



Condition Monitoring of Rotary Shaft Seals in Experimental Tests



Y. Stiemcke, O. Koch, S. Thielen



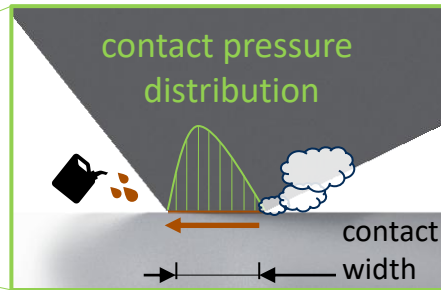
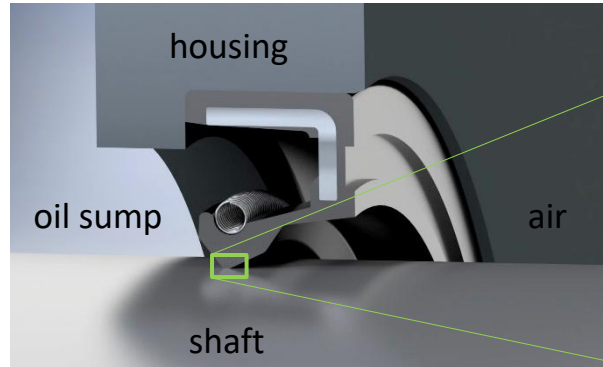
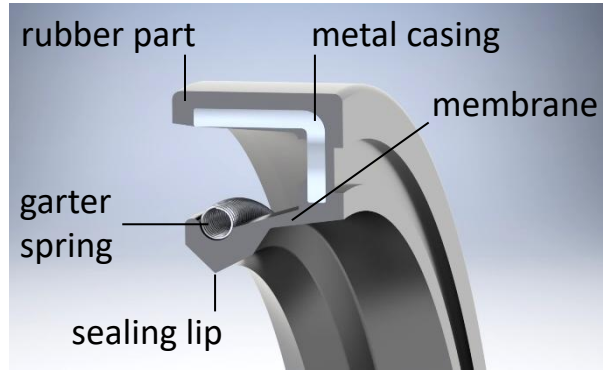
T. Becker, J. Seewig



J. Feldmann, N. Wehn



The Tribological System Rotary Shaft Seal



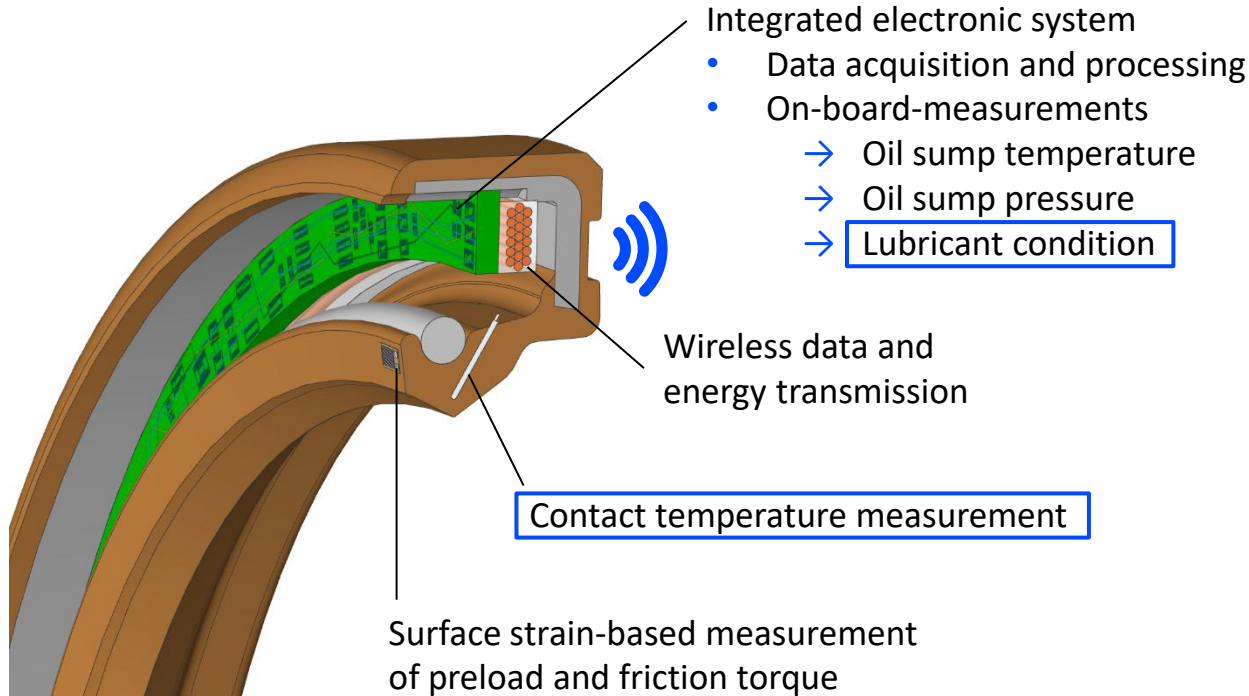

Alternative:

In situ monitoring of

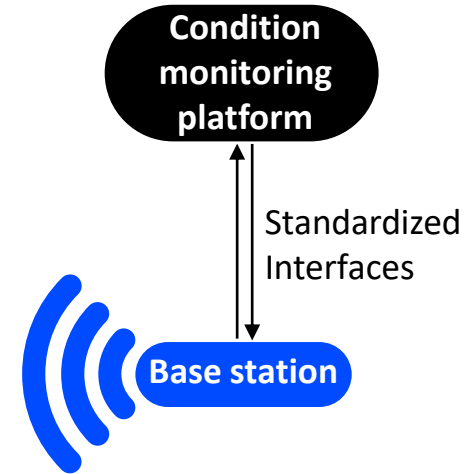
- operational state
- resulting individual damage progression

- Rotary shaft seals (RSS)
 - Dynamic sealing of shaft exits from lubricated machinery
- Contacting seal
 - Contact pressure $\approx 1 \text{ MPa}$ / Contact width $\approx 100 \text{ }\mu\text{m}$
 - Friction power density $\approx 300\text{-}500 \frac{\text{W}}{\text{cm}^2}$
- Complex tribological interactions
 - Highly system-dependent operational behaviour
 - Missing reliable methods for service life estimation

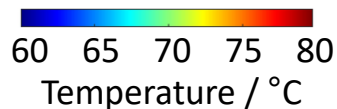
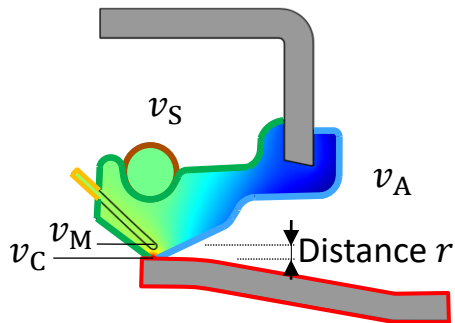
Concept for Sensor-integrating Machine Element Rotary Shaft Seal (SiME-RSS)



