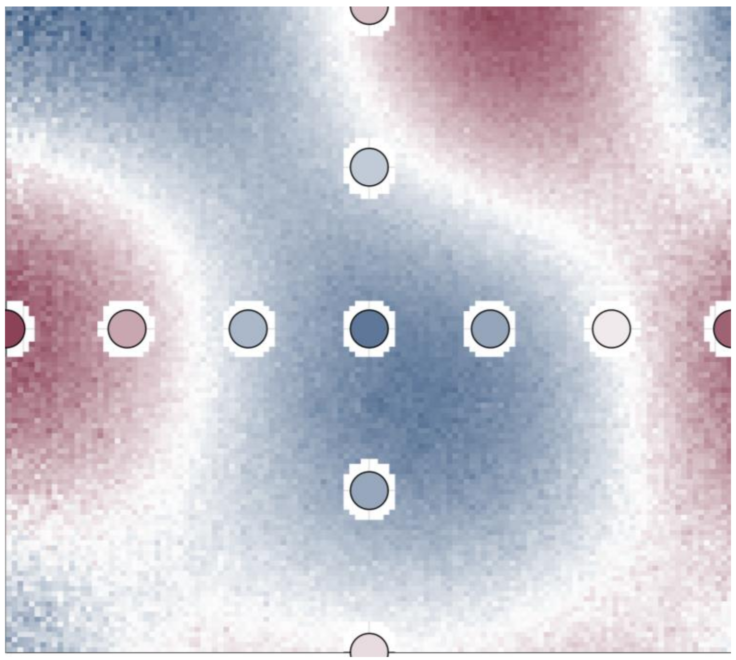


Advanced optical techniques for fan deformation and noise propagation measurements

CA3ViAR Dissemination Event #1

September 6th, 2022
Hannover, Germany

Jan Goessling, Joerg R. Seume
Institute of Turbomachinery and Fluid Dynamics
Leibniz University Hannover

Prof. Dr. Seume
Institute of Turbomachinery and Fluid Dynamics
Leibniz Universität Hannover

Agenda

1) Motivation
2) Digital Image Correlation (DIC) for deformation measurements
3) Pressure-Sensitive Paint (PSP) for acoustic measurements
4) Conclusions and Outlook

Project partners

Motivation

<u>Design trends of future turbofan engines</u>

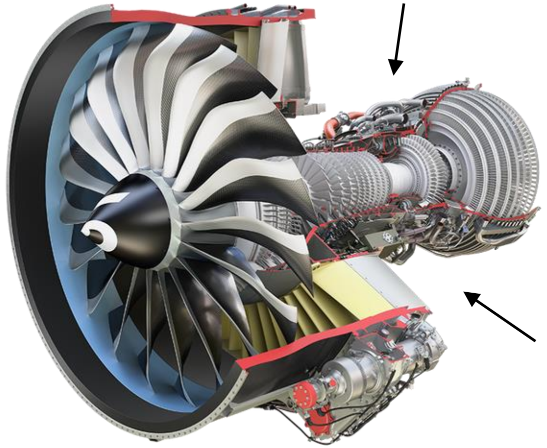
- increase bypass ratio to reduce specific fuel consumption
- shorten intake to reduce weight and wetted intake surface
- reduce weight by fiber composites

<u>Structural design challenges</u>

- slender and highly loaded blades
- hot-to-cold shape transformation
- reduced stall margin with increased risk of flutter

<u>Noise emission</u>

- stringent requirements
- but short intake increases noise emission
- ➢ cut-off fan design
- ➢ decreased rotational speed



Modern turbofan engine - CFM International LEAP-1C [1]

Experimental investigations mandatory to validate design tools and engine performance.

Deformation measurements by Digital Image Correlation (DIC)

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Digital Image Correlation (DIC) – Idea

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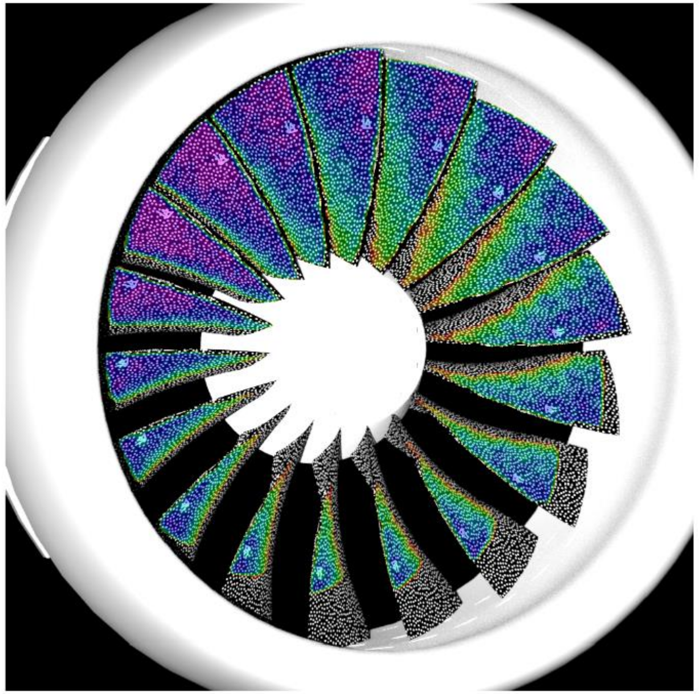
Advanced optical techniques for fan deformation and noise propagation measurements

Method DIC: **Optical measurement technique for spatial deformation vs. reference**
Idea: **Deformation measurements of loaded rotor blades**



Target measurements

- blade geometry
- hot-to-cold shape transformation
- vibration due to forced response and flutter

Difficult measurement condition due to fast rotation and small vibration amplitudes:

- short exposure time $t < 1.7$ µs to eliminate motion blur
- high frame rate $f > 1000$ Hz to resolve vibration
- high spatial resolution, cameras limited to 1 MPx

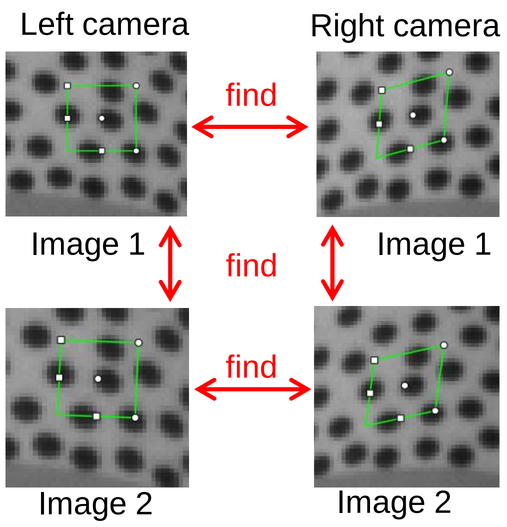
New high-speed DIC setup required to measure both deformation and vibration. → Pre-Tests

Digital Image Correlation (DIC) – Principle

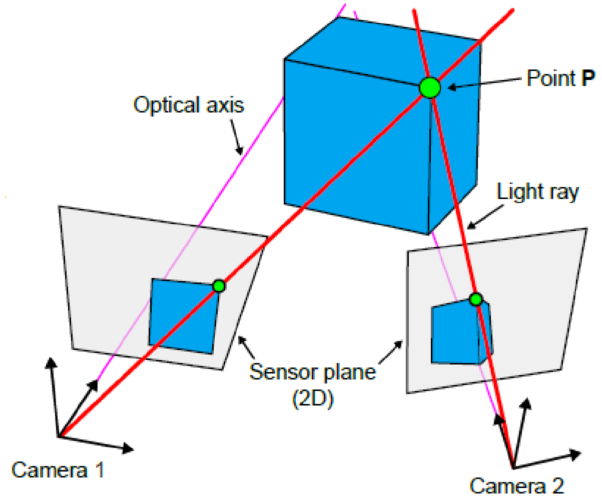
Principle

1) Calibrate camera system
2) Find corresponding points/subsets
3) Triangulate: Recover the 3D position
4) Calculate displacement relative to reference position

Greyscale signature of an image



Triangulation



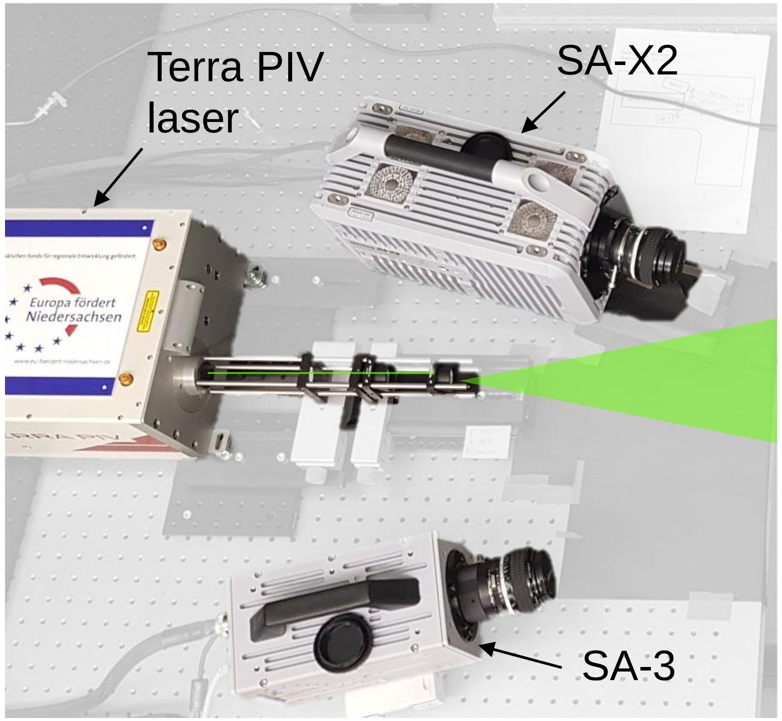
Digital Image Correlation (DIC) – Hardware

Hardware for high-speed DIC

Camera	**Photron SA-X2**	**Photron SA-3**
Resolution	1024x1024 Pixel	1024x1024 Pixel
Frame rate	12.500 Hz	2000 Hz
Min. exposure time	1 µs	2 µs
Max. no. of images	21839	2726

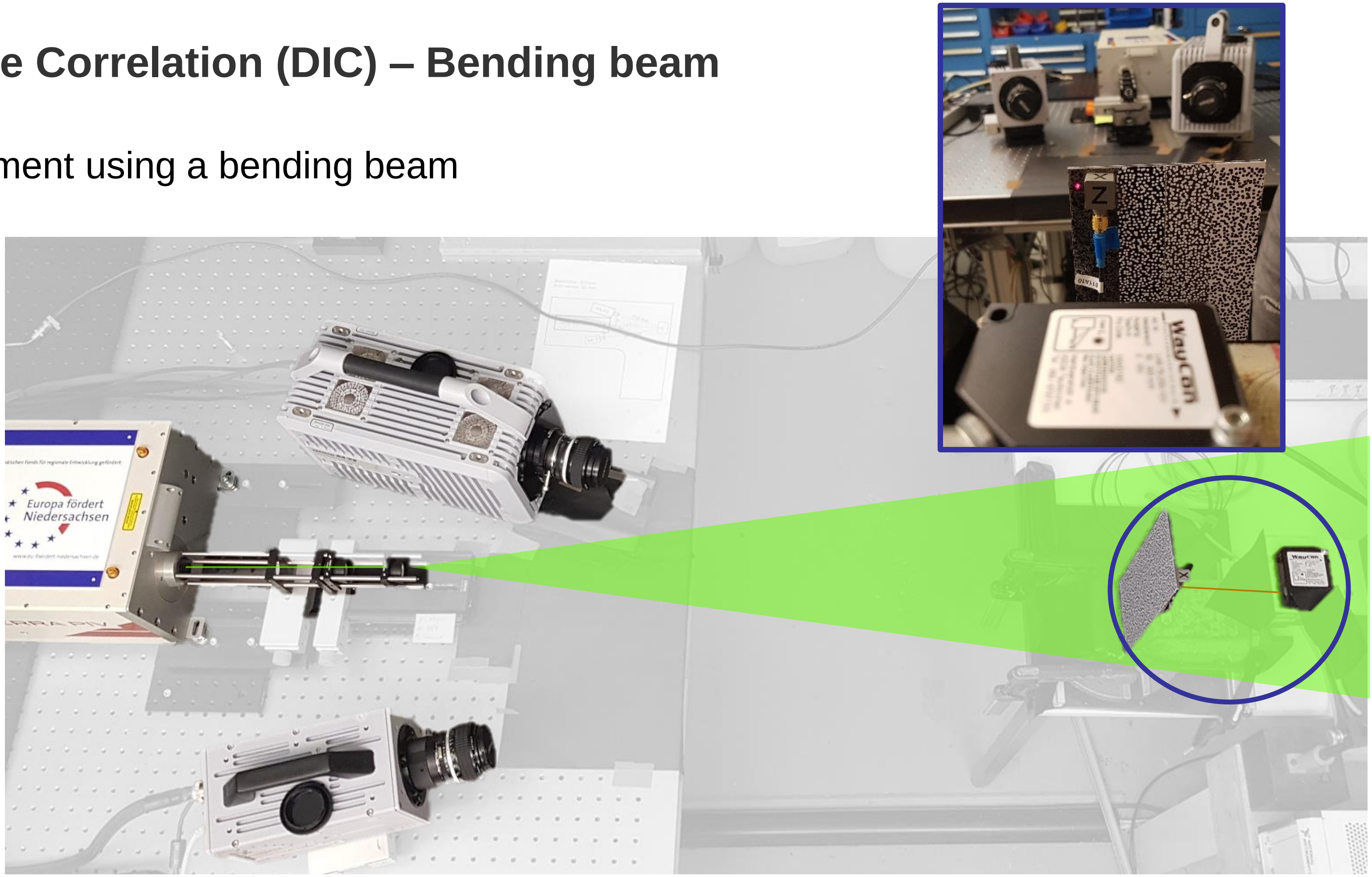
Use a pulsed high-speed laser to decrease exposure time and improve camera synchronisation.

