Spatially resolved non-invasive strain measurement on fast rotating composite rotors

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Abstract

Fiber reinforced plastics (FRP) have a high potential for the application in high performance rotors as they provide high specific tensile strength and stiffness as well as low density. This combination enables composite rotors to run at very high rotational speeds. However, the complex mechanical behavior of FRP impedes accurate failure prediction of the rotors. At TU Dresden, numerical simulation models are developed to describe the structural vibration and deformation behavior of FRP rotors as a function of their rotational speed and their structural health. To validate these models, measurement techniques are developed and applied to track the vibrational behavior of the FRP rotors and consequently their mechanical properties spatially and temporally. A rotor test rig accelerates the cylindrical specimens to rotational speeds up to 200 Hz and circumferential speeds above 300 m/s.

The Laser Doppler Distance Sensor, developed at MST, was already used to investigate the radial expansion of rotors as a function of their rotational speed. Next, the strain as a function of the rotor radius is measured.

To measure the strain, a holographic diffraction grating foil is applied to the rotor surface. A collimated laser beam illuminates the grating, which splits the beam into several diffraction orders. The diffracted beams are analyzed via cross correlation in order to measure the strain and the tilt of the observed spot on the surface simultaneously. By using a high-speed line scan camera, measurement rates up to 12 kHz are achievable and vibrational measurements as well as real time processing can be performed.

Contrary to conventional strain gauges, the spot of measurement does not move with the rotor. This enables an angular scan of the rotor behavior. A radial movement of the Sensor enables radial scan. Arbitrarily many spots on the surface are measurable with a spatial resolution of under 3 mm. Furthermore, no cables, slip rings or telemetric transmitters are necessary.

The robustness of the sensor towards rigid body movements, like in-plane displacement, out-of-plane displacement and tilt was demonstrated. As a next step, the system will be tested on a rotating object for the first time.

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1. Motivation

Advantages of composite rotors

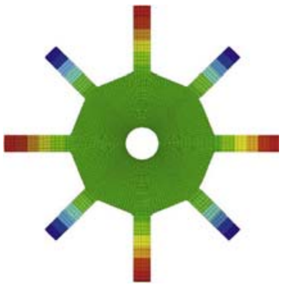
- High specific stiffness and tensile strength, low density
  - Large diameters
  - High rotational speeds
  - High performance and efficiency
- Advantageous fatigue behavior
- Adaptability of two component material

Fan blade of a GE90 -Turbine in Boeing 777 [GE18]

1. Motivation

Validation of models

- Models can be used to increase rotor performance and safety
- Validation and calibration by in-situ measurements
- Required: In-plane deformation and out-of-plane vibration behavior as a function of:
  - Rotational speed
  - Damage state



FEM Model: Out-of-Plane eigenmode of static FRP rotor [GUD15]

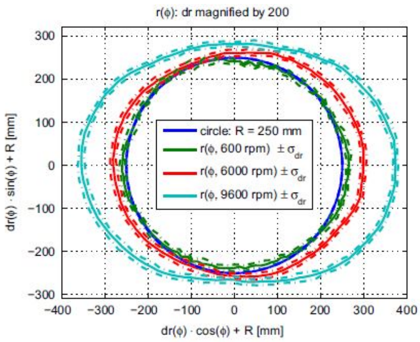
↔

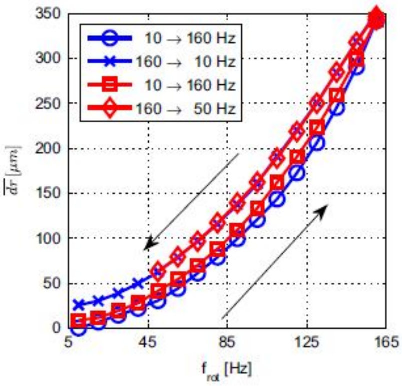
Rotor test rig

2. Preliminary Work

Integral in-plane deformation

- 3 Laser-Doppler Distance Sensors →
  - Surface speed 300 m/s, 120 spots measured
- Fatigue and hysteresis
- Directionally anisotropic





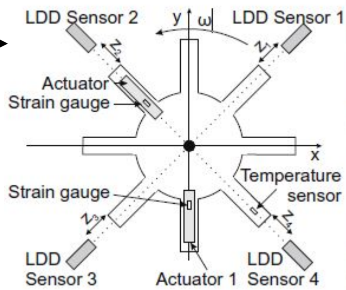
Source of Image and plots: [KUS14]