Concept SiME-RSS



Contact Temperature – Simulation-Based Calibration Model

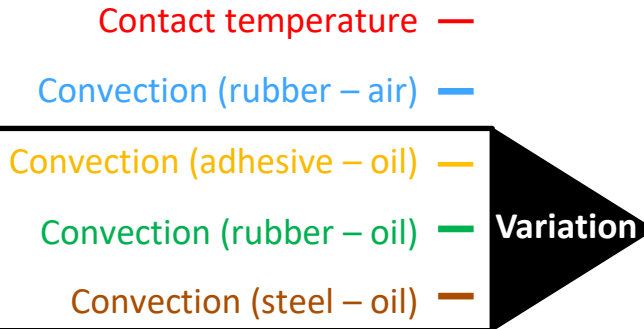


Empirical relationship

$$v_C = f(v_M, v_S, v_A, \dots)$$

$m_{ref}, \dots$

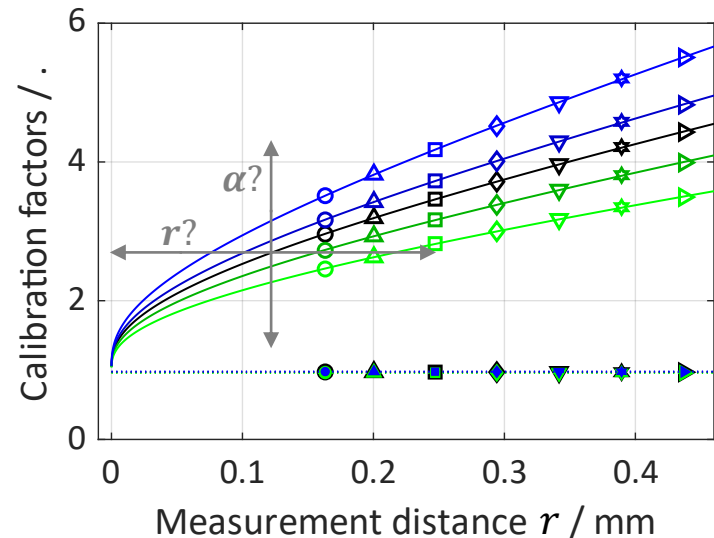
m_{cal}



Challenge:
Calibration depends on

Measurement distance
→ $m_{cal}(r)$

Heat dissipation
→ $m_{cal}(\alpha)$



●▲◆▼★▶ m_{ref} (simulation series)
 m_{ref} (constant fit)
 ○△◇◇▼★▶ m_{cal} (simulation series)
 ——— m_{cal} (Bessel regression)

■ oil convection: +60 %
 ■ oil convection: +20 %
 ■ reference oil convection
 ■ oil convection: -20 %
 ■ oil convection: -40 %

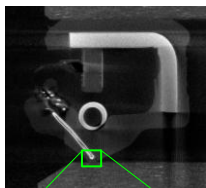
Contact Temperature – Experimentally Supported System Calibration



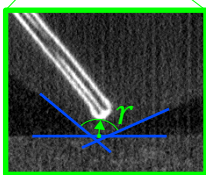
Prototype SiME-RSS

Measurement distance

→ $m_{cal}(r)$

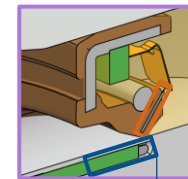
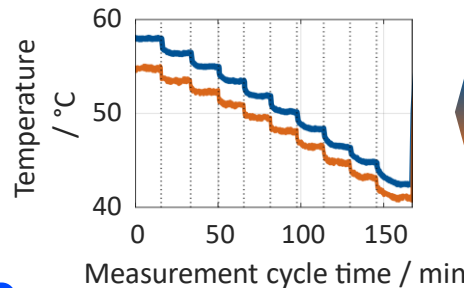
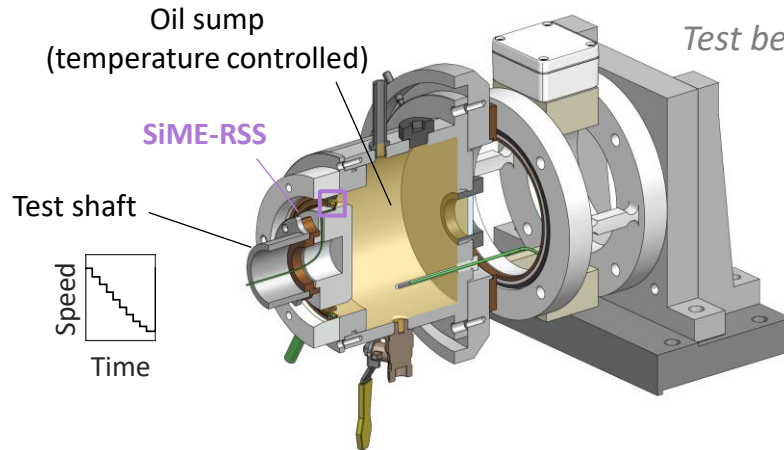
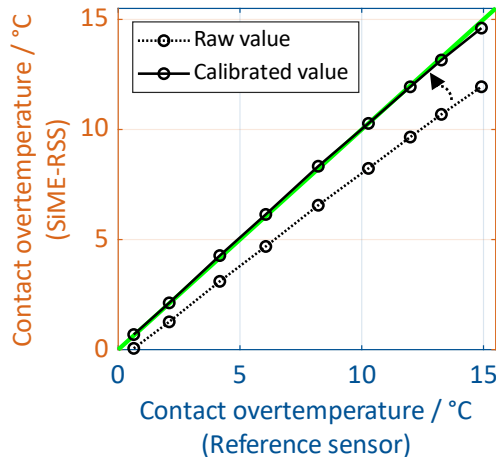