Laser	**Terra PIV 527-100-M**
Wave length	527 nm
Pulse rate	1.000-10.000 Hz
Pulse width	< 210 ns



Digital Image Correlation (DIC) – Bending beam

Test measurement using a bending beam



Gößling MS Thesis, 2020

- test of different speckle pattern
- measurement of vibration
- comparison of DIC results with
  - reference data in time and frequency domain
  - modal analysis calculated using FEM

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Advanced optical techniques for fan deformation and noise propagation measurements

Motivation

DIC

PSP

Conclusions

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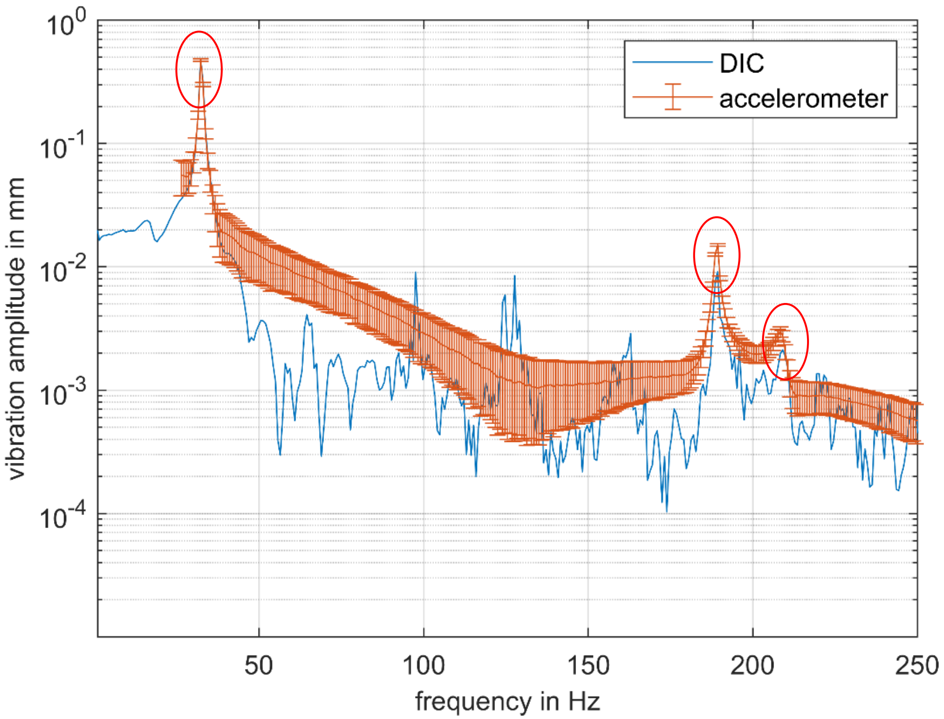
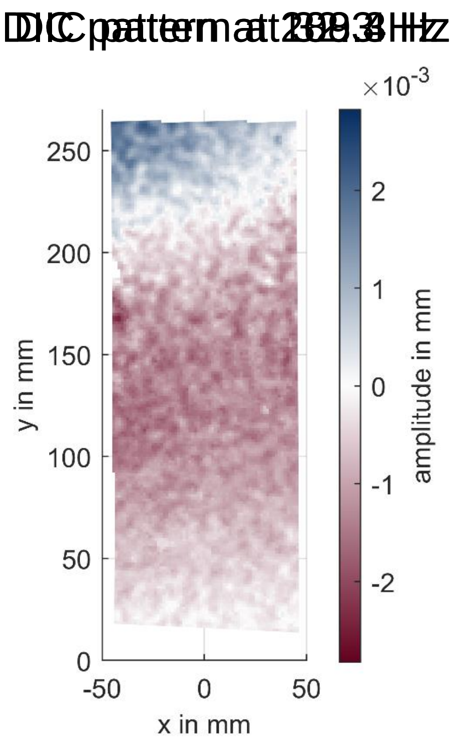
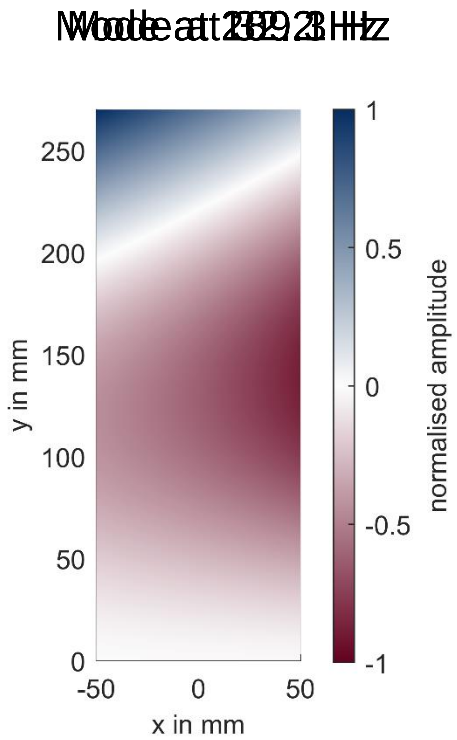
Digital Image Correlation (DIC) – Bending beam

Measurement results in frequency domain







Uncertainties of accelerometer are given with 95% confidence interval

- detection of 3 peaks up to a frequency of 250 Hz
- amplitude of first peak within measurement uncertainties
- underestimated amplitude of low amplitude peaks

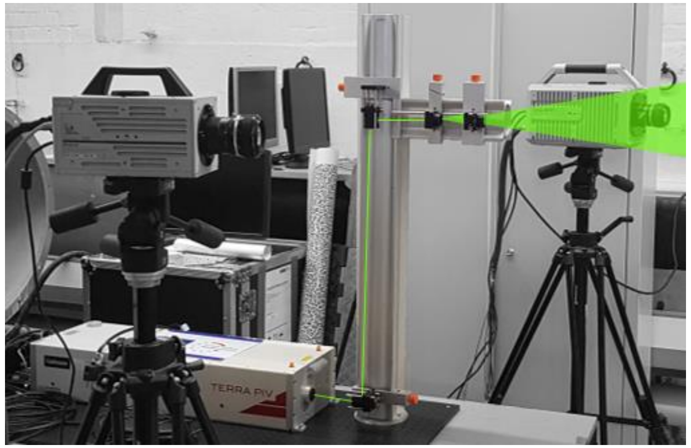
➢ Spatial deformation pattern agrees with mode shape from FEM.

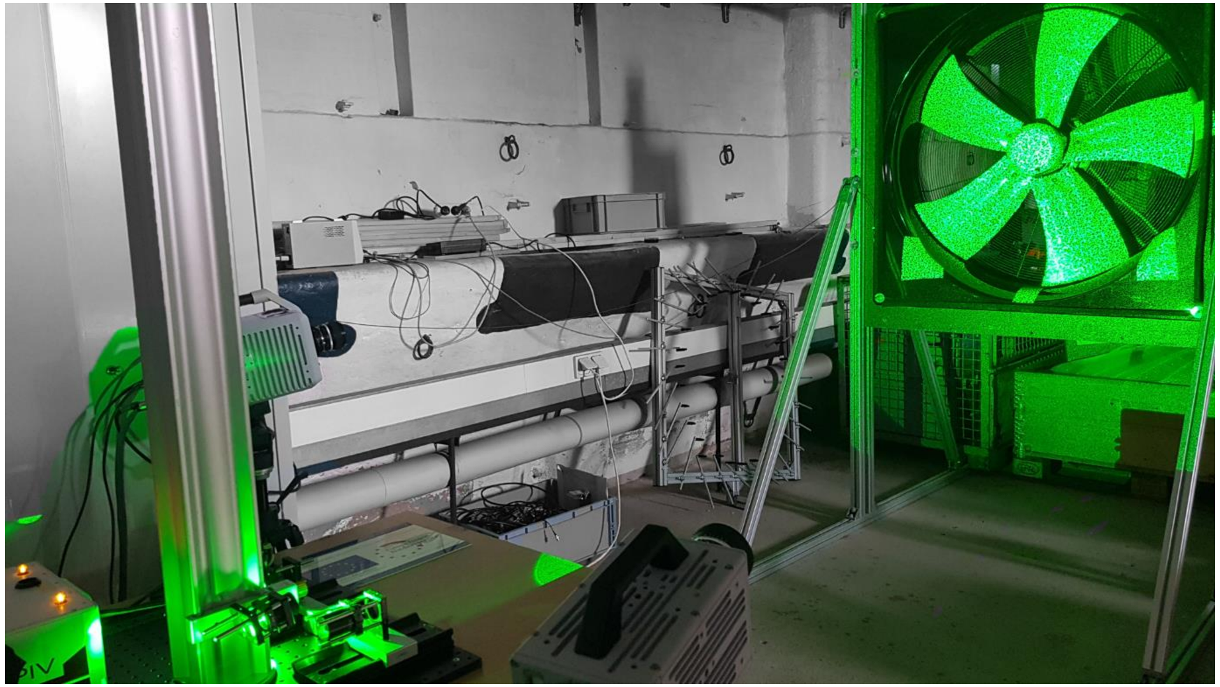
Digital Image Correlation (DIC) – Axial blower

An axial blower is used to test on a rotating object similar to CA3ViAR fan.

Specifications

- max. rotational speed: 1000 RPM
- diameter: 1 m
- no. of blades: 5
- speckle pattern with 5 mm dot diameter





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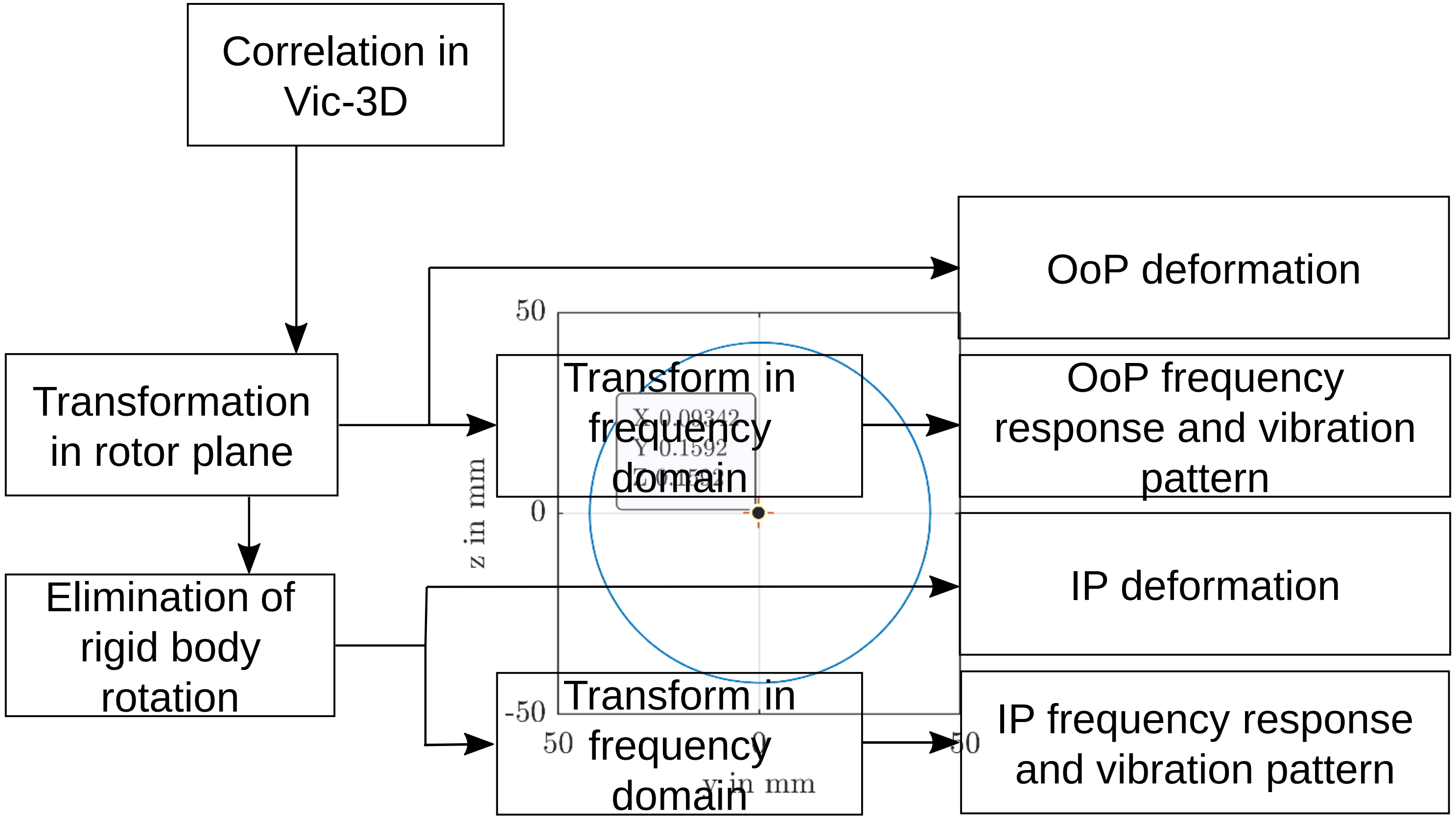
Digital Image Correlation (DIC) – Axial blower

Data analysis method

- correlation and triangulation with commercial software Vic-3D 8
- further data analysis required for rotor plane alignment and rigid body rotation elimination
- fast Fourier Transform to transform into frequency domain.