➢ High angular resolution, no radial resolution

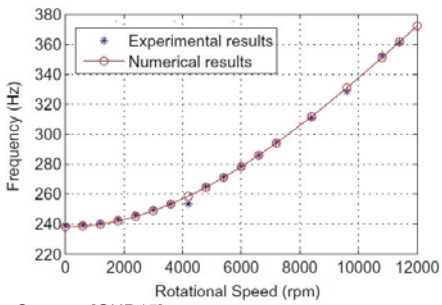
2. Preliminary Work

In-plane vibration measurement

- Excitation with 2 piezoelectric actuators →
- 2 strain gauges
- Eigenfrequency depends on rotational speed



Source: [GUD15]



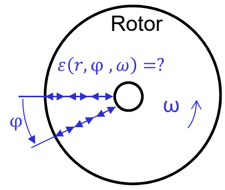
Source: [GUD15]

➢ Spatial resolution limited by number of strain gauges

3. Approach

Required

- Higher radial and angular resolution
  - In-Plane deformation
  - Tilt/ out-of-plane vibration



Aim: full-field measurement on moving rotor

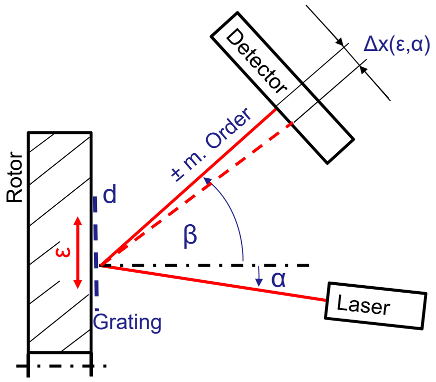
Approach

- Optical far field measurement
- Use diffraction grating

Bragg equation:

$$sin\alpha + sin\beta = \pm m\lambda/d(\varepsilon)$$

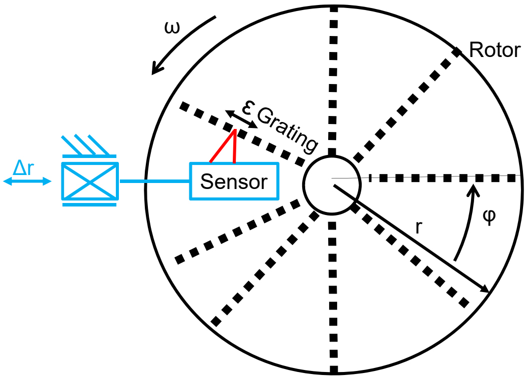
➢ diffraction angle β yields deformation ε



3. Approach

Strain and tilt measurement with optical grating

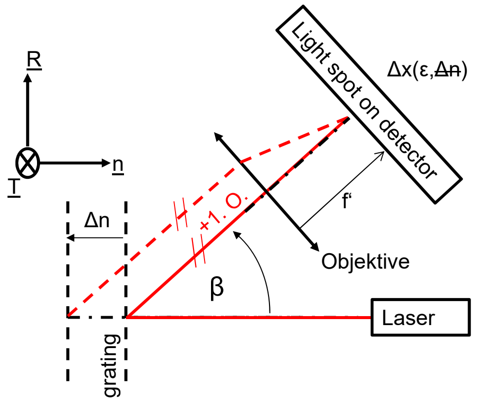
- Apply several gratings at different rotor angles
- Probe rotation → angular scan
- Sensor translation → radial scan

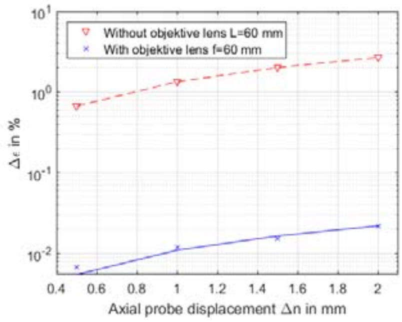


3. Approach

Strain and tilt measurement with optical grating

- Problem: Position of light spot on detector depends on axial rotor position
- Solution: Use objective lens



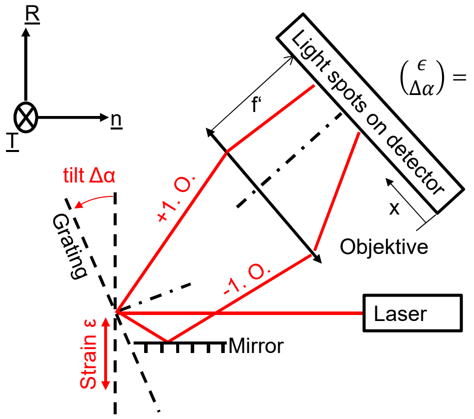


➢ Measurement independent of axial rotor position

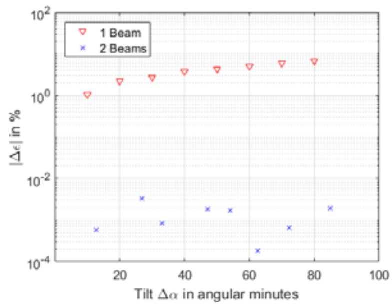
3. Approach

Strain and tilt measurement with optical grating

- Problem: Crosstalk between strain and tilt
- Solution: Use two diffraction orders



$$\begin{pmatrix} \epsilon \\ \Delta\alpha \end{pmatrix} = \begin{bmatrix} k_1 & k_2 \\ k_3 & k_4 \end{bmatrix} \begin{pmatrix} x_+ \\ x_- \end{pmatrix}$$