CT-scan



Heat dissipation

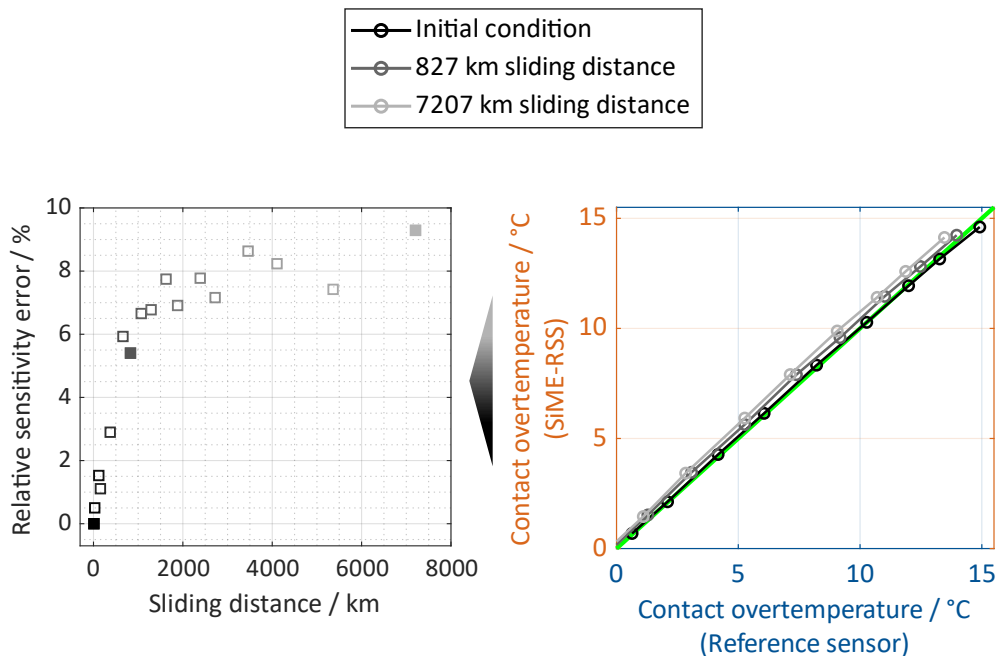
→ $m_{cal}(\alpha)$



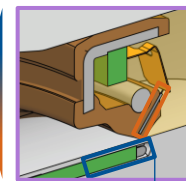
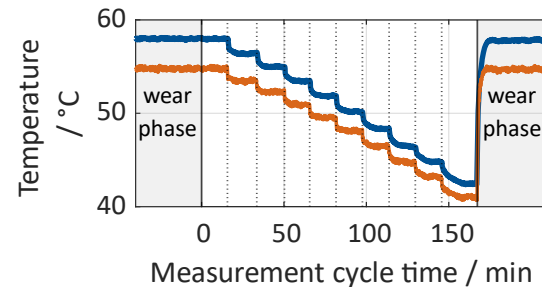
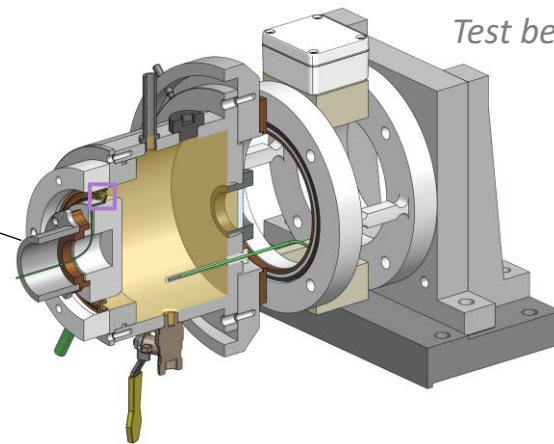
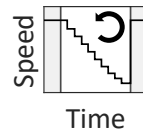
Reference sensor

Result: Functional proof - unworn state

Contact Temperature – Long-term Testing



Test shaft



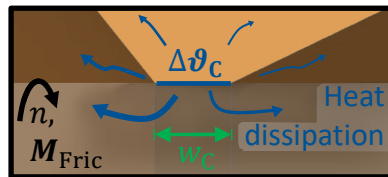
Reference sensor

Challenge: ensure long-term accuracy

Contact Temperature – Wear Progress Model

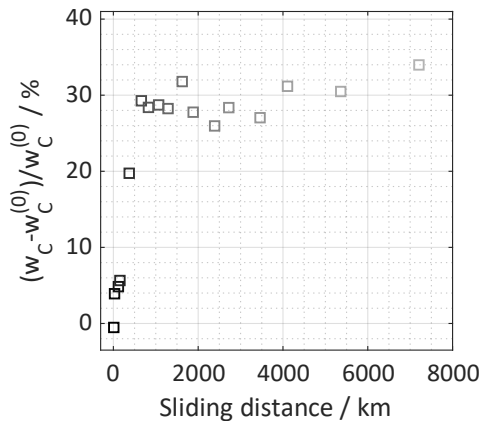
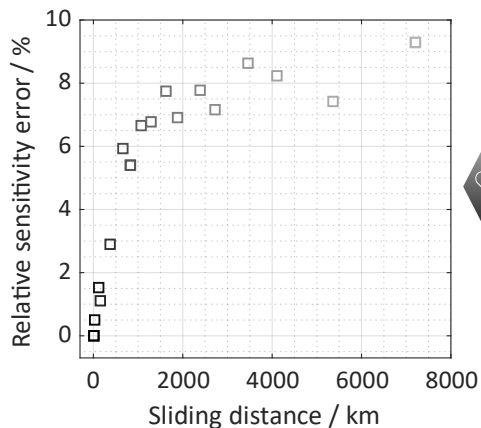
BRINK's approach (*)

$$\Delta\vartheta_C = \vartheta_C - \vartheta_S = R_{th} \frac{2\pi n M_{Fric}}{2\pi r w_C}$$

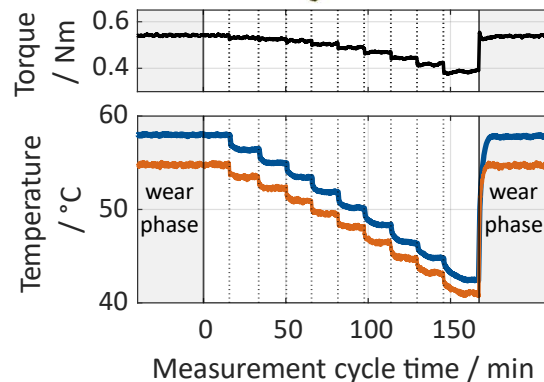
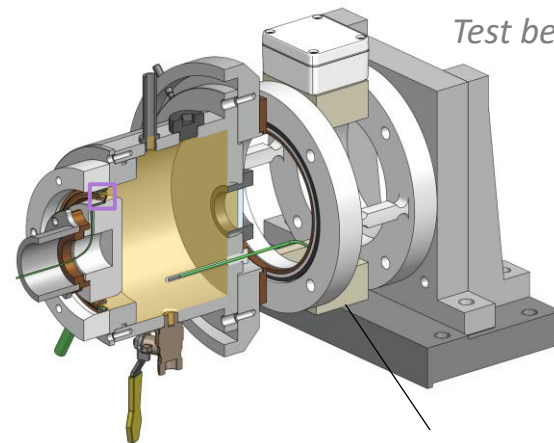


$$w_C \sim \frac{n M_{Fric}}{\Delta\vartheta_C} \quad \text{Relative to initial state (0)}$$

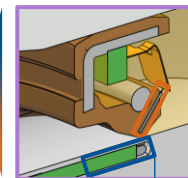
$$\frac{w_C - w_C^{(0)}}{w_C^{(0)}} = f(n, M_{Fric}, \Delta\vartheta_C)$$