OoP: Out-of-Plane   IP: In-Plane

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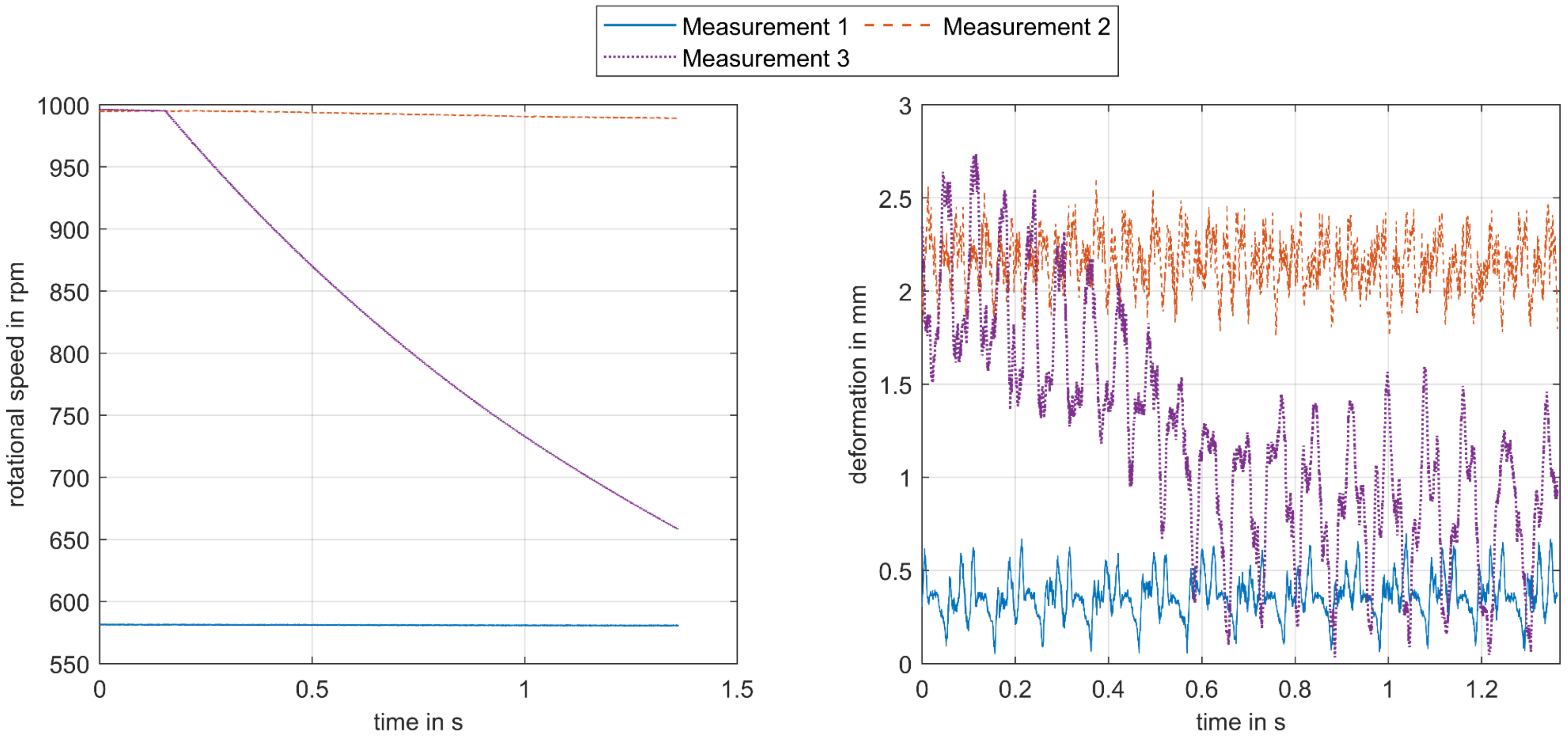
Digital Image Correlation (DIC) – Axial blower

Deformation at blade tip for different rotational speeds

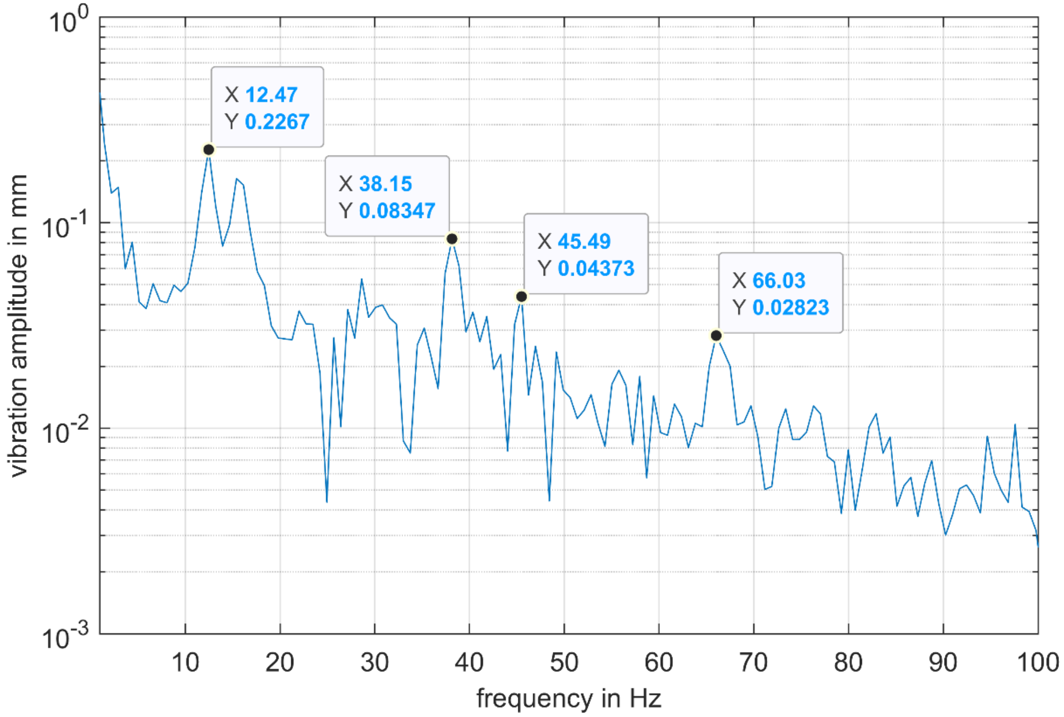


Deformation depends on rotational speed, as expected:

- increased deformation at higher rotational speeds
- constant mean deformation at constant rotational speeds
- increase in oscillation due to blower shut-off in measurement 3

Digital Image Correlation (DIC) – Axial blower

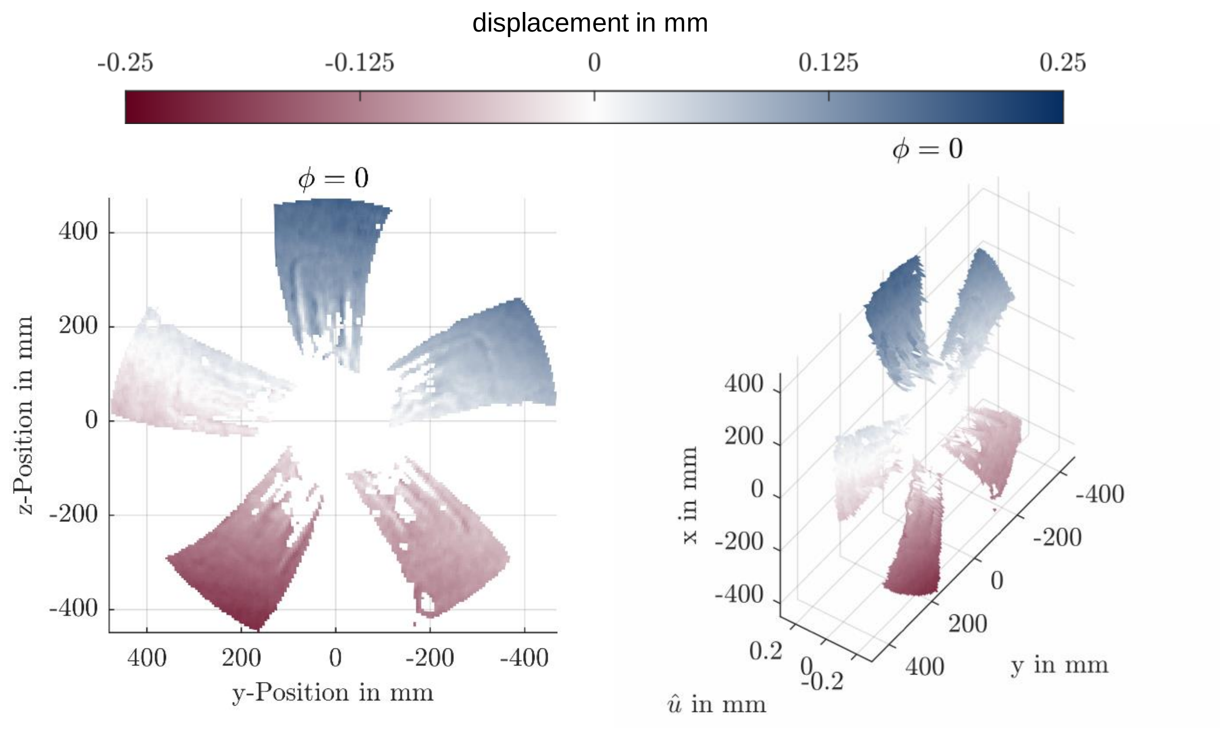
Frequency spectrum of measurement 3 due to forced excitation by rapid shut-off of blower



Specific peaks in frequency response!
Frequency peaks agree with eigenfrequencies measured by accelerometer at rest→ detailed spatial analysis

Digital Image Correlation (DIC) – Axial blower

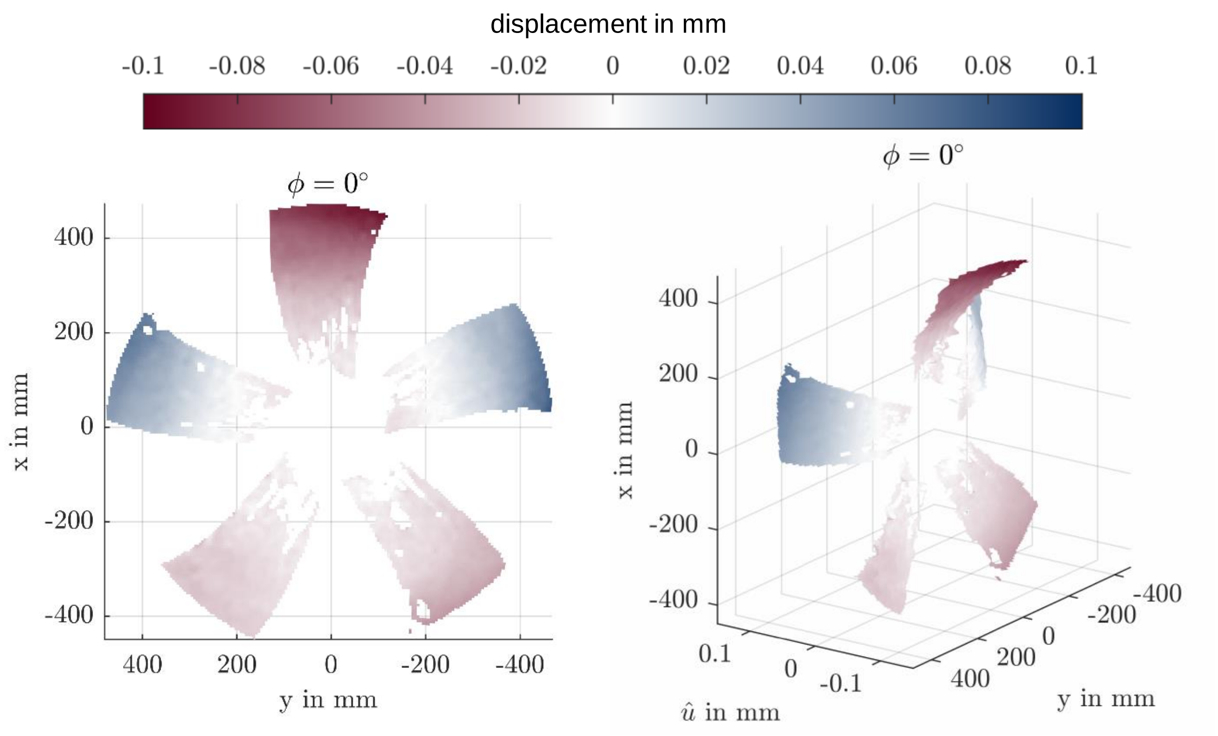
Displacement of OoP vibration pattern at 12.5 Hz:



Analysis of pattern reveals rigid-body gyration of rotor due to elasticity of support of bearing housing.

