Inspection techniques: Thermography

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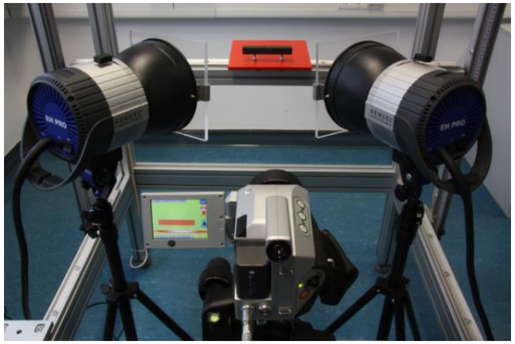
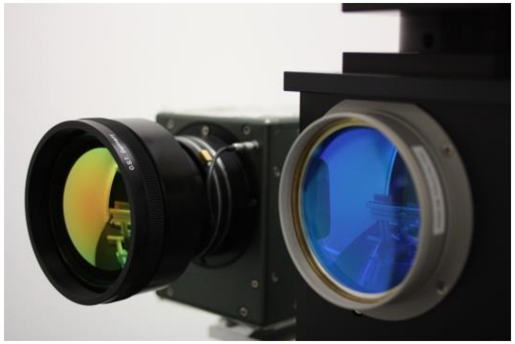
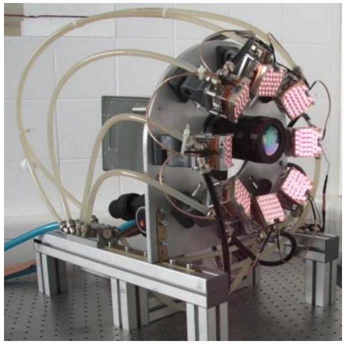
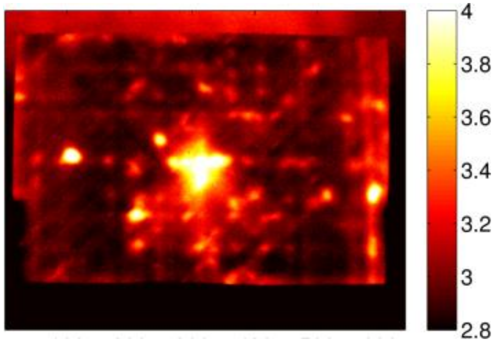
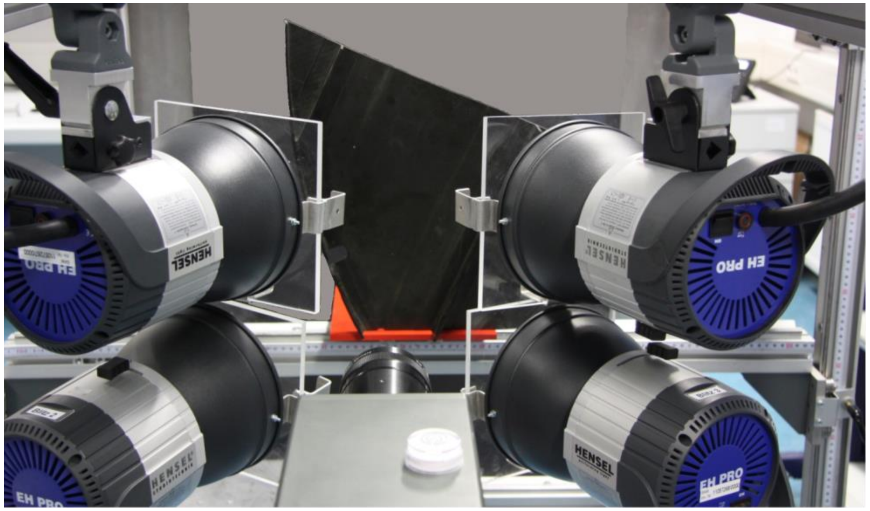





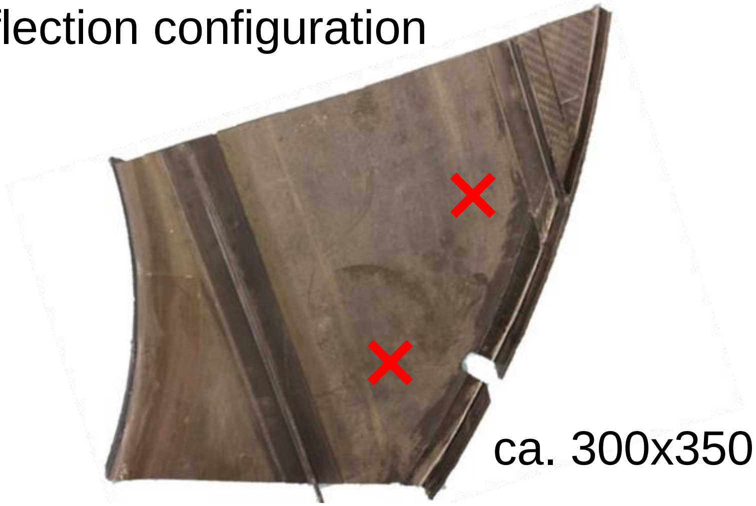
Flash thermography of an airplane side rudder