Result: In-situ wear estimation feasible

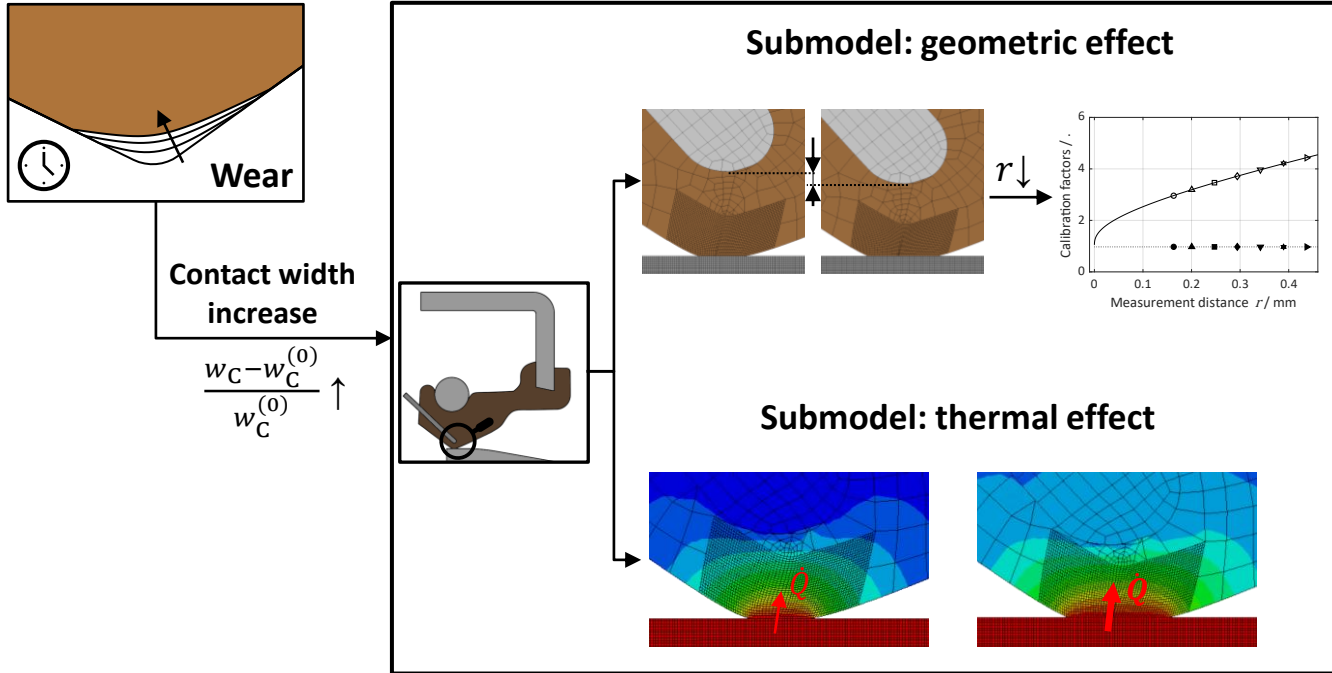


Torque transducer



Reference sensor

Contact Temperature – Wear Compensation Model



Sensitivity increase

$$m_{\text{cal}} \left(\frac{w_C - w_C^{(0)}}{w_C^{(0)}} \right) \uparrow$$

Result: Wear metric enables sensitivity compensation

Contact Temperature – Proof of Function and Outlook

Calibration model



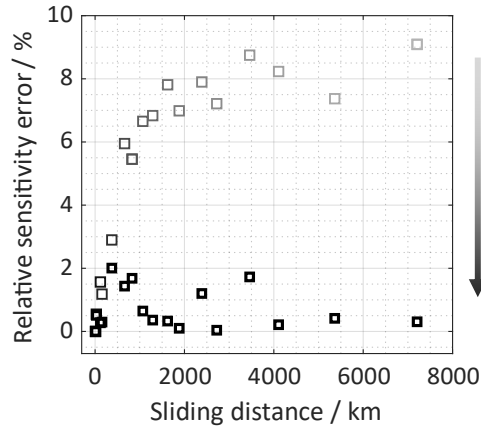
Wear progress model



Wear compensation model



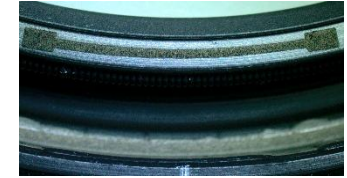
Consolidation



Prototype SiME-RSS

Next Steps

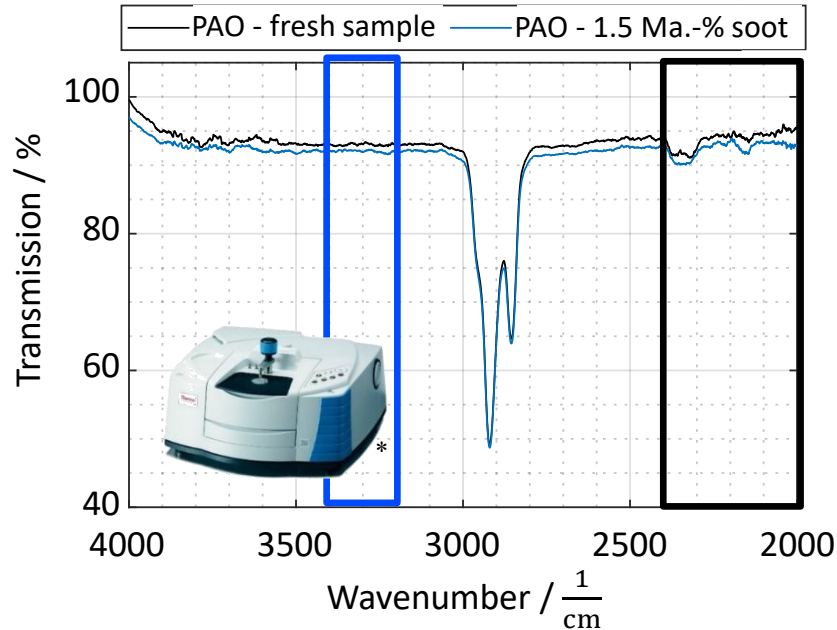
- Refine and extend submodels
- Transferability and application readiness
- Finalize friction torque measurement



Result: In-situ measurement of

- contact temperature
- and wear





Potential benefits of in situ approach

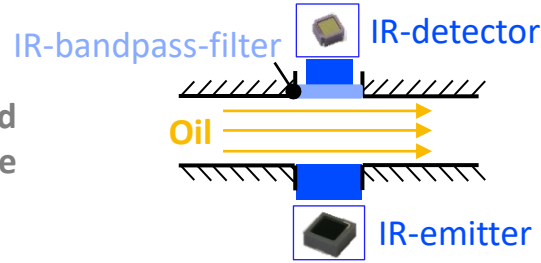
- In situ detection of ageing and contamination
- Changeover in oil exchange strategy interval-cycled → demand-controlled

Existing ex situ approaches

- Fourier Transform Infrared Spectroscopy (FTIR)
 - Soot content
 - Water ingress
 - Oxidation
 - Nitration
 - Total acid number
 - Additive consumption

* Nicolet™ iS™ 10 FT-IR-Spectrometer

Principle of miniaturized IR-spectroscope



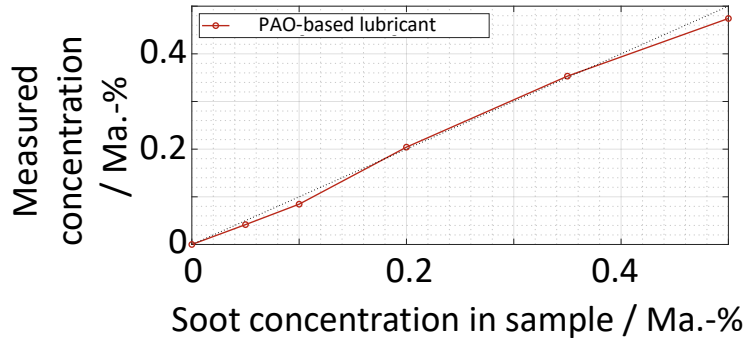
Prototype for quantitative analysis

- Existing proof of concept:

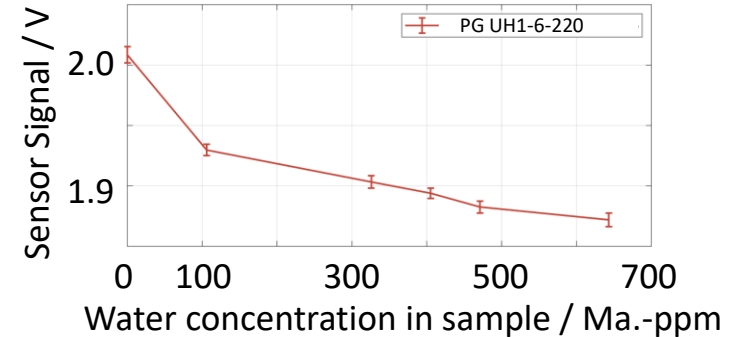
Soot Content

- Running transfer to new measurands
Water ingress

Carbon black loaded oil sample series



Water loaded oil sample series



Thank you for your attention!