Digital Image Correlation (DIC) – Axial blower

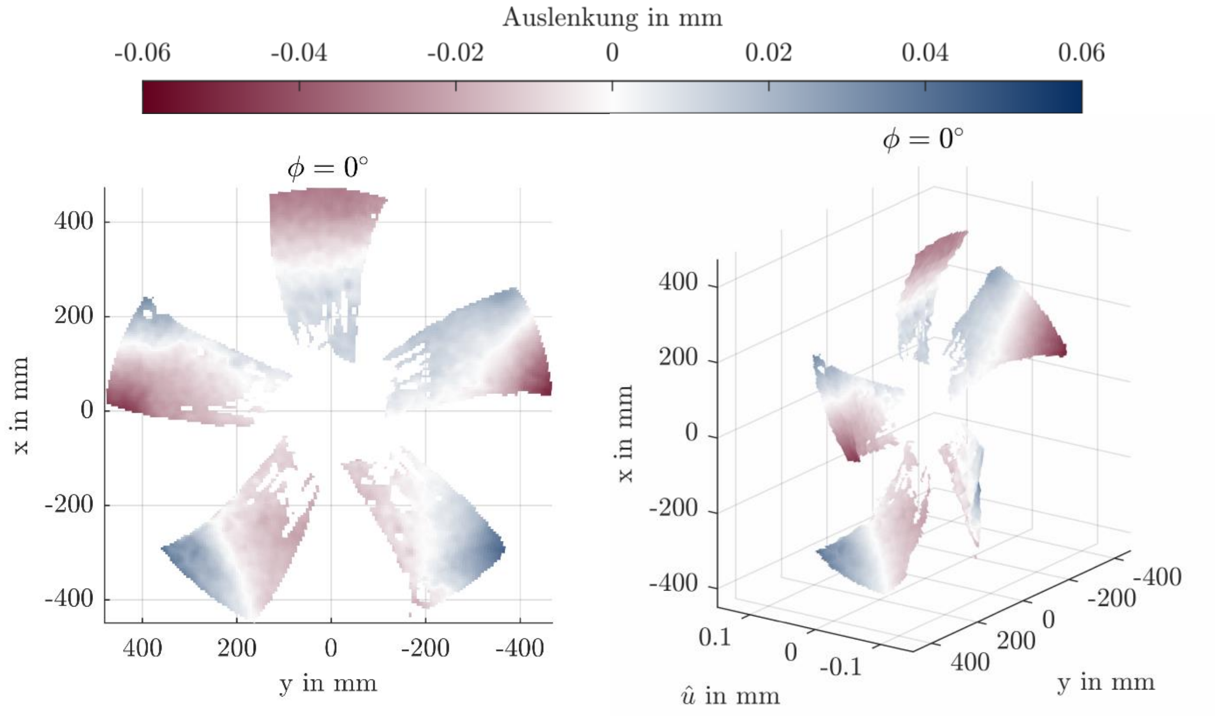
Displacement of OoP vibration pattern at 38.2 Hz:



Analysis of pattern reveals
- deformation of blade in vibration pattern noticeable → 1F-mode
- blades vibrate with relative phase difference
  - nodal diameter 2 dominant
  - possibly superposition of several nodal diameters

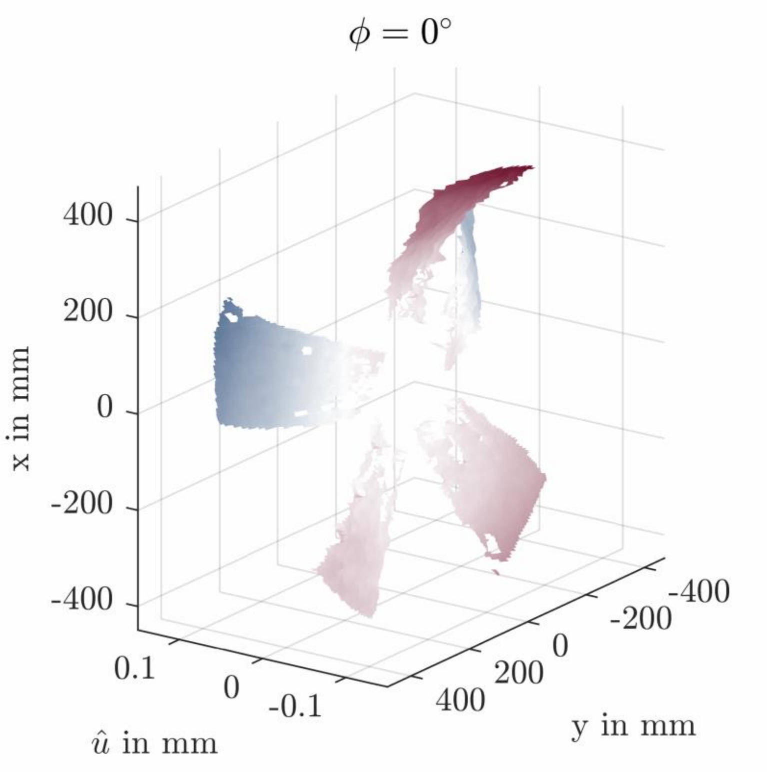
Digital Image Correlation (DIC) – Axial blower

Displacement of OoP vibration pattern at 66.03 Hz



Complex vibrational pattern
- displacement with different phase angles at single blade tip
- possibly superposition of several modes (e.g. 1T/2F)
  Modal analysis would be required to identify mode shapes.

Digital Image Correlation (DIC) – Conclusions

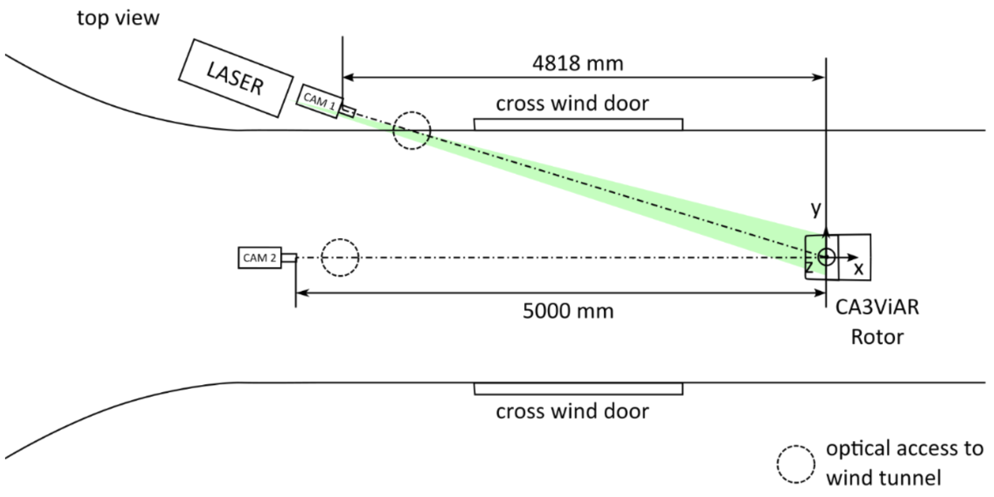


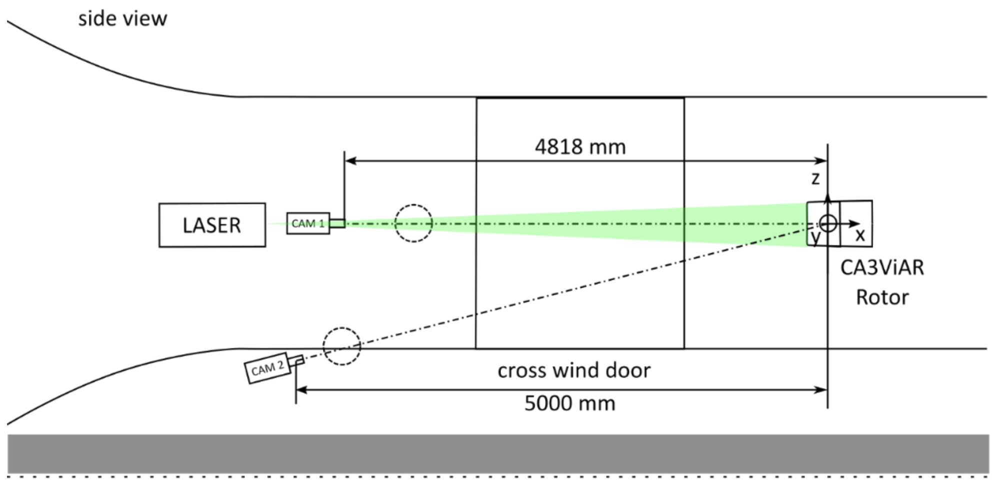
Conclusions of DIC pre-tests

- general applicability of high-speed DIC demonstrated
- setup validated in bending-beam test case
- blade mode successfully extracted by subtracting rigid body motion
- spatial vibration pattern analysis in frequency domain

→ Instrumentation concept for CA3ViAR measurement is derived from DIC pre-tests.

→ Reference measurements with strain gauges will be used for CA3ViAR.

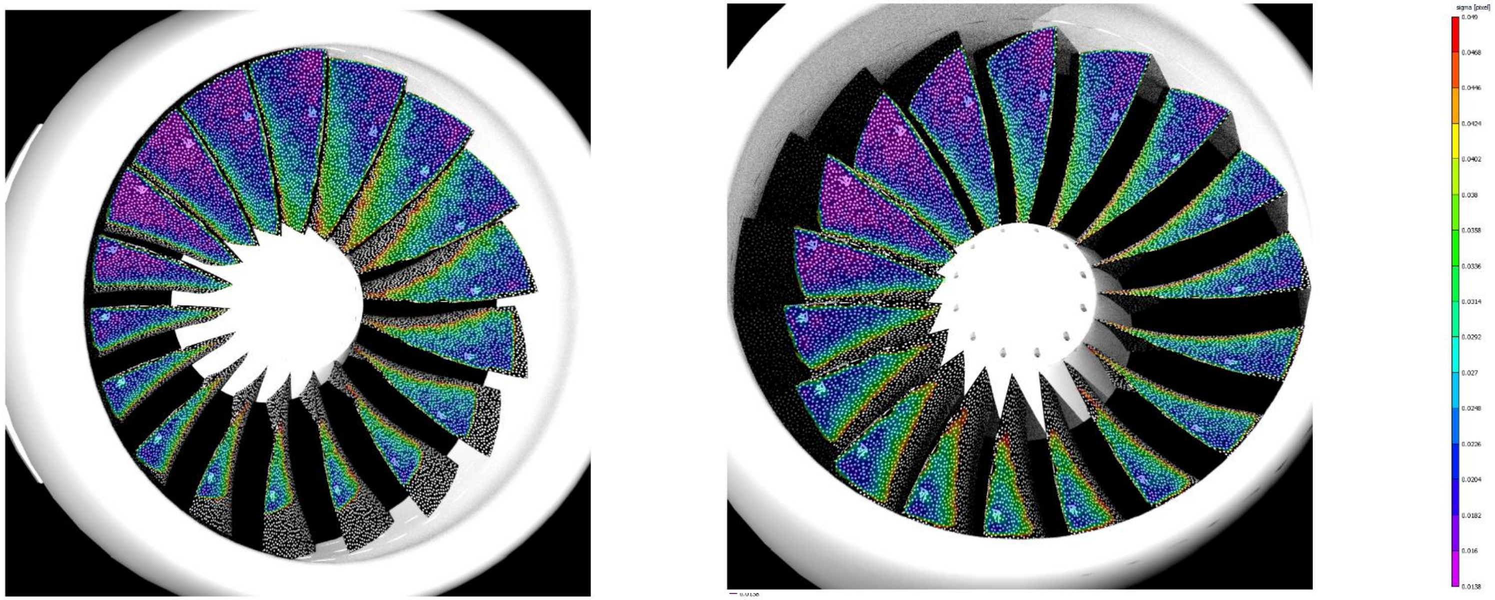




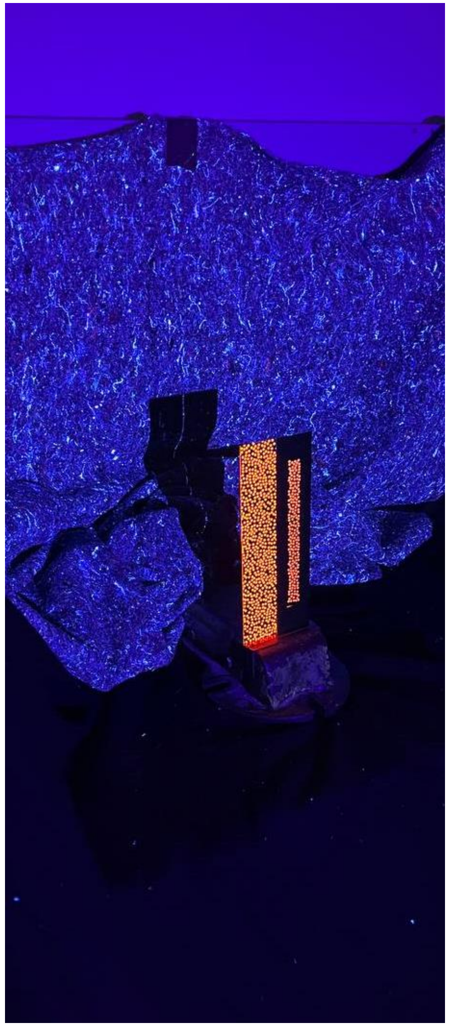
Digital Image Correlation (DIC)

- Optimisation of …
  - camera positioning
  - speckle pattern plus labelling
  - marker tracking

  … using 3D rendering
- Test of speckle pattern application on composite surface
  - correlation quality based on reflection and contrast
  - small influence on surface



Correlation of left and right camera (3D-rendering)