➢ Separation of strain and tilt information

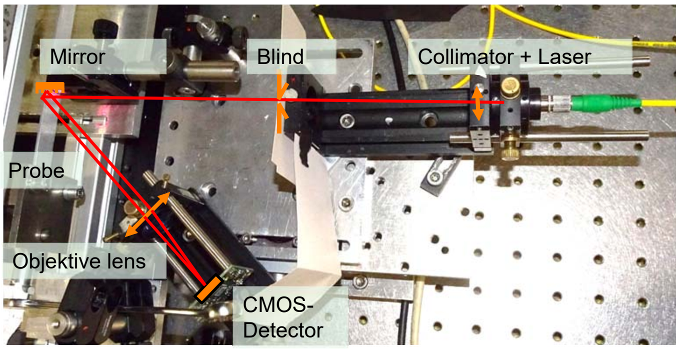
4. Setup and Characterization

Measurement Setup

Static tensile testing
with FRP specimen

Aluminum specimen with strain gauge and grating

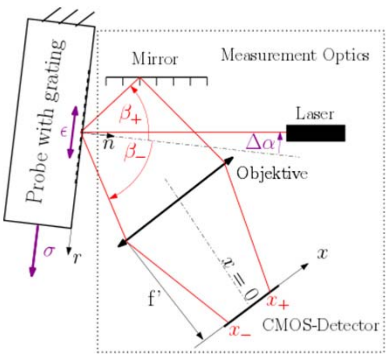
Measurement Setup



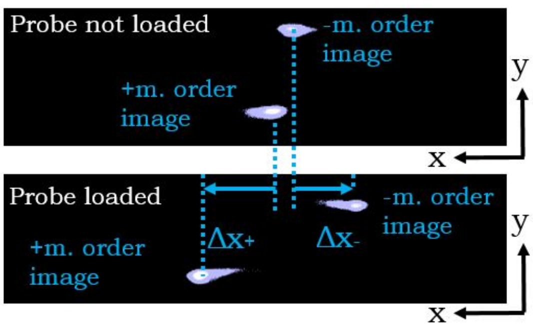
4. Setup and Characterization

Signal Processing

- Analyze movement of two diffraction orders on matrix camera
  - ➢ Determination of strain ε and surface tilt Δα



Principle

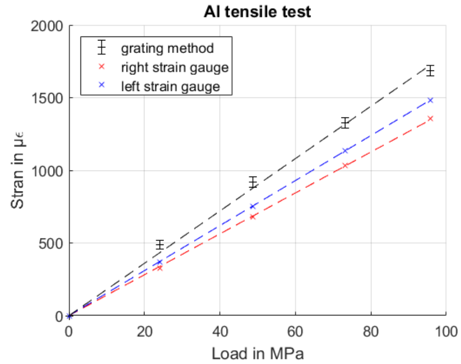


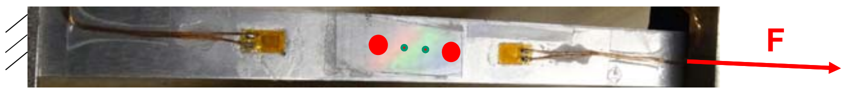
Diffraction orders ±m. on CMOS Sensor

5. Results

Static tensile test Aluminum

- Validation with strain gauges
- 8 spots every 1 mm on grating measured
- Standard deviation: 50 με
- R^2 of mean value: 99.63%
- Systematic deviation from strain gauges: ΔE=(11…18) GPa
  - ➢ Calibration





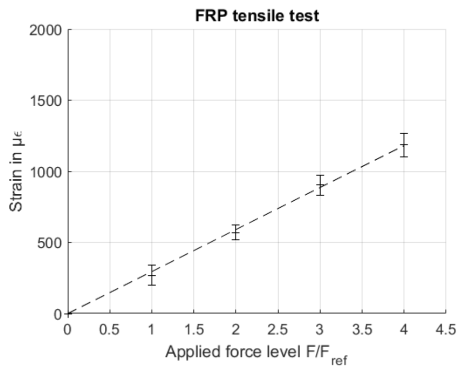
Aluminum specimen with strain gauges and grating

➢ Validated for static Al probes

5. Results

Static tensile test FRP

- 8 spots every 1 mm on grating measured
- Standard deviation: 80 με
- R^2 of mean value: 99.84%