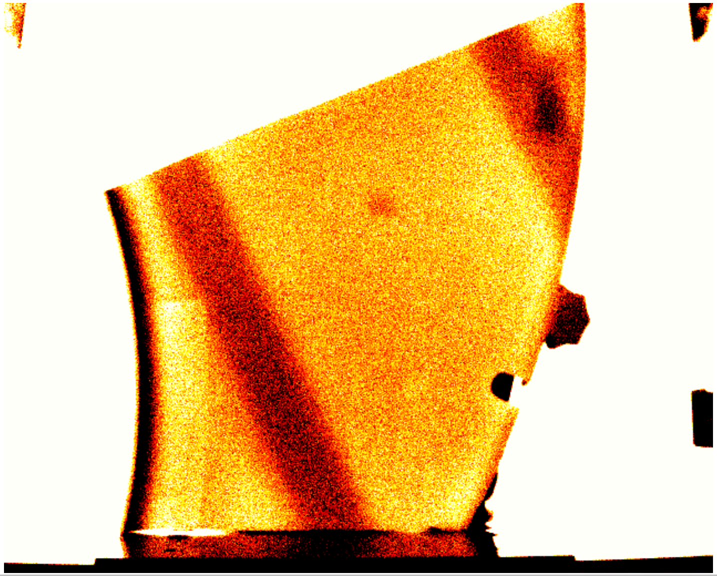
Reflection configuration

- Reflection configuration using 4 flashes from the front side
- InSb IR camera, 640x512 pixel
- 100 Hz frame rate
- Subtraction of zero image
- Measurement duration: 10 s

C. Maierhofer et al, Composites Part B 57, 2014, 35-46



ca. 300x350 mm²



Tasks for active thermography

- Development of theoretical models for **analytical and numerical simulation** of heat transfer in anisotropic or partially translucent materials
- Investigations of **artificial defect artefacts**
- Investigation of **natural defect artefacts**
- **Round robin tests** and **field trials**
- **POD study**
- Comparison to the **other NDT methods**

- Characterisation of **flat panel reference source** for infrared camera temperature calibration
- Determination of **anisotropic thermal properties** of CFRP materials
- Determination of **optical properties of partial translucent** GFRP material

Heat equation

Non-stationary heat conduction process in anisotropic solids is described by the proportionality of heat flux and temperature gradient using the **heat equation** (diffusion equation):

$$\rho(\vec{r})c_p(\vec{r})\frac{\partial T(\vec{r},t)}{\partial t} = \nabla \cdot \left[\lambda(\vec{r})\nabla T(\vec{r},t)\right] + q(\vec{r})$$

T: temperature
$\vec{r}$: position vector
t: time
λ: therm. conductivity
ρ: density
c: spec. heat capacity
q: introduced heat per volume
∇: nabla operator

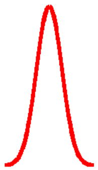
Solution of parabolic DE:

- Spatial boundary conditions (temperature or heat flux) have to be set
- Temporal starting conditions, i.e. temperature distribution at t = 0, have to be set
- Strong attenuation

Comparison to solution of hyperbolic DE (wave equation):

- Spatial boundary conditions have to be set
- Two temporal starting conditions: temperature distribution at t=0 and first derivative to time
- Little attenuation

1D analytical solutions



Solution for Dirac pulse (flash excitation)

$$T(z,t) = \frac{q}{\varepsilon\sqrt{\pi\, t}} e^{-z^2/4\alpha t}, \quad T(0,t) = \frac{q}{\varepsilon\sqrt{\pi\, t}}$$

1D, for semi-infinite isotropic bodies

$\varepsilon = \sqrt{\lambda\,\rho c}$ Effusivität

$\alpha = \frac{\lambda}{\rho c}$ Diffusivität

$$L_{\max} = \frac{q}{\rho c} \frac{1}{n \cdot \Delta T_{NETD}}$$

Max. penetration depth L_{max} depends on heat density, NETD of IR camera **and on density a**nd **spec. heat capacity** (n=2 to3)

Solution for periodic heating (lockin excitation)

$$T(z,t) = T_0\, e^{-z/\mu} \cdot e^{-i(\omega t - z/\mu - \pi/4)}$$

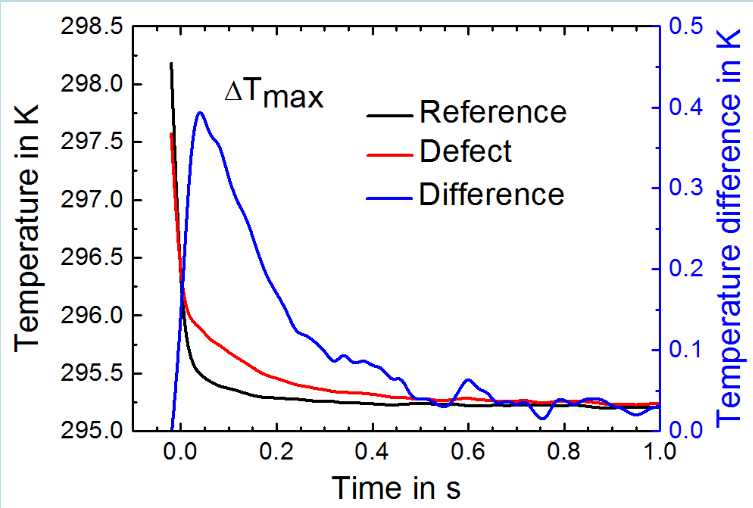
$$\mu = \sqrt{\frac{2\alpha}{\omega}}$$

Penetration depth of thermal wave:

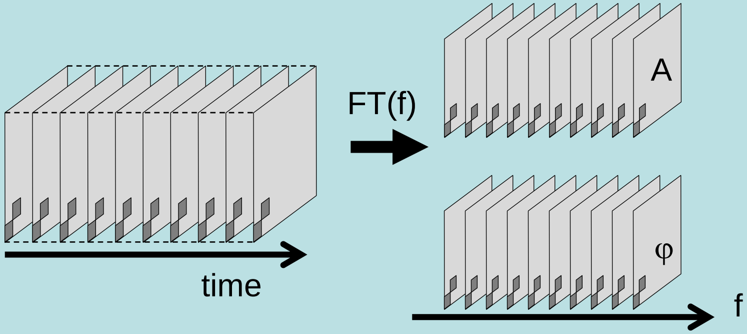
- decreases with increasing frequency
- increases with increasing diffusivity α

Active thermography

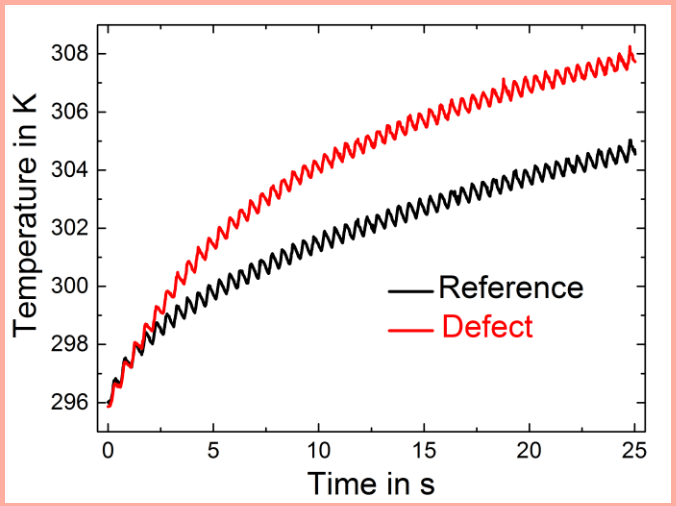
Flash thermography



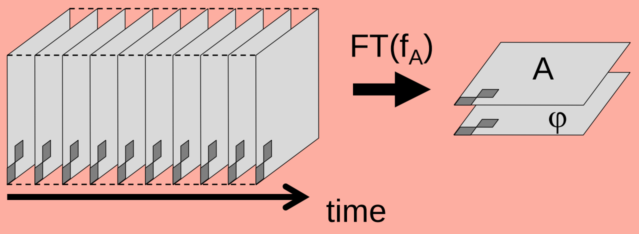
- Thermograms at raising or max. contrast
- **Pulse-Phase-Thermography (PPT)**
- Thermal signal reconstruction (TSR)



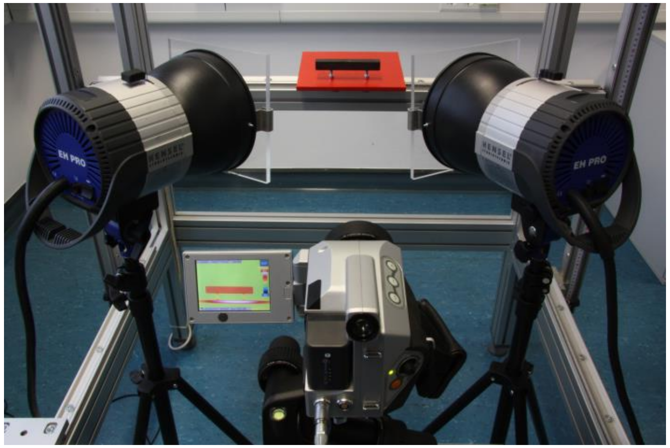
Lockin thermography



- Online **FFT** or 4 point method at excitation frequency
- Offline **FFT** at excitation frequency