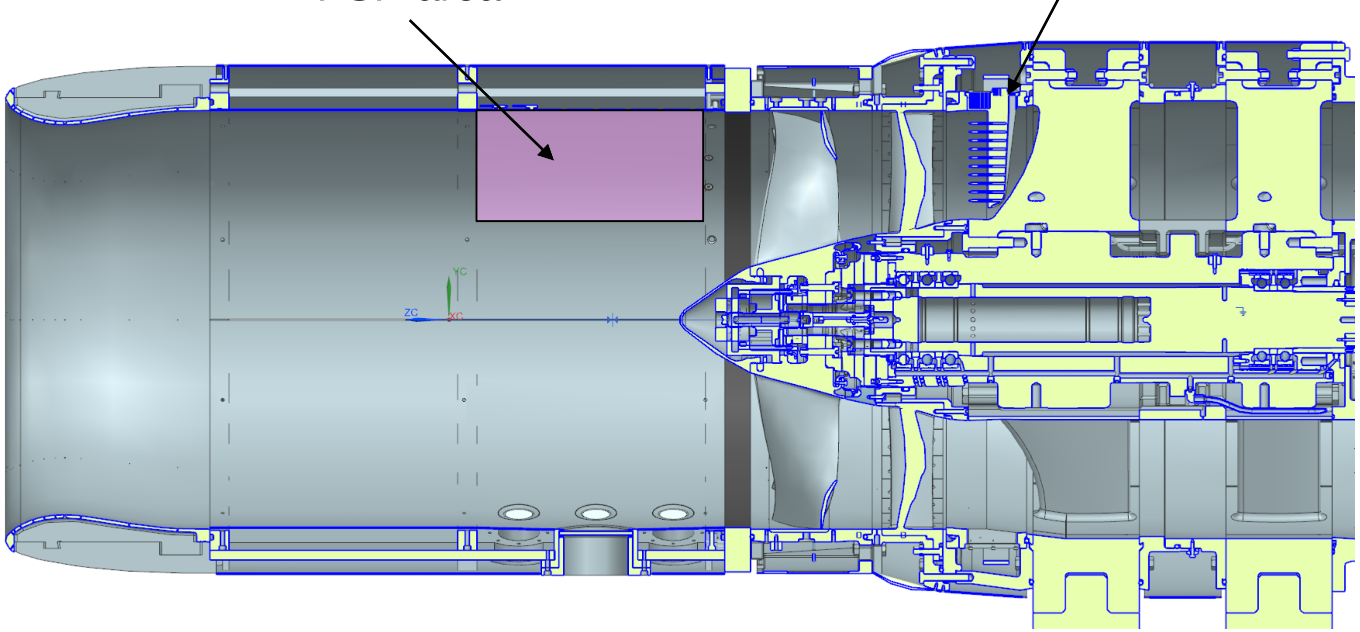
Fluorescent paint on CFRP surface

Acoustic measurements by Pressure-Sensitive Paint (PSP)

Pressure-sensitive paint (PSP)

Aim: Design an **extended PSP-Intake** to measure tonal noise propagating **upstream of the rotor**.

- Perform spatial measurement of sound pressure at intake duct wall up to 5 kHz.
- Analyse pressure distribution and compare it to computational aeroacoustics (CAA) simulation.
- Use microphone reference measurements.



Challenge: Sufficient resolution of acoustic fluctuations at high frequencies with PSP → Pre-Test

Pressure-sensitive paint (PSP) – Principle

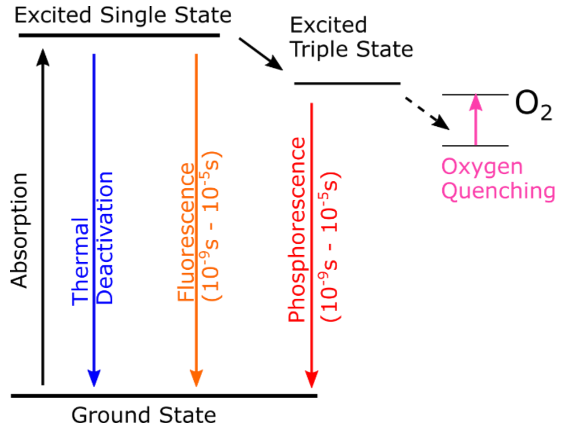
Pressure-sensitive paint is an optical measurement technique based on the luminescence of molecules (luminophore).

<u>Principle</u>

- excitation of luminophore with light of specific wavelength (395 nm)
- release of energy by emitting light with increased wavelength (650 nm)

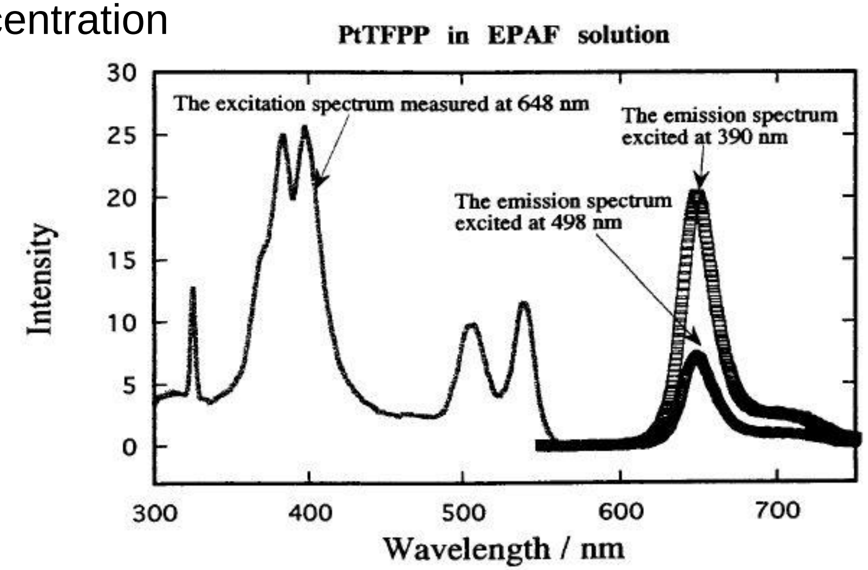
Or

- release of energy to oxygen molecule due to oxygen quenching without light emission
- probability of oxygen quenching proportional to oxygen concentration



Jablonski Diagramm

- ➢ Oxygen concentration is proportional to pressure.
- ➢ **Intensity** of luminescence is **inversely proportional** to surface **pressure.**



(Puklin et al. 2000)

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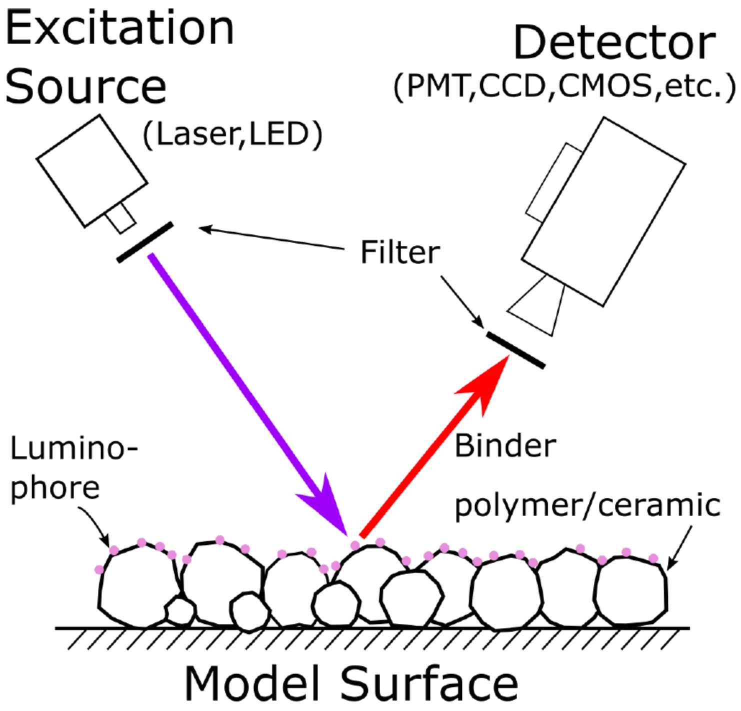
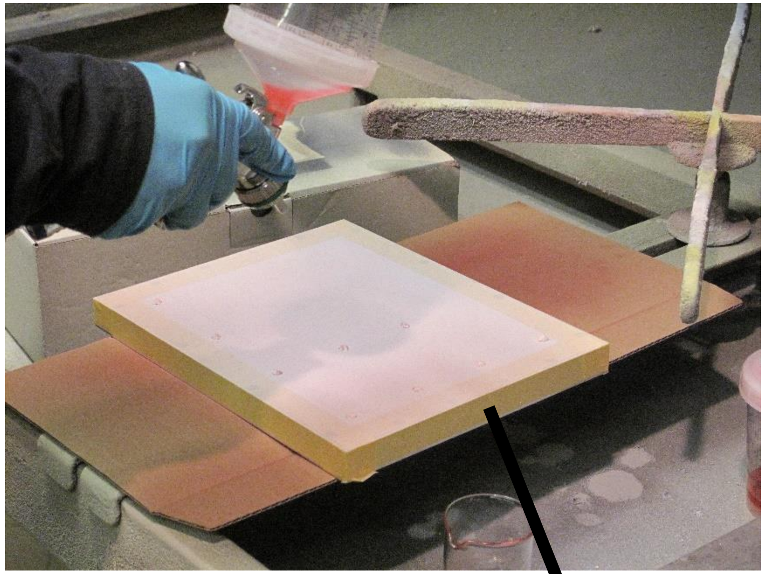
Jan Gößling

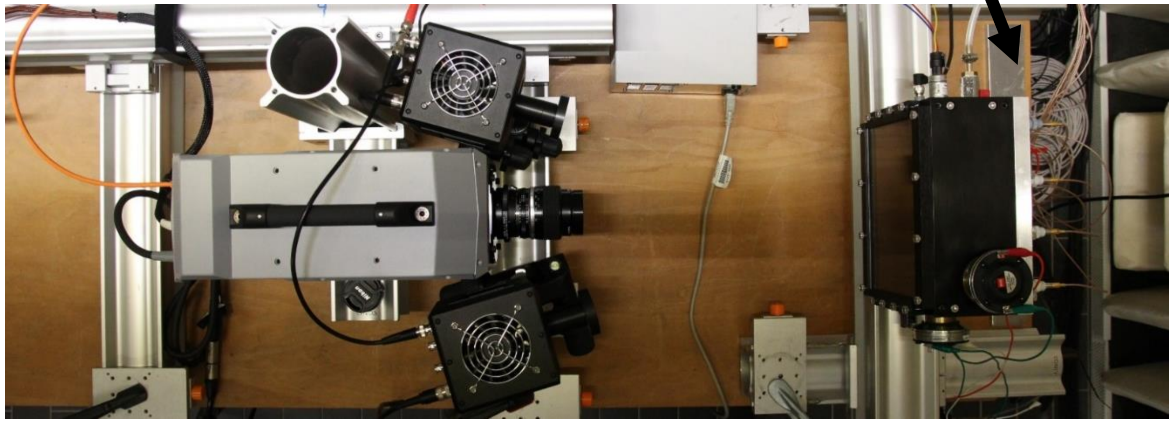
September 6th, 2022

Pressure-sensitive paint (PSP) – Test setup

Typical measurement setup







Pressure-sensitive paint (PSP) – Test setup

Pre-test in Aeroacoustic wind tunnel (AWT)
Simplified test environment for aeroacoustic analysis under aero engine-like conditions

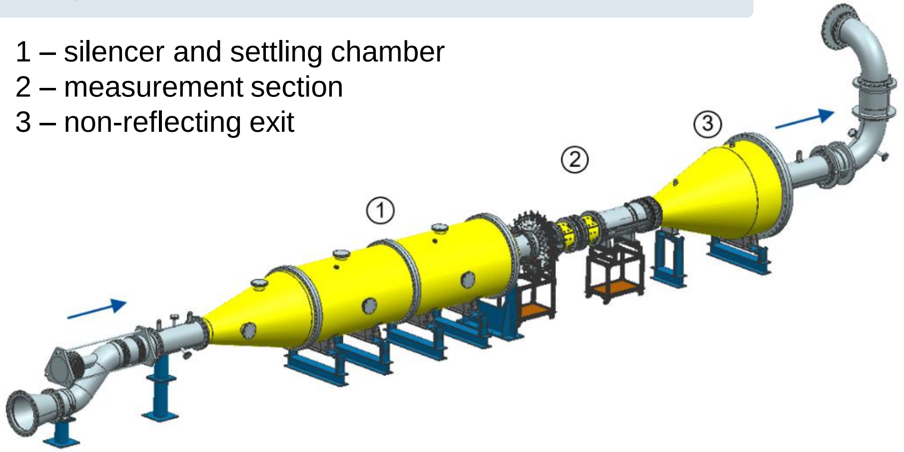
Specifications

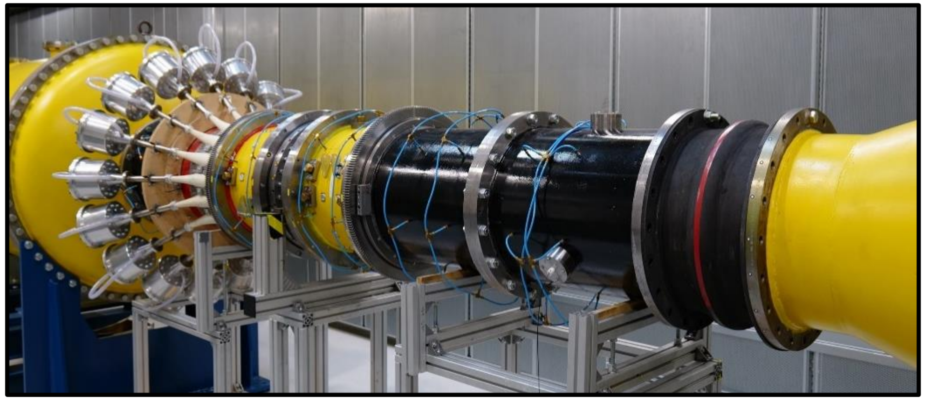
- max. mass flow rate $\dot{m}$ = 25 kg/s
- Reynolds number $Re_D \leq 6{,}2 \cdot 10^6$
- max. pressure ratio $p/p_U \leq 6$
- diameter of test section D = 500 mm
- background noise < 70 dB(A) at u_∞= 40 m/s
- 360° access to measurement section
- homogenous, axial inflow