Yvo Stiemcke

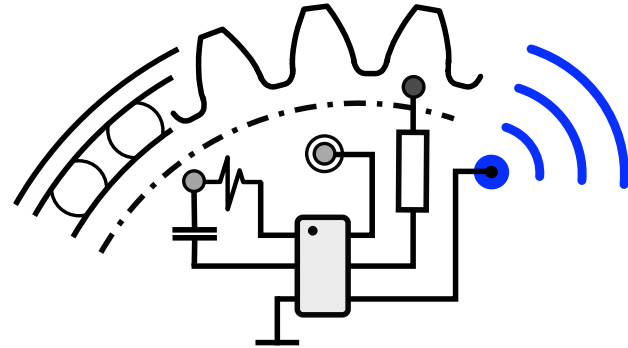
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The participating institutes would like to thank the German Research Foundation (DFG) for funding the project „Sensor-integrated machine element radial shaft seal for monitoring of operation conditions and lubricant quality “ (Project number 466192751).

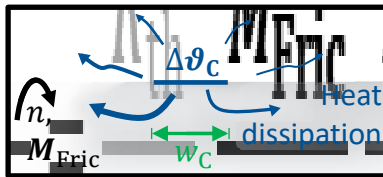
Questions and answers

In-situ wear estimation

Contact Temperature – Wear Progress Model

1.) BRINK's approach (*)

$$\Delta\vartheta_C = \vartheta_C - \vartheta_S = R_{th} \frac{2\pi n M_{Fric}}{2\pi r w_C}$$



(*) Brink, R.V.: „The Heat Load of an Oil Seal“,
6th International Conference on Fluid Sealing, 1973

$$\rightarrow w_C = R_{th} \frac{1}{r} \frac{M_{Fric}}{\Delta\vartheta_C} \quad \text{Reference to Initial state (0)}$$

$$\frac{w_C - w_C^{(0)}}{w_C^{(0)}} = \frac{R_{th}}{R_{th}^{(0)}} \frac{M_{Fric}}{M_{Fric}^{(0)}} \frac{\Delta\vartheta_C}{\Delta\vartheta_C^{(0)}} \frac{n}{n^{(0)}} - 1$$

$$\text{BRINK: } \frac{R_{th}}{R_{th}^{(0)}} = 1$$

→ Valid for limited operation ranges

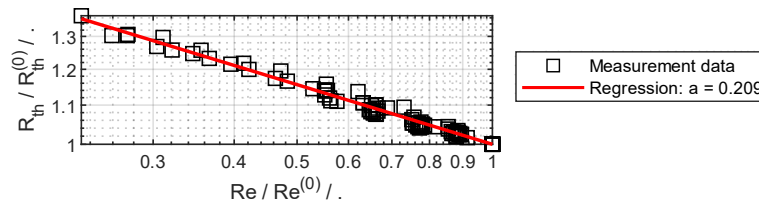
2.) Extension to broader operation ranges

→ Assumption:
changes in heat dissipation
dominated by oil convection

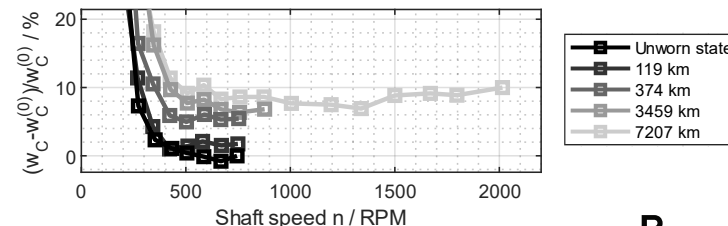
$$\frac{R_{th}}{R_{th}^{(0)}} \approx \frac{\frac{1}{\alpha}}{\frac{1}{\alpha^{(0)}}}$$

$$\frac{R_{th}}{R_{th}^{(0)}} \approx \left(\frac{Re^{(0)}}{Re} \right)^a$$

→ Submodel from
NUSSELT correlation

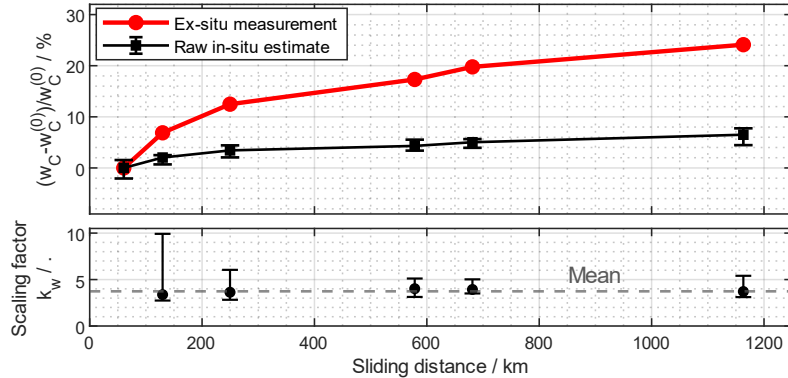
$$\alpha = \frac{Nu \lambda}{L_c} = \frac{k Re^a \lambda}{L_c}$$


$$\frac{w_C - w_C^{(0)}}{w_C^{(0)}} = \frac{M_{Fric}}{M_{Fric}^{(0)}} \frac{\Delta\vartheta_C}{\Delta\vartheta_C^{(0)}} \left(\frac{n}{n^{(0)}} \right)^{1-a} \left(\frac{\nu(\vartheta_S)}{\nu(\vartheta_S^{(0)})} \right)^a - 1$$

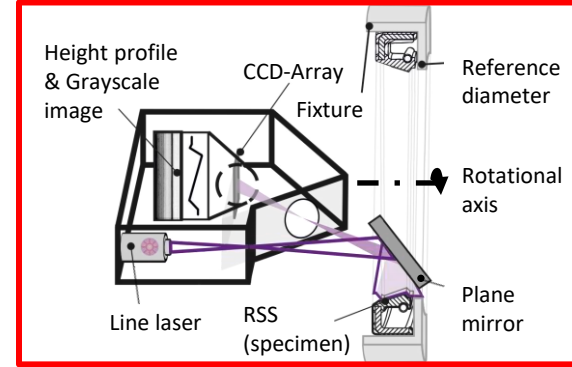


Contact Temperature – Wear Progress Model

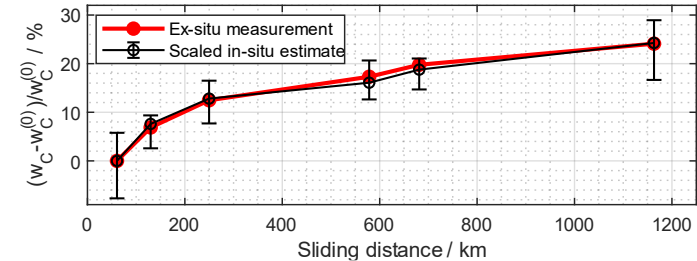
3.) Mapping to measured contact width



$$\frac{w_C - w_C^{(0)}}{w_C^{(0)}} = k_w \left(\frac{M_{\text{Fric}}}{M_{\text{Fric}}^{(0)}} \frac{\Delta \vartheta_C}{\Delta \vartheta_C^{(0)}} \left(\frac{n}{n^{(0)}} \right)^{1-a} \left(\frac{v(\vartheta_S)}{v(\vartheta_S^{(0)})} \right)^a - 1 \right)$$