Experimental set-up



Flash excitation

4 flash lamps with
6 kJ each

>> 24 kJ

Duration of impulse:
2.6 ms

Duration of measurement:
1 to 3 min

Infrared camera

InSb detector 640x512

2 to 5 µm

NETD of 25 mK

Full frame rate: 300 Hz

Lockin excitation

2 halogen lamps with
1.25 kW each **>> 2.5 kW**

Frequencies: 0.01 to 1 Hz

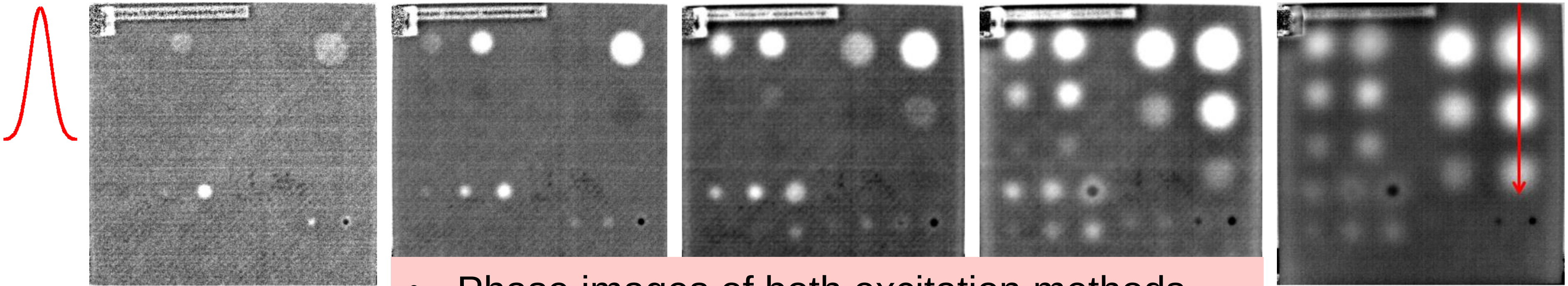
Periods: 10 to 180

>> 250 to 1500 kJ

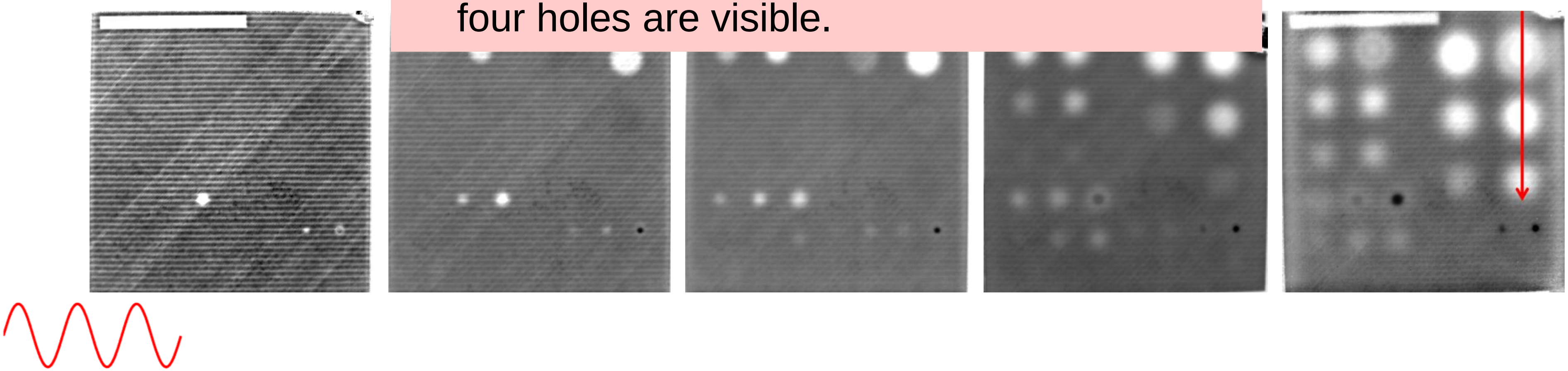
Duration of measurement:

3 to 15 min

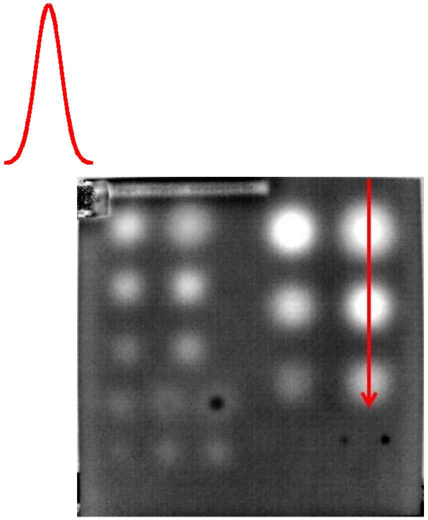
Phase images of artificial FBH

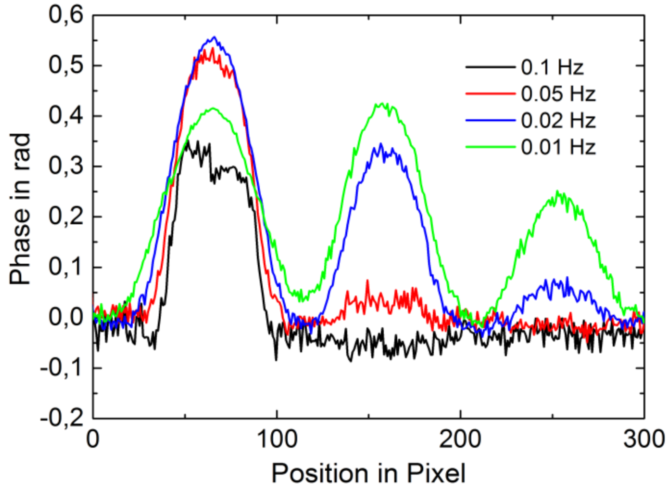


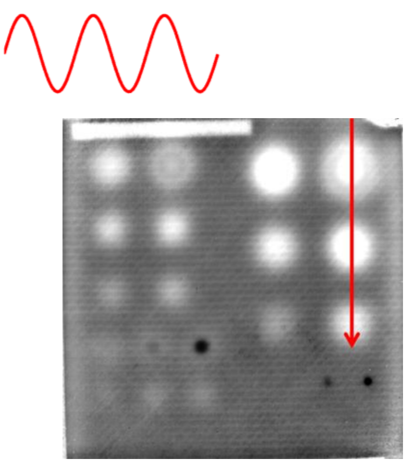
- Phase images of both excitation methods look very similar, phase wrap is similar
- For flash excitations, the holes appear slightly earlier (at higher frequencies)
- All holes with larger diameter could be detected. For the 4 mm holes, only three to four holes are visible.

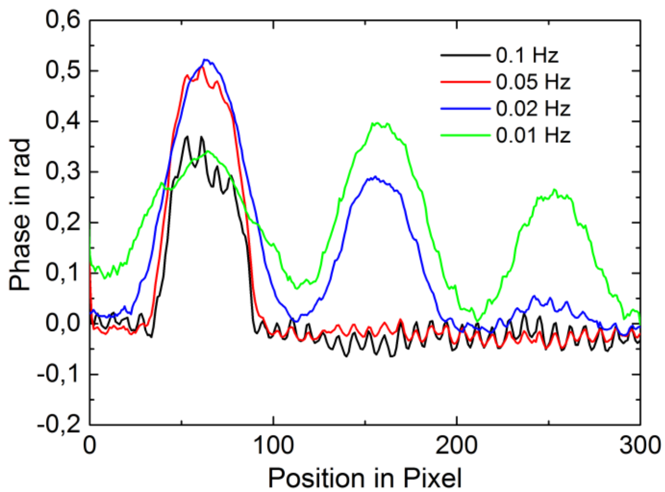


Results: CFRP with FBH









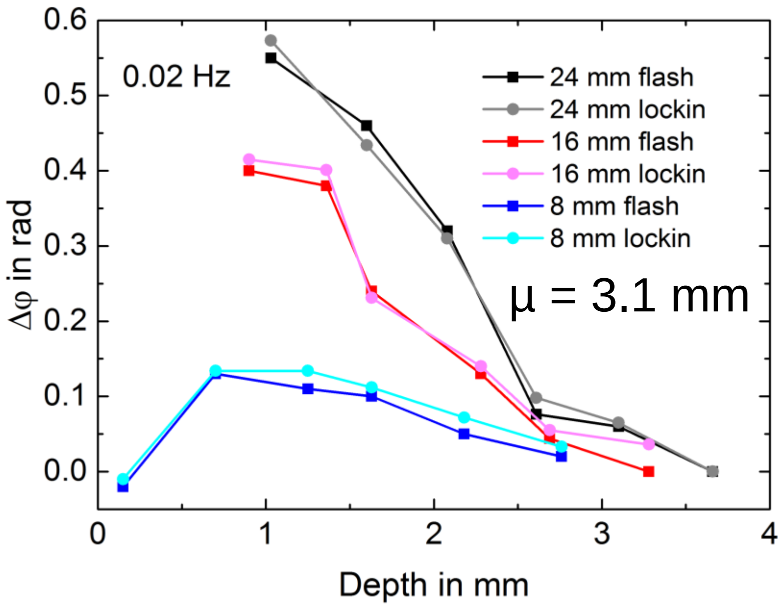
0.01 Hz

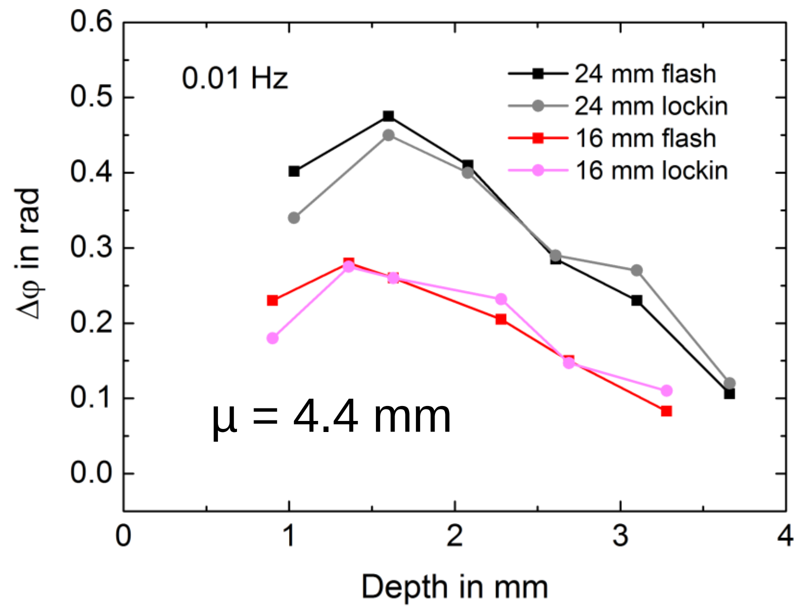
Comparison of spatial resolution of the phase images