Applications/Fields of research

- development and test of aeroacoustic measurement and analysis
- validation of numerical and analytical sound propagation model
- sound transmission through ring cascade

1 – silencer and settling chamber
2 – measurement section
3 – non-reflecting exit





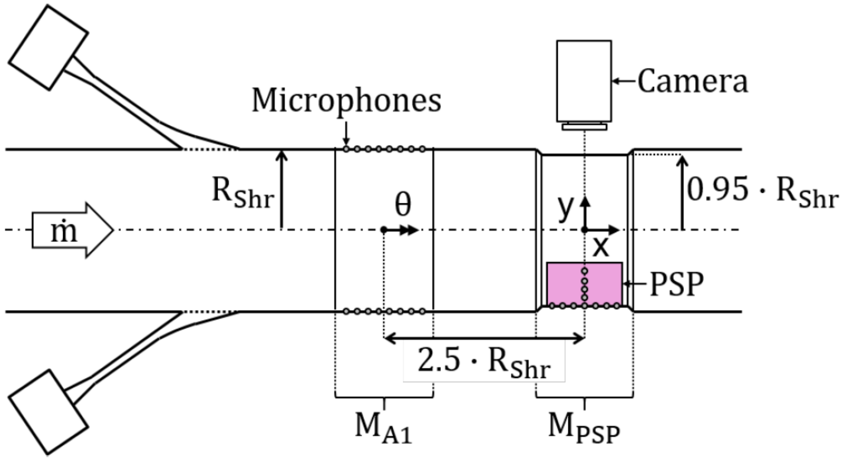
Measurement section of AWT at new campus

1. Bartelt, M., Meinzer, C.E., Laguna, J.D., Seume, J.R. (2012): Design Methodology and Experimental Validation of an Aeroacoustic Test Rig for Turbomachinery Applications. , ISUAAAT-S12-4, Tokyo, 2012
2. Bartelt, M.; Seume, J. R. (2011): Auslegung und Optimierung eines Aeroakustik-Kanals für Turbomaschinenanwendungen unter Verwendung numerischer Methoden, DGLR-Kongress, 27.-29. Sep. 2011, Bremen

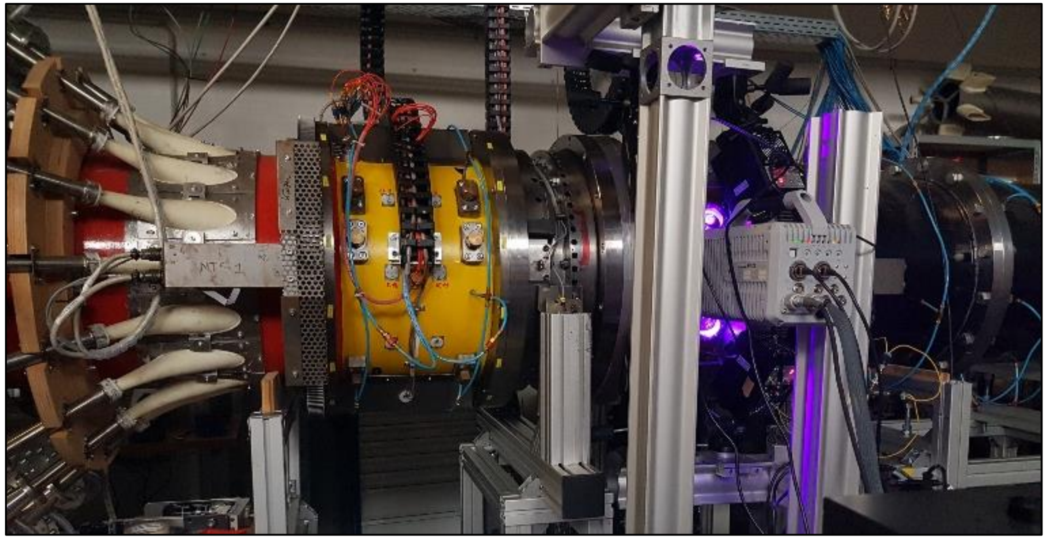
Pressure-sensitive paint (PSP) – Test setup

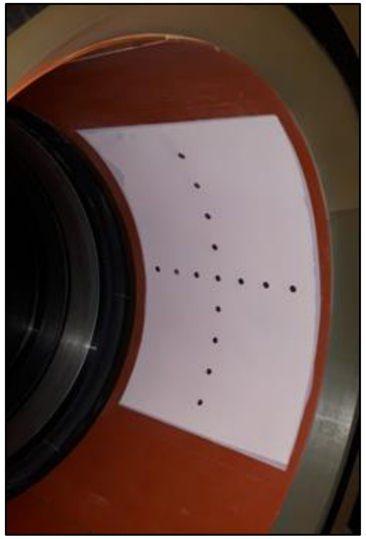
Instrumentation of PSP measurements:

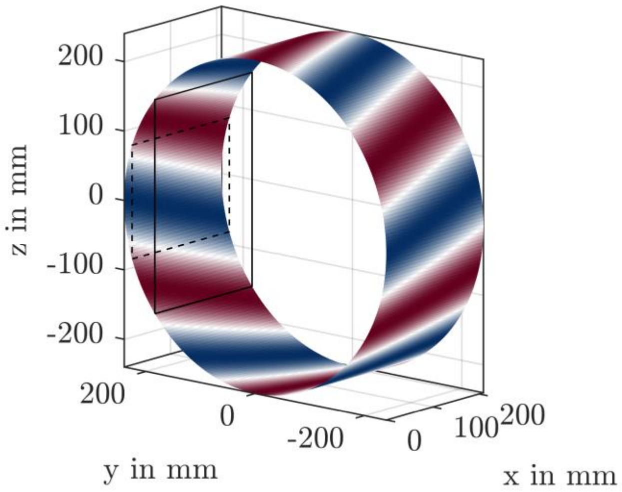
- Porous-ceramic PSP paint by ISSI
- Photron Fastcam SA-X2
  - 1 MPx resolution
  - 10 kHz frame rate
  - 21839 images per measurement
- Band pass filter CWL 650 nm $\pm$ 10nm
- UV-LED: 4x HARDsoft IL-107 UV in continuous wave mode



Excitation of spinning acoustic modes with frequencies up to 5 kHz.
Measurement on inner duct wall surface with PSP and reference microphones.

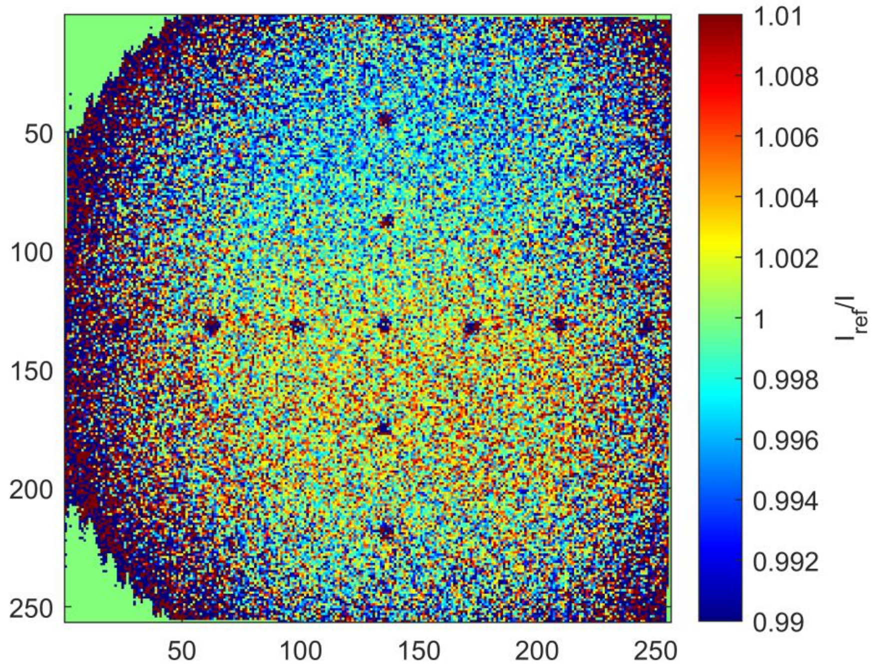






Pressure-sensitive paint (PSP) – Data Analysis

- load, undistort images, and calculate intensity deviation $I_r = I_{ref}/I$
- detect position of the microphones
- calculate camera pose using 2D (camera) and 3D (world) position of microphones
- calculate camera extrinsic
- create 3D mesh of PSP-segment
- project world mesh in camera coordinates with camera extrinsic
- interpolate image intensity on mesh in camera coordinates
- pixel-wise Fast-Fourier Transform → extract amplitude and phase
- pressure scaling with complex microphone pressure in frequency domain



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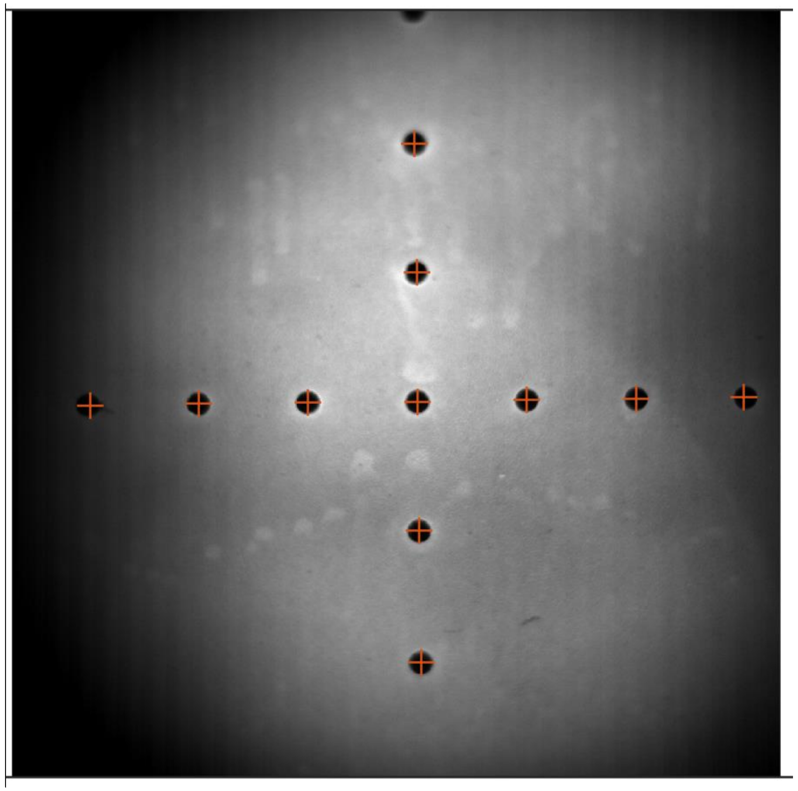


Pressure-sensitive paint (PSP) – Data Analysis

load, undistort images, and calculate intensity deviation $I_r = I_{ref}/I$

↓

detect position of the microphones

↓

calculate camera pose using 2D (camera) and 3D (world) position of microphones

↓

calculate camera extrinsic

↓

create 3D mesh of PSP-segment

↓

project world mesh in camera coordinates with camera extrinsic

↓

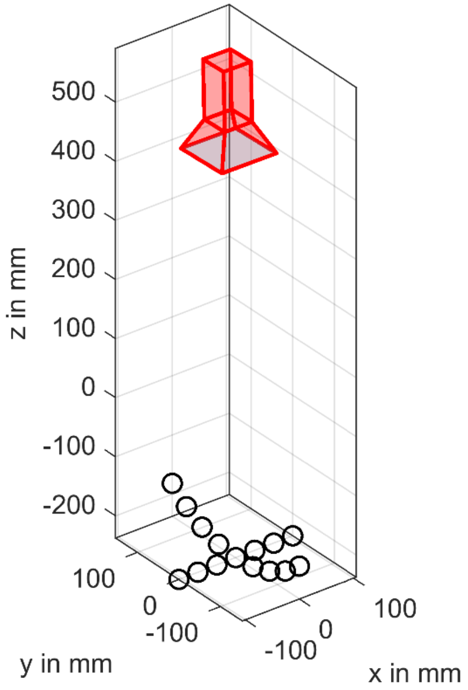
interpolate image intensity on mesh in camera coordinates

↓

pixel-wise Fast-Fourier Transform → extract amplitude and phase

↓

pressure scaling with complex microphone pressure in frequency domain



Pressure-sensitive paint (PSP) – Data Analysis

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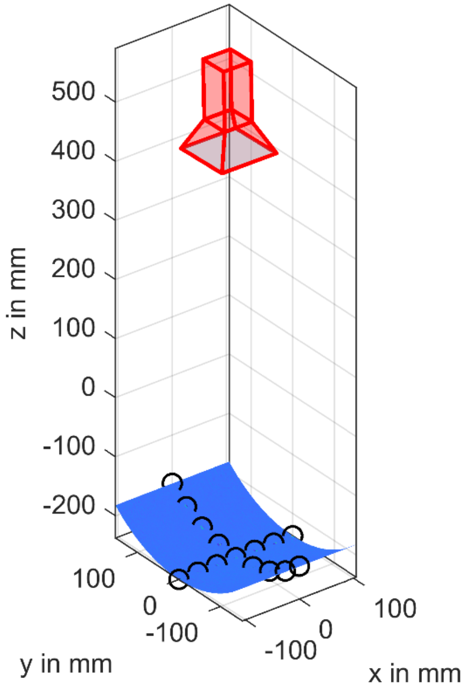


