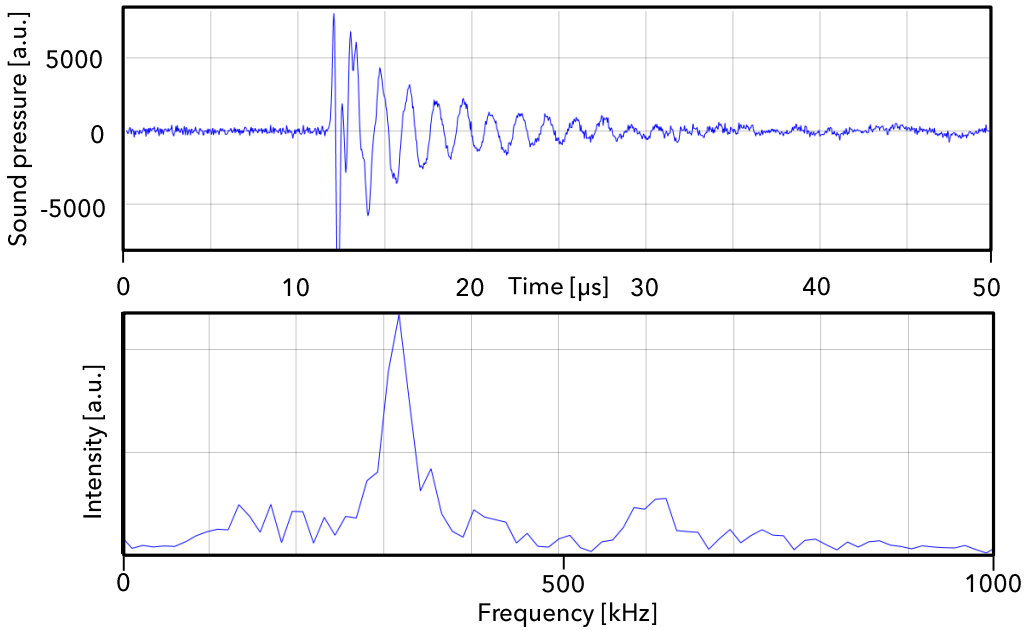


$$d = \frac{c}{2 * f_0}$$



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