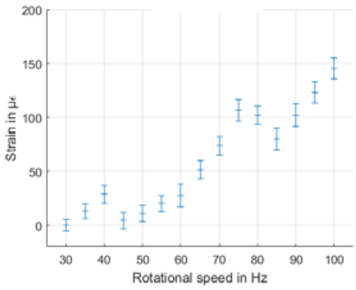

FRP specimen with gratings

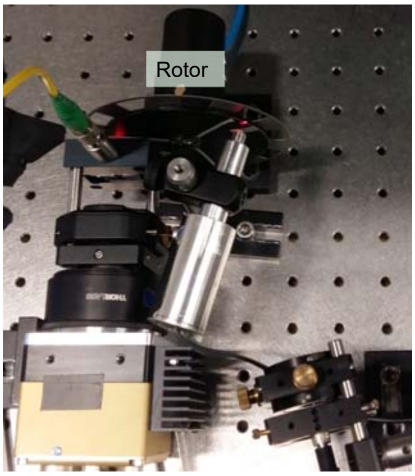
➢ Validated for static FRP probes

5. Results

Dynamic test

- Compact Setup with line Camera and light barrier trigger
- Rotational speeds: (20…100) Hz
- Strain standard deviation: < 11 µε
- Angle standard deviation < 2.5''

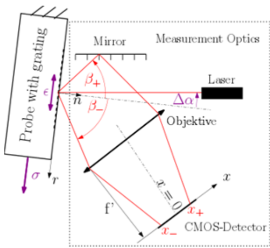


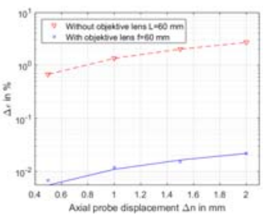


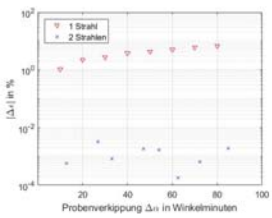
➢ Validated for moving probes

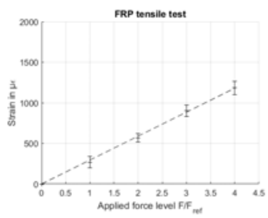
6. Conclusion

- FRP advantageous for rotors, validated models necessary
- Validation + calibration with measurements
- Strain measurement with diffraction grating method
  - ➢ Optical: fast and contactless
  - ➢ Robust towards vibrations
  - ➢ High linearity (R^2=99.63%)
  - ➢ Low uncertainties (s ≈ 10 µε possible)
  - ➢ Applicable on moving rotor









7. Outlook

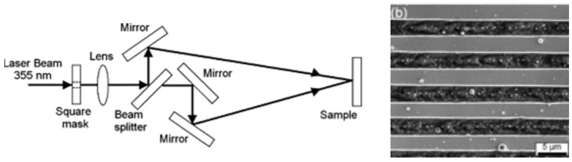
Measurement in rotor test rig

- Validation and calibration of numerical simulation models

Grating application

- Currently: Glued holographic grating film
  - ➢ Cheap, high diffraction efficiency
- Surface patterning
  - ➢ Surface = grating → no strain transmission errors

Holographic diffraction grating film [ED18]



Laser Interference Patterning an Fe/Cu/Al-Schicht [LAS07]

Sources

[GUD15] M. Gude, A. Filippatos, A. Langkamp, W. Hufenbach, A. Fischer, J. Czarske, “Model assessment of a composite mock-up bladed rotor based on its vibration response and radial expansion”, Composite Structures, 2015

[KUS14] R. Kuschmierz, A. Filippatos, P. Günther, A. Langkamp, W. Hufenbach, J. Czarske, A. Fischer, „In-process, non-destructive, dynamic testing of high-speed polymer composite rotors,“ Mechanical Systems and Signal Processing, 2014.

[LAS07] A.Lasagni, C. Holzapfel, T. Weirich, F. Mückrich, “Laser interference metallurgy: A new method for periodic surface microstructure design on multilayered metallic thin films”, Applied Surface Science, 2007

[SON14] T. V. Son and A. Haché, “Thermal expansion and stress and measurement using high-order diffraction: Possibilities and theoretical limits,” Optics Communications, vol. 326, pp. 134–138, 2014.

[Zha00] B. Zhao, H. Xie, A. Asundi, “Optical strain sensor using median density grating foil: Rivaling the electric strain gauge”, Review of Scientific Instruments, vol. 72, nr. 2, 2000

[GE18] ge.com/reports/the-art-of-engineering-the-worlds-largest-jet-engine-shows-off-composite-curves/ (15.06.2018)

[LS18] lightsoftllc.com/ (23.06.18)

[ED18] edmundoptics.com/optics/gratings/Holographic-Diffraction-Grating-Film/ (23.06.18)