Pressure-sensitive paint (PSP) – Data Analysis

load, undistort images, and calculate intensity deviation $I_r = I_{ref}/I$

↓

detect position of the microphones

↓

calculate camera pose using 2D (camera) and 3D (world) position of microphones

↓

calculate camera extrinsic

↓

create 3D mesh of PSP-segment

↓

project world mesh in camera coordinates with camera extrinsic

↓

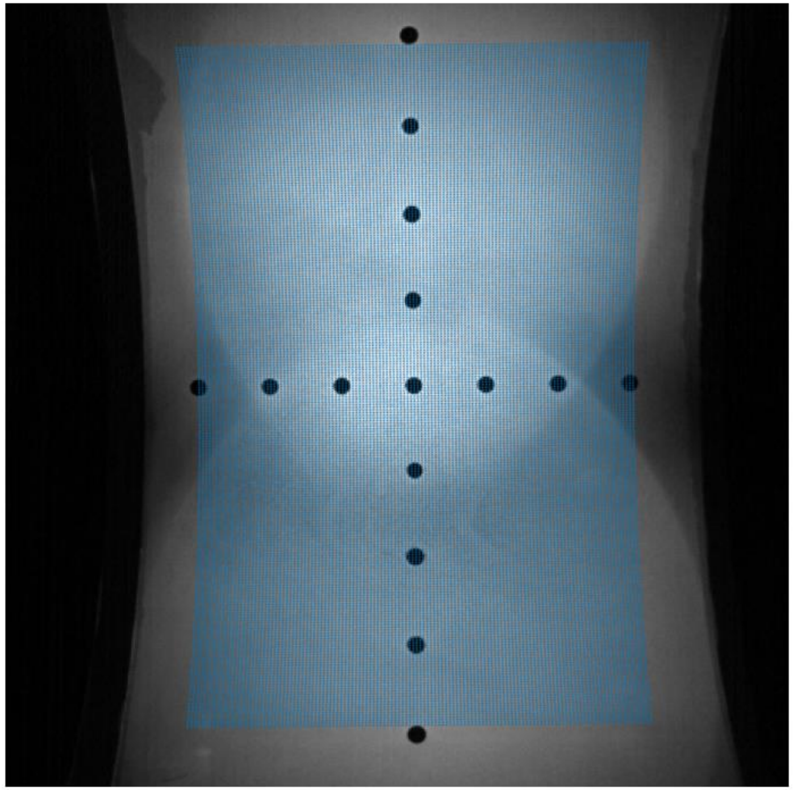
interpolate image intensity on mesh in camera coordinates

↓

pixel-wise Fast-Fourier Transform → extract amplitude and phase

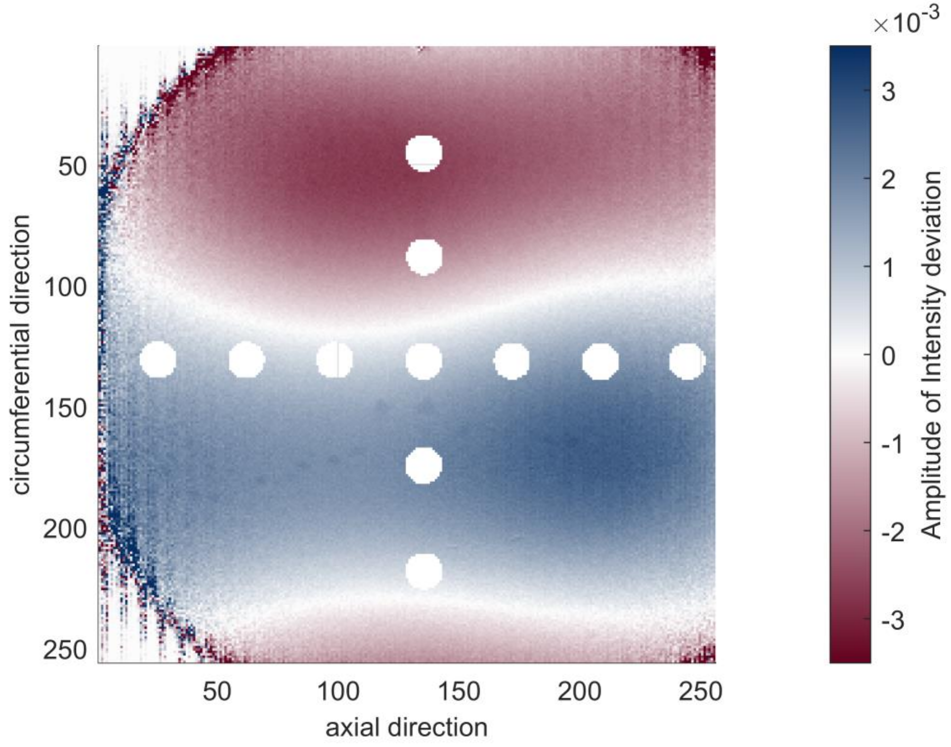
↓

pressure scaling with complex microphone pressure in frequency domain



Pressure-sensitive paint (PSP) – Data Analysis

- load, undistort images, and calculate intensity deviation $I_r = I_{ref}/I$
- ↓ detect position of the microphones
- ↓ calculate camera pose using 2D (camera) and 3D (world) position of microphones
- ↓ calculate camera extrinsic
- ↓ create 3D mesh of PSP-segment
- ↓ project world mesh in camera coordinates with camera extrinsic
- ↓ interpolate image intensity on mesh in camera coordinates
- ↓ **pixel-wise Fast-Fourier Transform → extract amplitude and phase**
- ↓ pressure scaling with complex microphone pressure in frequency domain



Pressure-sensitive paint (PSP) – Data Analysis

- load, undistort images, and calculate intensity deviation $I_r = I_{ref}/I$
- ↓ detect position of the microphones
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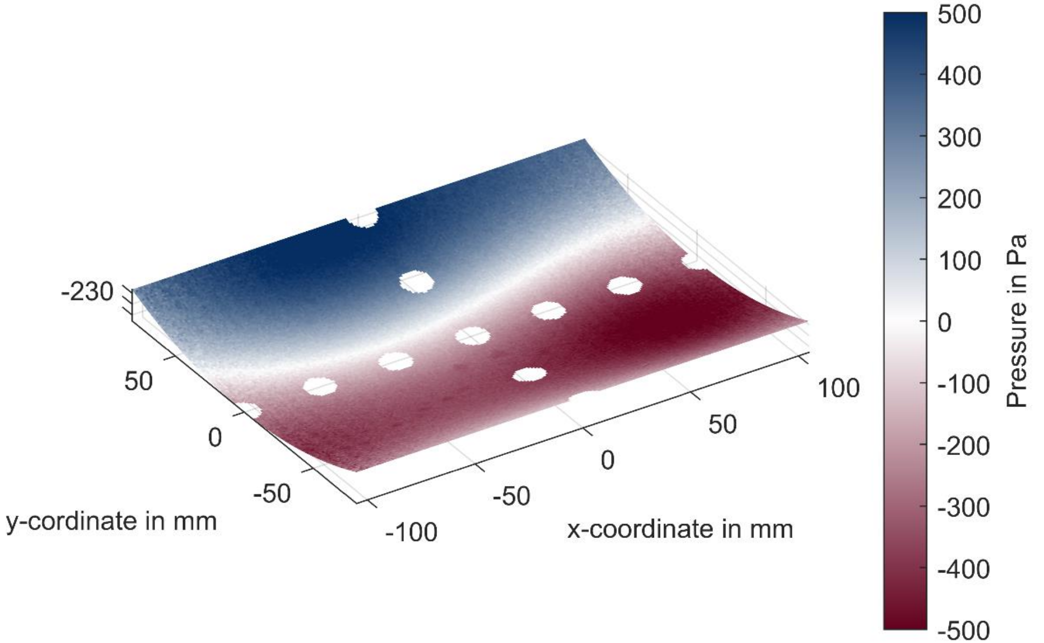
- ↓ calculate camera extrinsic
- ↓ create 3D mesh of PSP-segment
- ↓ project world mesh in camera coordinates with camera extrinsic
- ↓ interpolate image intensity on mesh in camera coordinates
- ↓ pixel-wise Fast-Fourier Transform → extract amplitude and phase
- ↓ **pressure scaling with complex microphone pressure in frequency domain**



Institute of Turbomachinery and Fluid Dynamics

CA3ViAR DE #1

Advanced optical techniques for fan deformation and noise propagation measurements

Motivation

DIC

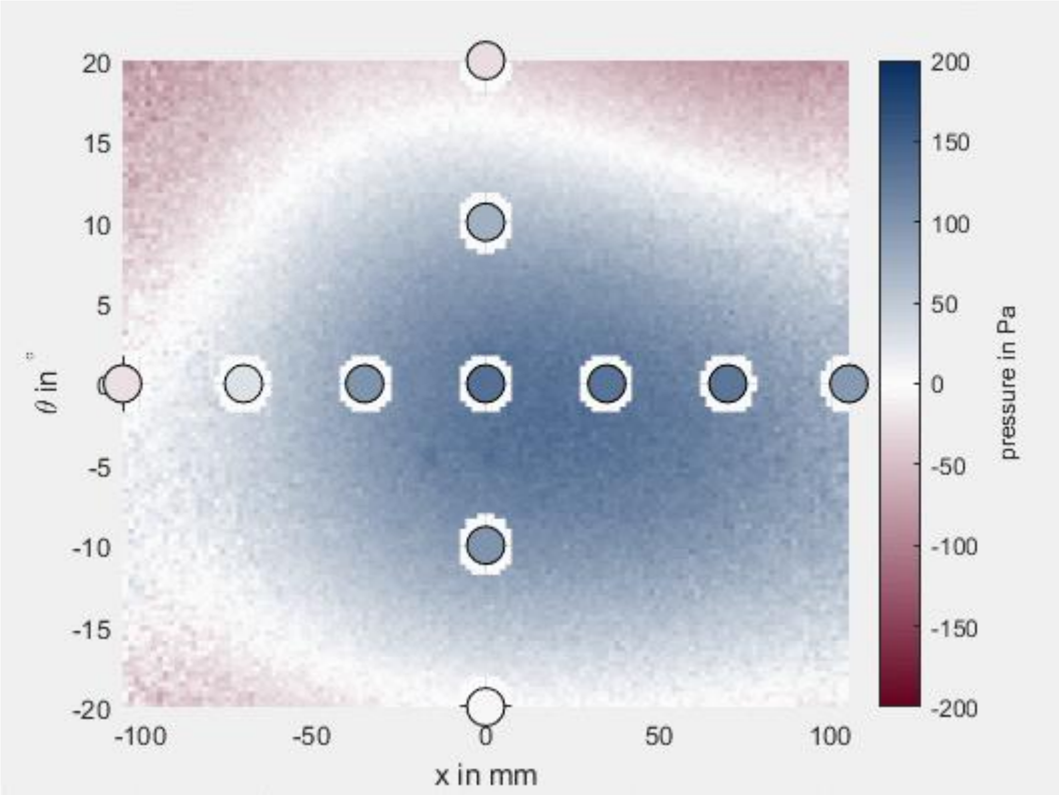
PSP

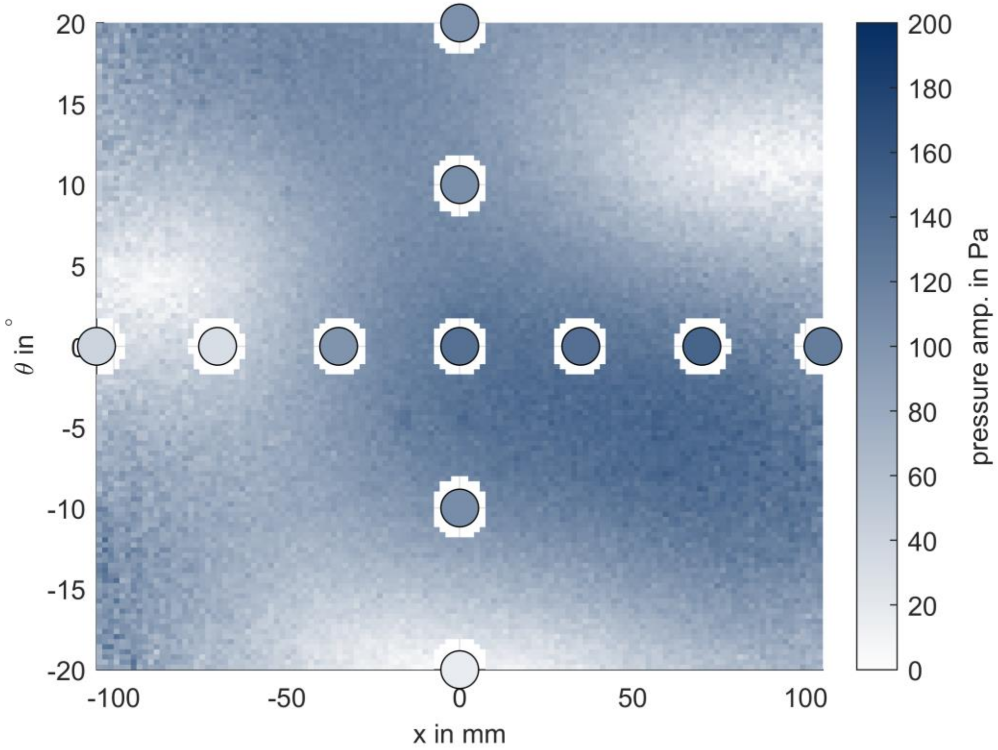
Conclusions

Pressure-sensitive paint (PSP) – Results

Acoustic excitation of circumferential mode -6 at 1800 Hz at Ma = 0.1

Measured spatial pressure distribution:





- maximum pressure amplitude below 150 Pa
- circumferential mode order -6 dominant
- interference observed → superposition of different modes expected due to reflection

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CA3ViAR DE #1

Advanced optical techniques for fan deformation and noise propagation measurements