Wear-Tester:
Laser triangulation system

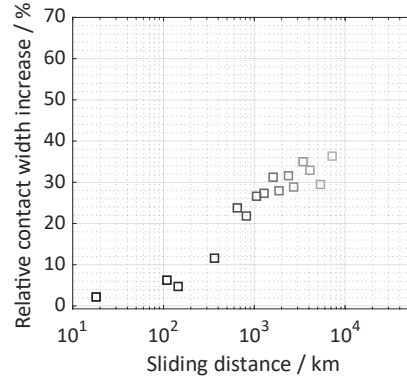
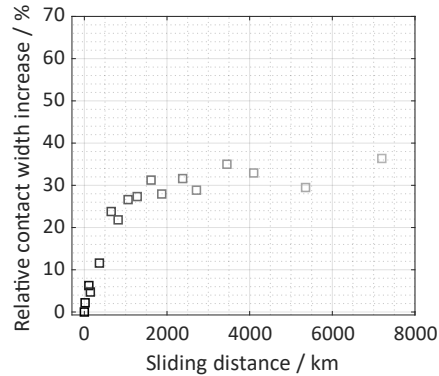


Potential Use

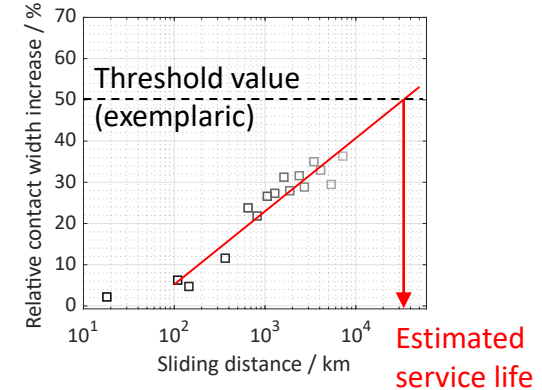
Potential Use – Estimation of Remaining Service Life

→ Wear as lifetime criterion

In-situ wear estimation



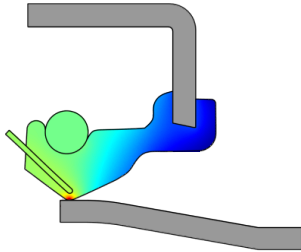
Wear trend extrapolation



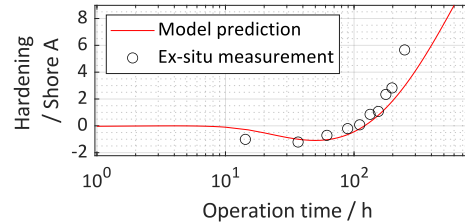
Potential Use – Estimation of Remaining Service Life

→ Elastomer aging as lifetime criterion

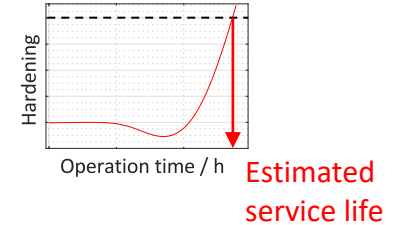
In-situ
contact temperature
measurement



Thermal damage
accumulation model (*)



Aging trend extrapolation (*)



Crack formation



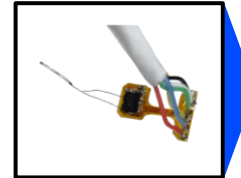
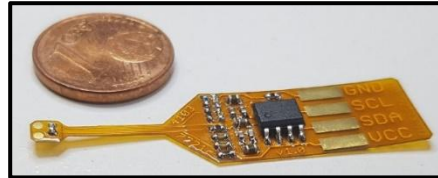
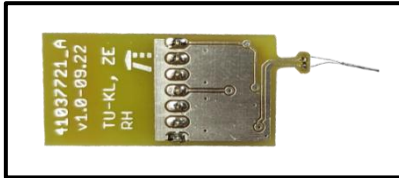
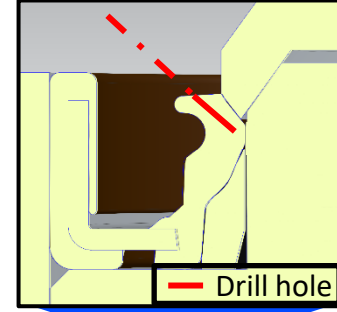
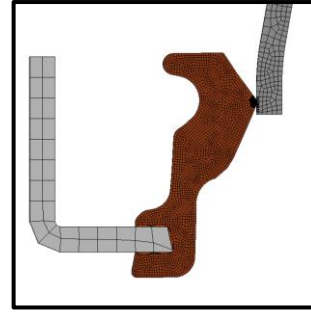
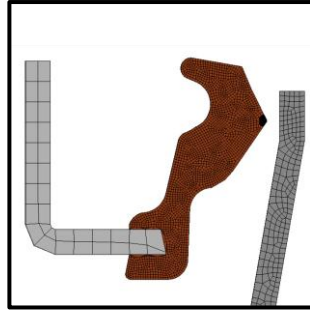
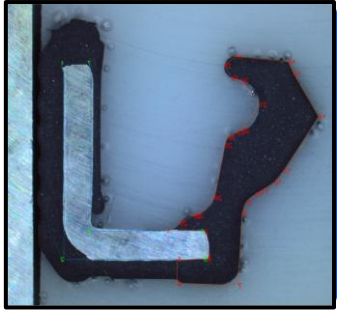
Discoloration

(*) Proof of concept: GRUTZA et al., „Model-based assessment of the cooling potential of additively manufactured shafts considering the ageing-related service life of radial shaft seals“ in *Production Engineering*, 2026