- along a line scan of 24 mm holes with wall thicknesses of 1, 2 and 3 mm
- **phase contrasts** of both methods are similar and are changing with frequency
- **SNR** is higher for lockin data
- **spatial resolution** of holes is better for flash data but …
- …in the lockin data, the **fibre bundles** could be resolved.

Results: CFRP with FBH

Influence of defect size, depth and excitation frequency on phase contrast





- Phase contrast is similar for flash and lockin excitation
- Phase contrast is higher for larger defects
- Optimum phase contrast depends on depth and frequency

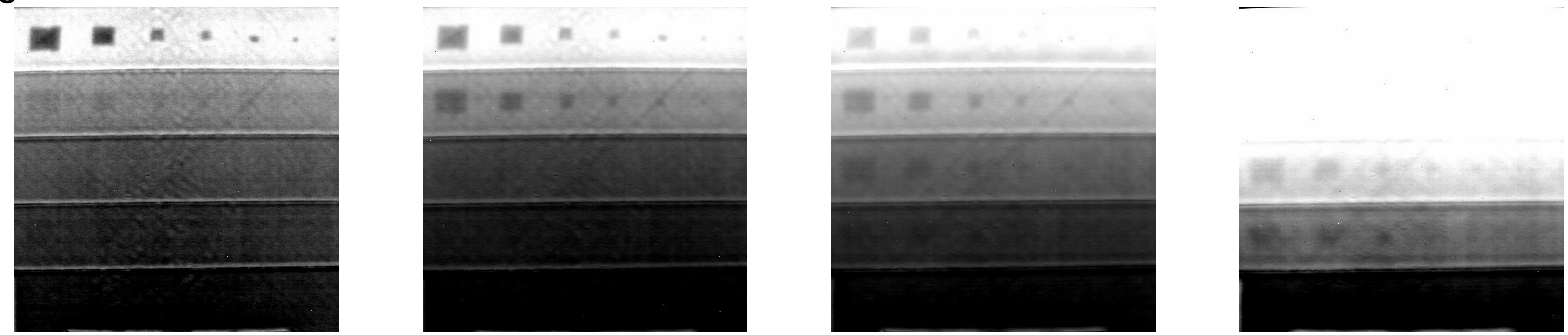
- Maximum penetration depth depends on frequency:

$$\mu = \sqrt{\frac{\alpha}{\pi f}}$$

μ: penetration depth
α: thermal diffusivity
f: frequency

coverage in mm

0.5
1.0
1.5
2.0
2.5



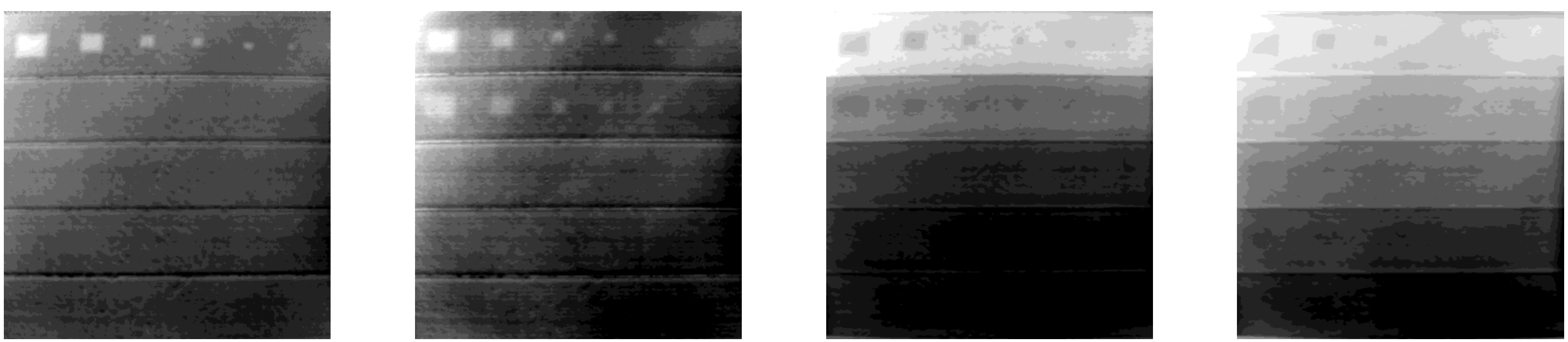
1 Hz
0.45 mm

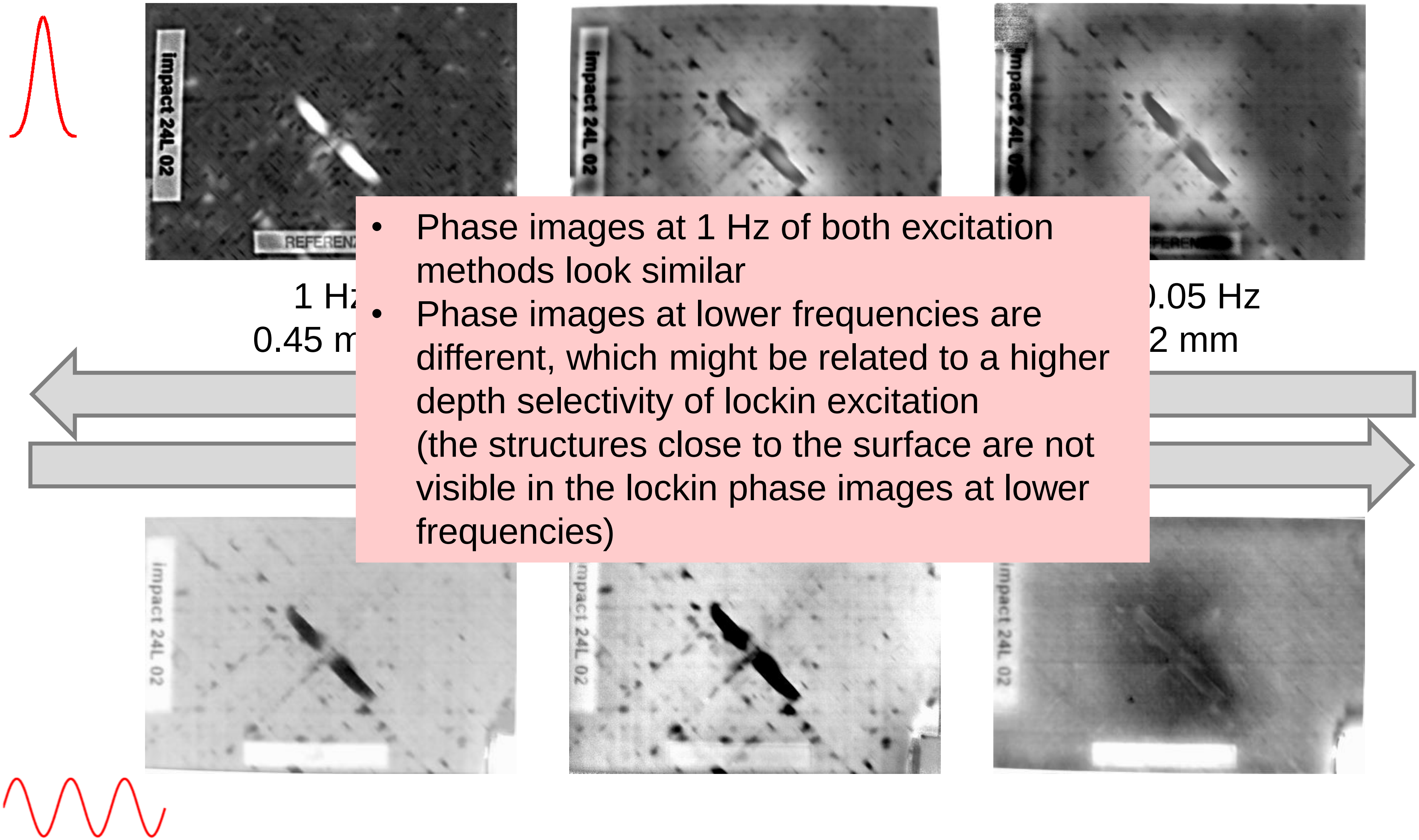
0.2 Hz
1 mm

- Phase images of both excitation methods look very different
- For flash excitations, larger defects up to a depth of 1.7 mm could be detected
- For lockin excitation, only the defects up to a depth of 0.9 mm could be detected

1 Hz, 190 peri
0.45 mm

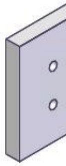
5 Hz, 25 periods
2 mm



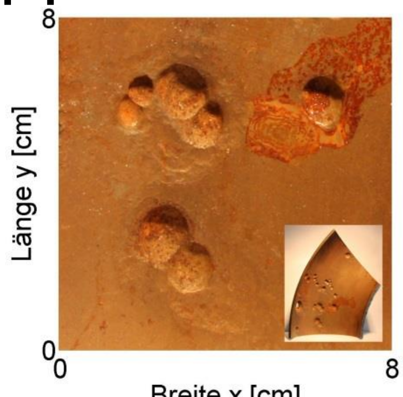


- Phase images at 1 Hz of both excitation methods look similar
- Phase images at lower frequencies are different, which might be related to a higher depth selectivity of lockin excitation (the structures close to the surface are not visible in the lockin phase images at lower frequencies)