Motivation

DIC

PSP

Conclusions

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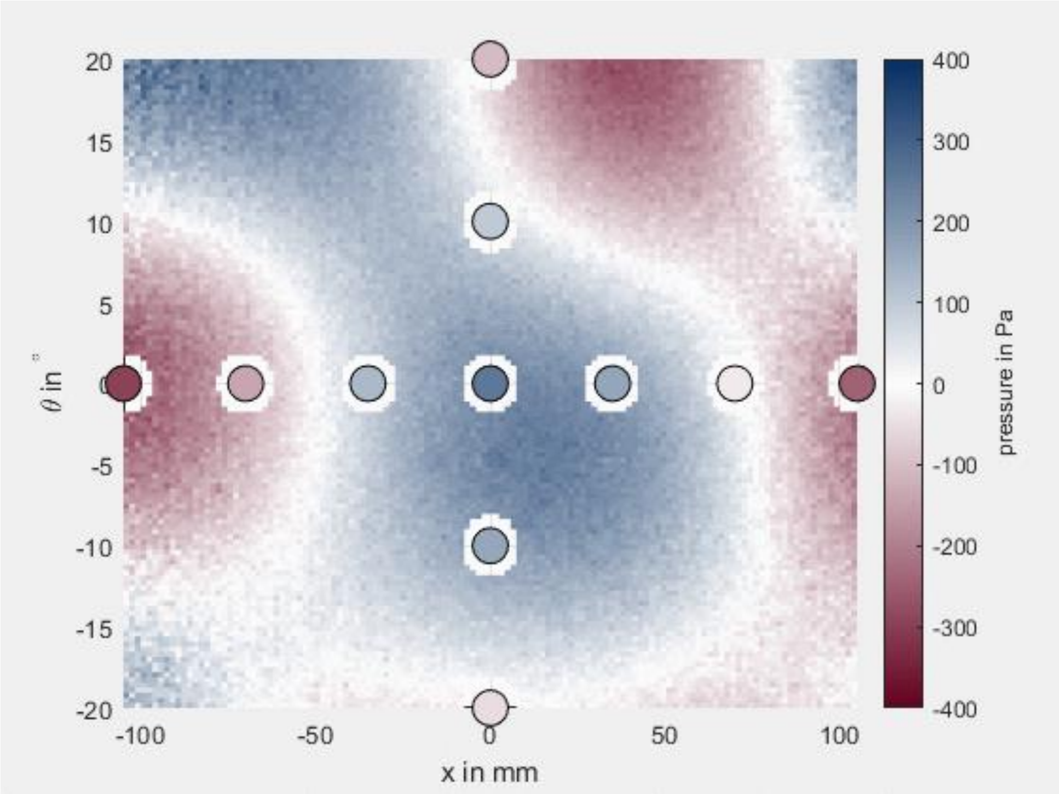
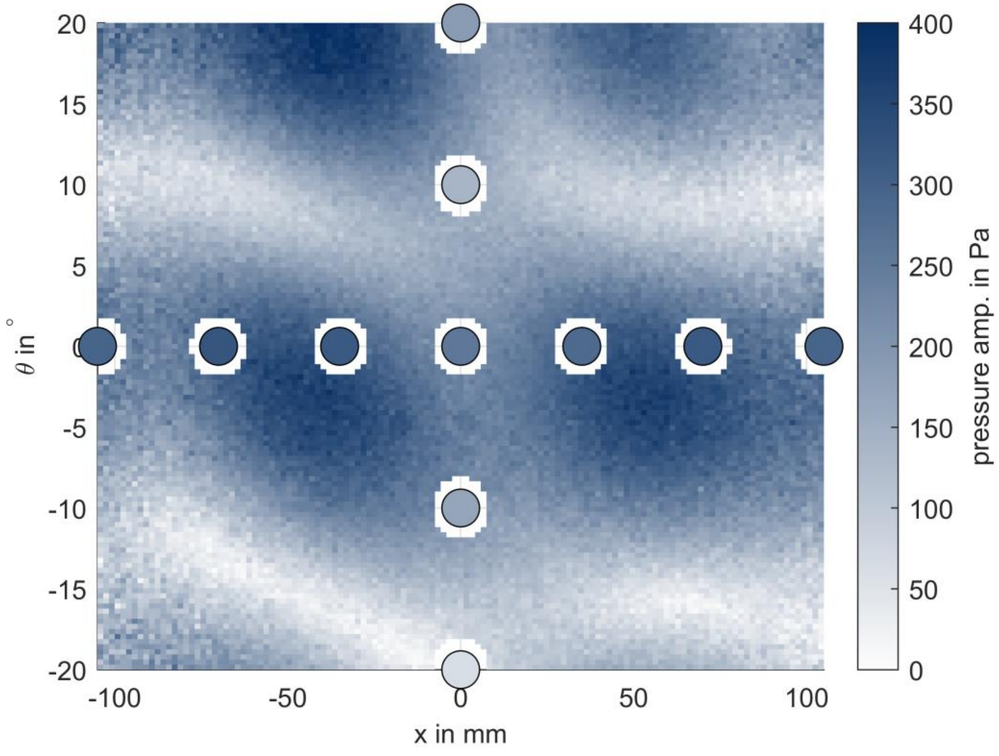
September 6th, 2022

Pressure-sensitive paint (PSP) – Results

Acoustic excitation of circumferential mode 8 at 2900 Hz at Ma = 0.1

Measured spatial pressure distribution:





- maximum pressure amplitude below 400 Pa
- superposition of circumferential mode order -8/8 dominant
- interference observed → superposition of different modes expected due to reflection (expected to occur in CA3ViAR test)

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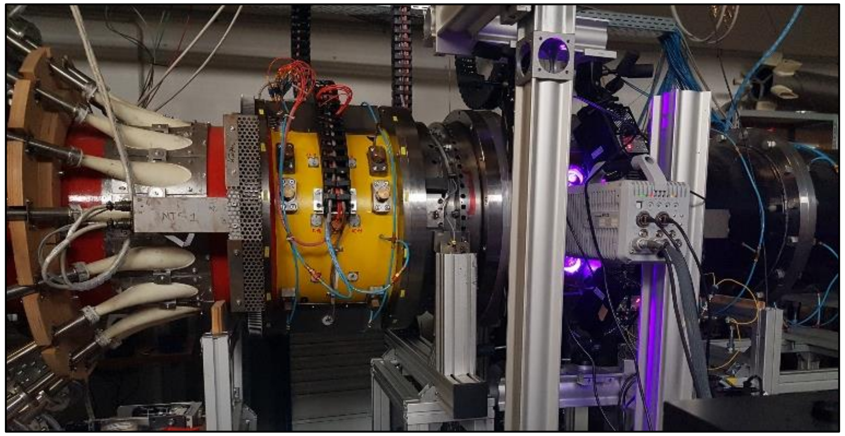
PSP

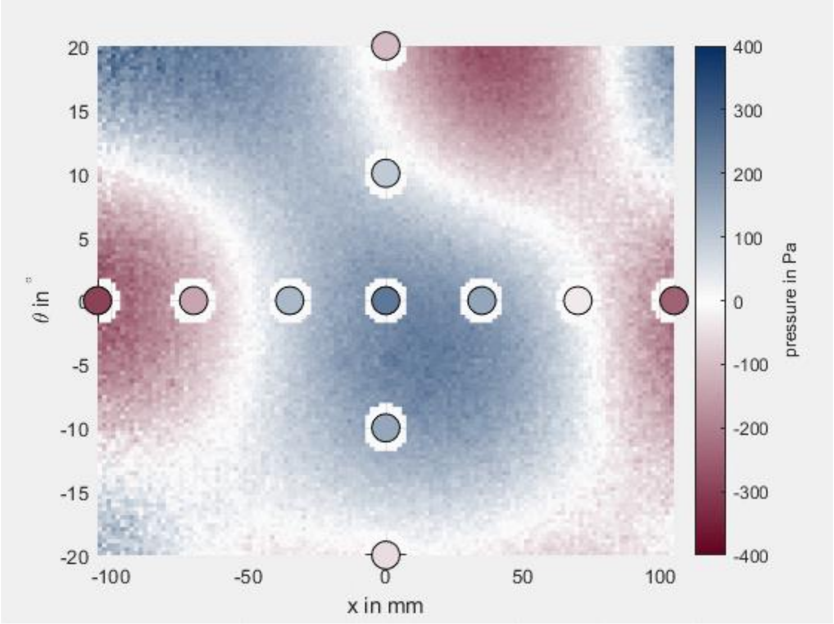
Conclusions

Pressure-sensitive paint (PSP) – Conclusions

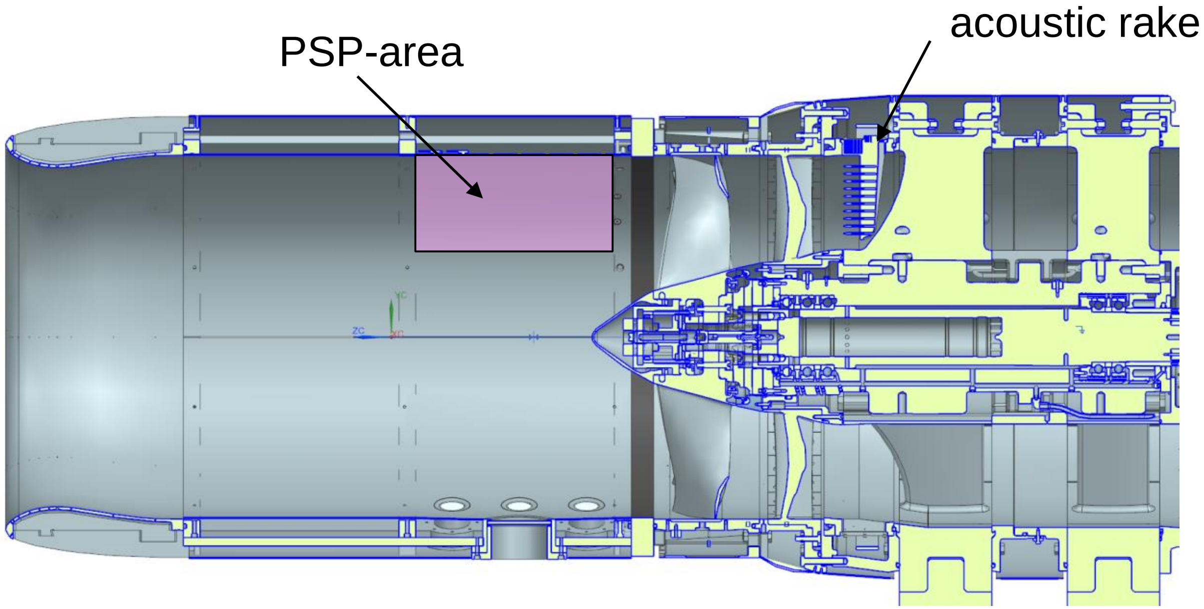


Conclusions of PSP pre-test

- general applicability of PSP is shown
- spatial pressure information visualizes acoustic field
- dense pressure information with high potential for further analysis (e.g. radial mode analysis)



Instrumentation concept for CA3ViAR measurement is elaborated based on PSP pre-tests.



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CA3ViAR DE #1

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Conclusions and outlook

Successfully tested DIC and PSP for application in CA3ViAR to measure deformation and surface sound pressure.

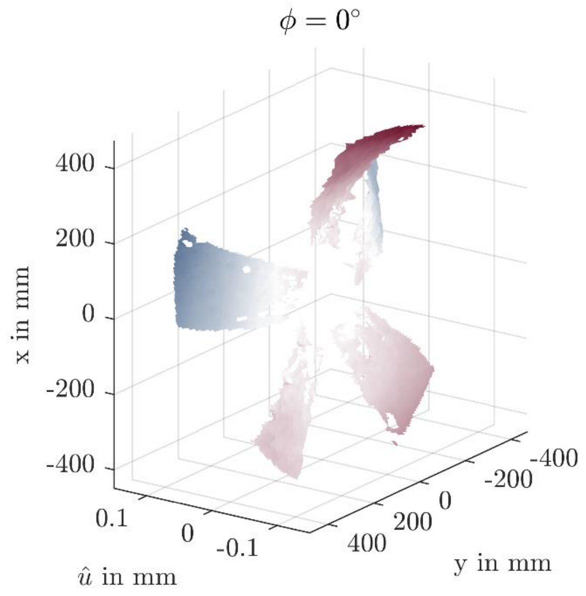
Detailed test concepts elaborated based on pre-tests.

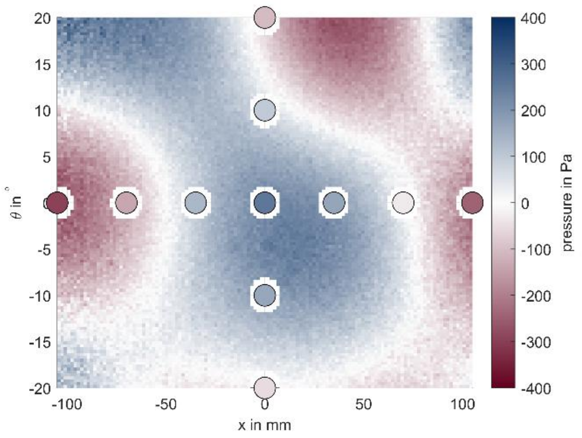
Both optical techniques show great potential to analyse aeroelastic and aeroacoustic fan performance.

Spatial information on pressure visualises data for detailed interpretation and analysis.

Outlook for future work:

- Possibility to analyse transient effects (PSP & DIC).
- Potential to measure unsteady excitation (PSP) and response (DIC) over full surface.
- Application of artificial intelligence to analyse data (PSP & DIC).
- Application on stator vanes (PSP & DIC) and rotor blades (PSP).





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September 6th, 2022

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https://www.ca3viar-project.eu/