Contact temperature

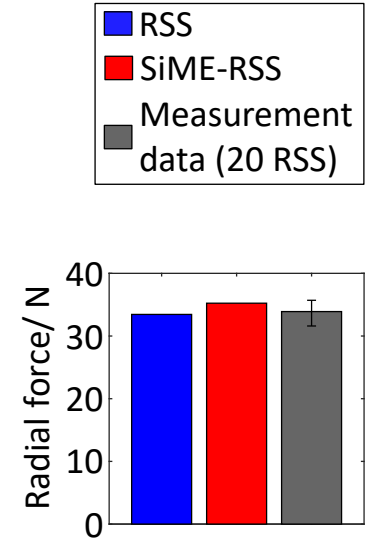
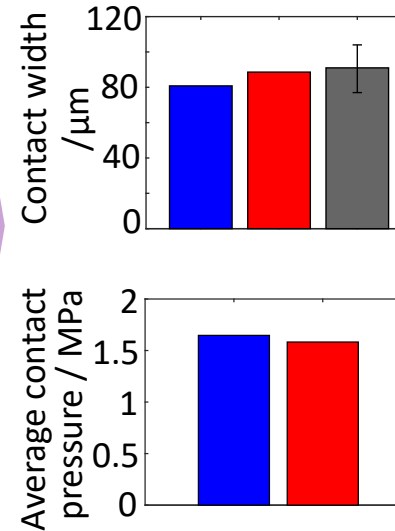
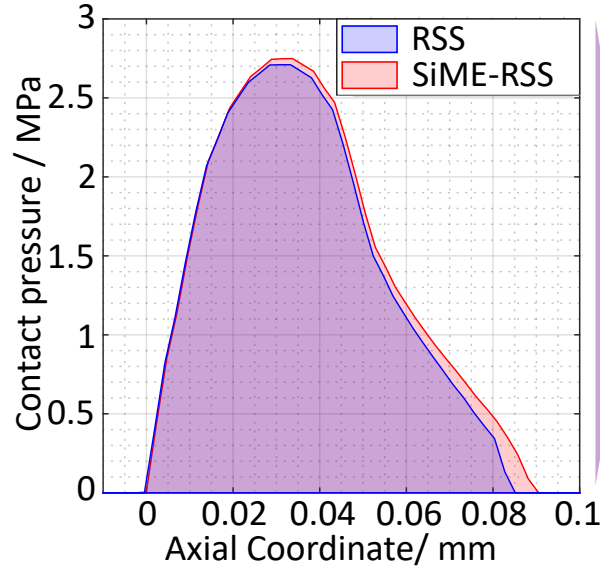
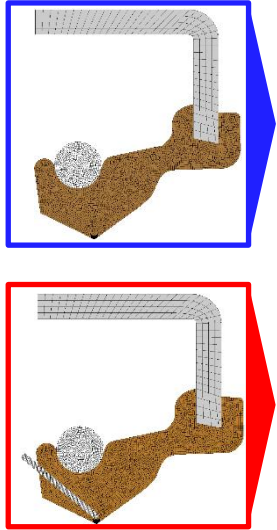
Manufacturing process

– Thermocouple integrating SiME-RSS



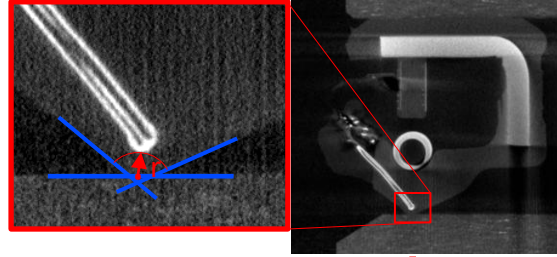
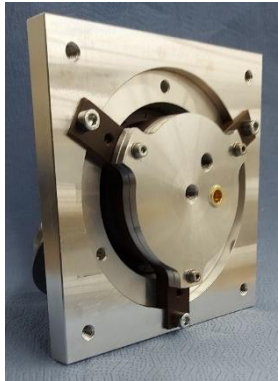
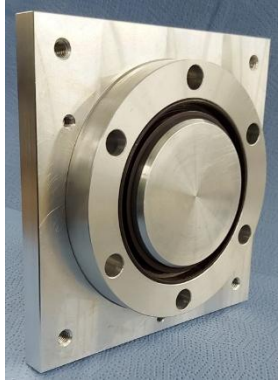
Interaction sensor-machine element

– Assessment of the thermocouple's impact on the seal function

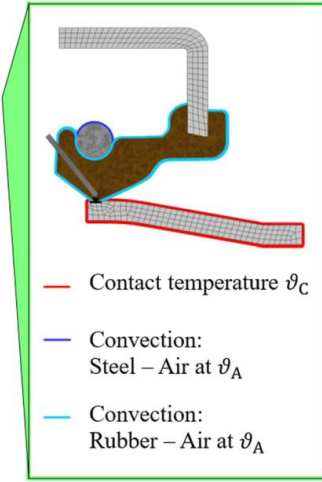
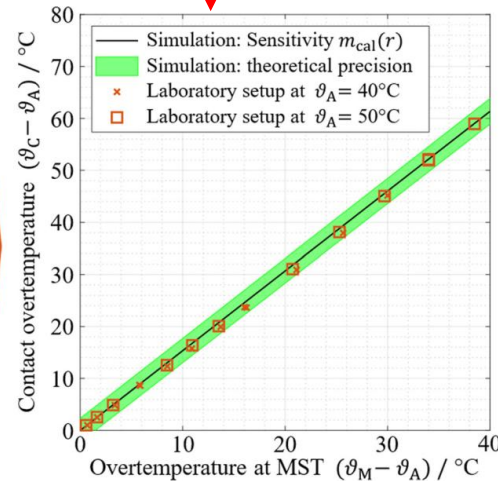
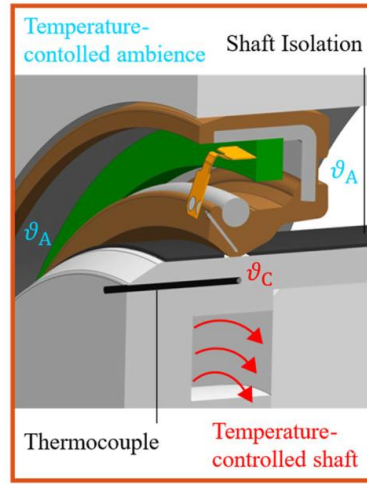


Contact Temperature

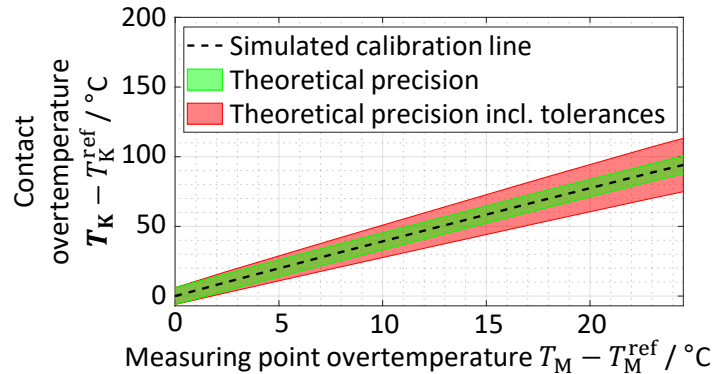
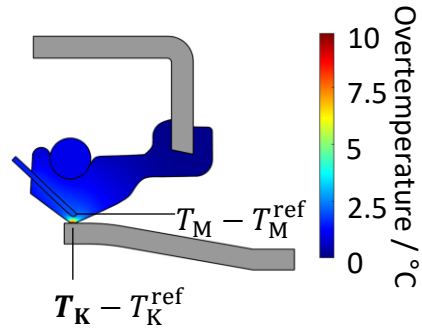
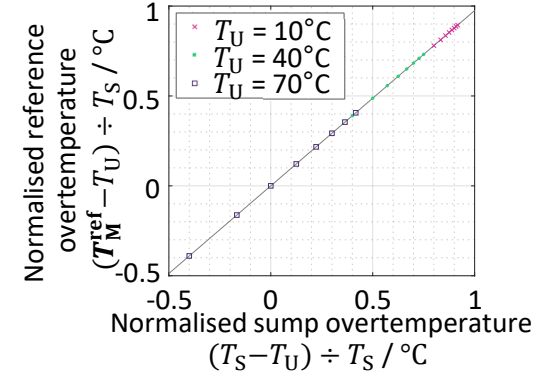
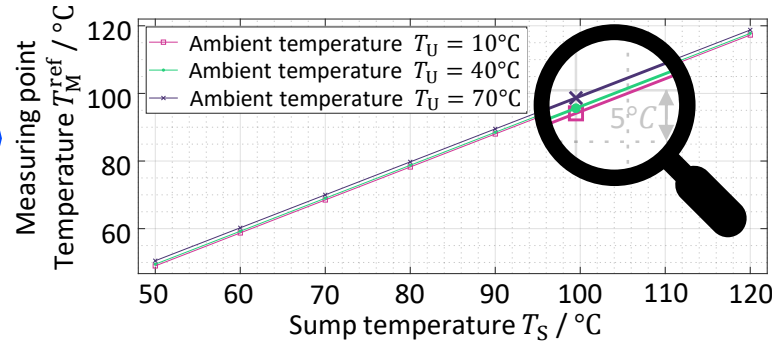
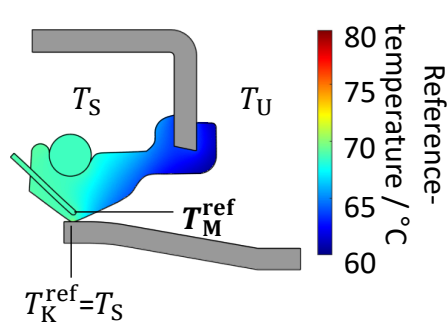
– First validation in static setup