back side
geometry
z

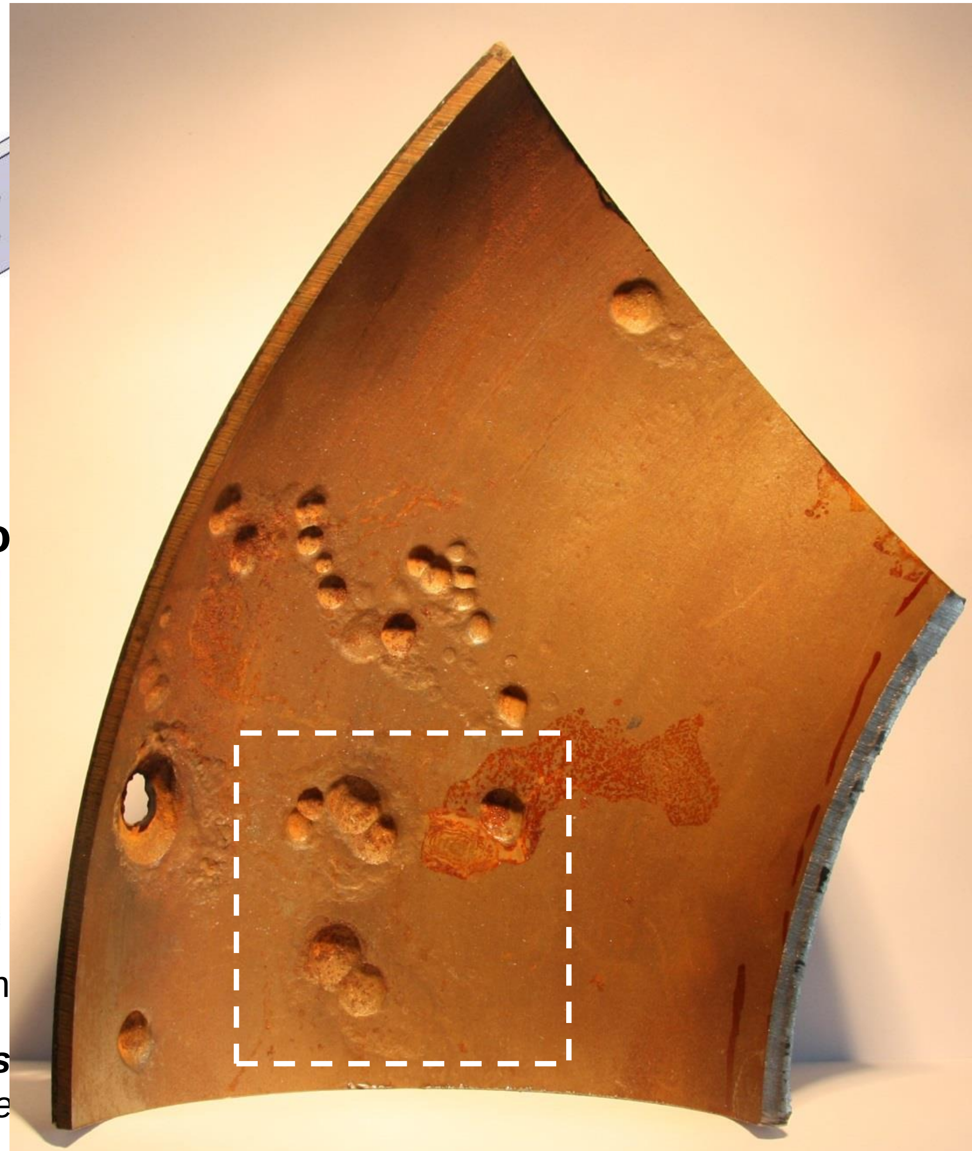


pipe with corrosio



Wall thickness: 3.6 m

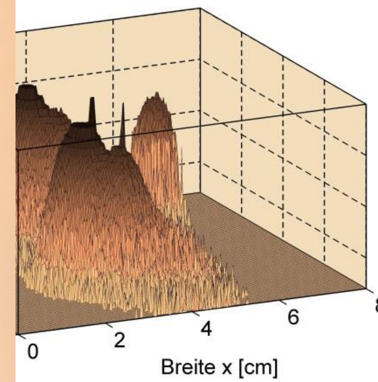
Regina Richter, Diss
TU Braunschweig, De



front side
temperature field
T(x, y, t)

lge:
ameters are known

nstruction



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ith ZIB

Criteria for validation

- Detectability of defects as a function of defect size and defect depth (remaining wall thickness)
- Quantitative phase contrast of defects as a function of depth (remaining wall thickness)
- Signal-to-noise ratio (SNR) of defects
- Penetration depth
- Depth resolution
- Spatial resolution

Outlook

Next steps:

- Determination of thermal and optical material properties
- Systematic testing of new artificial reference defect artefacts (RDAs) with flash and periodic excitation
- Systematic analytical und numerical modelling of RDAs
- Numerical reconstruction