CT scan



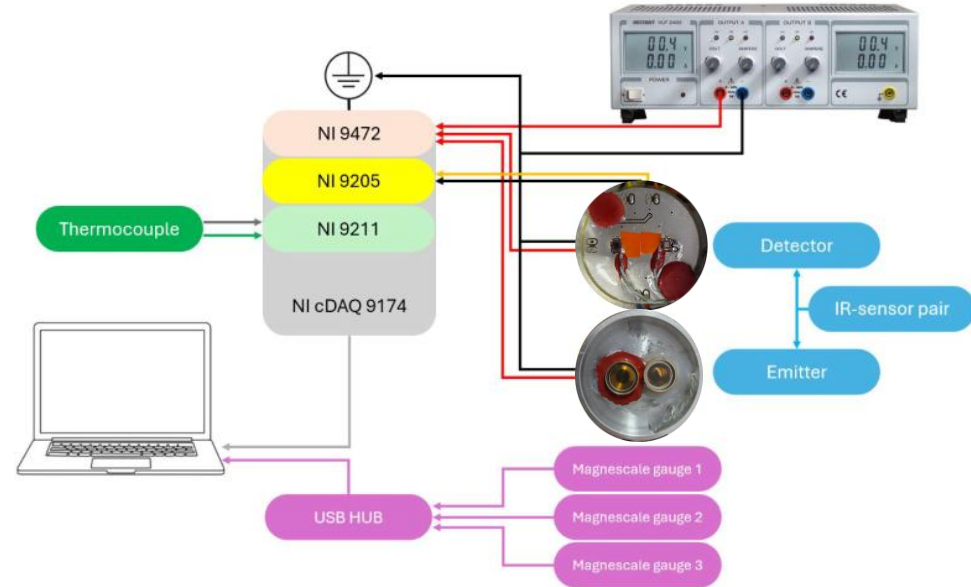
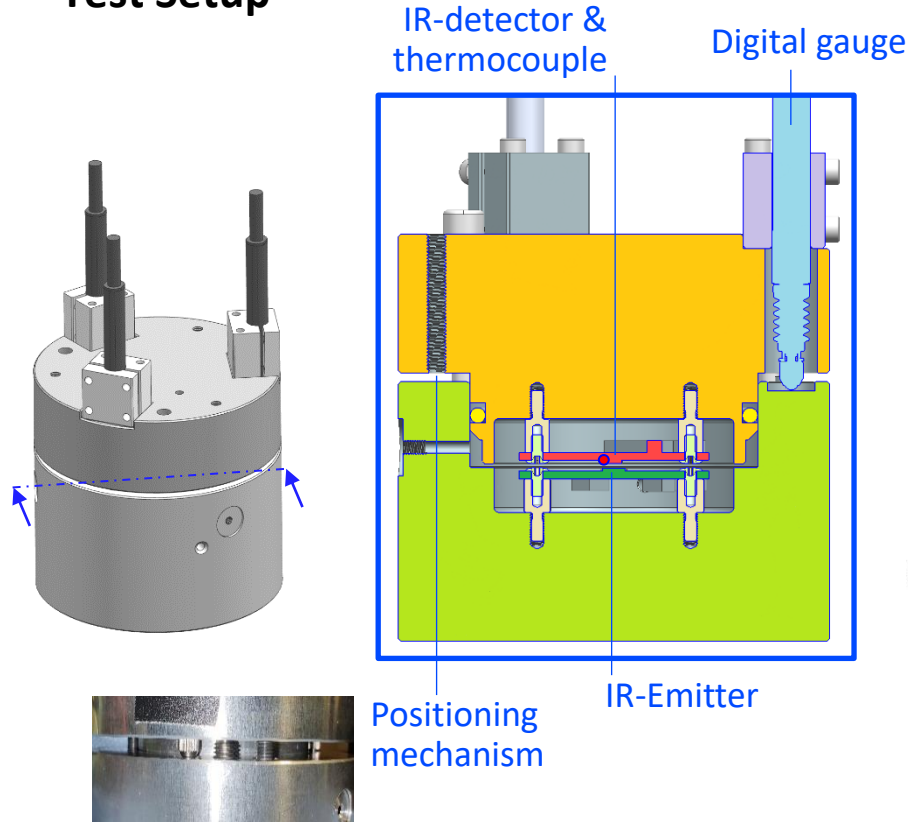
Contact temperature – Simulative calibration in detail



Infrared Spectroscopy

Infrared spectroscopy

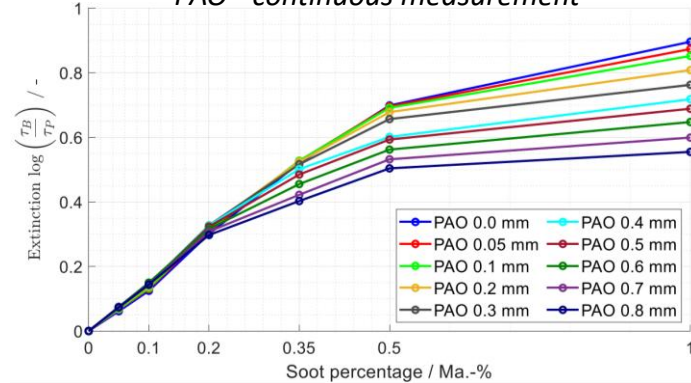
– Test Setup



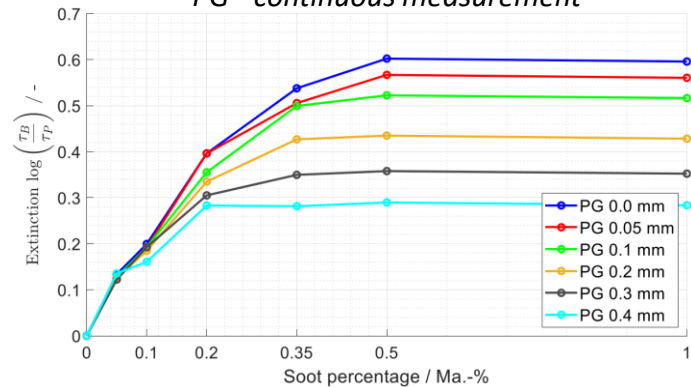
Limitations of infrared spectroscopy

– Dampening by pulse duration, base oil and sensor distance

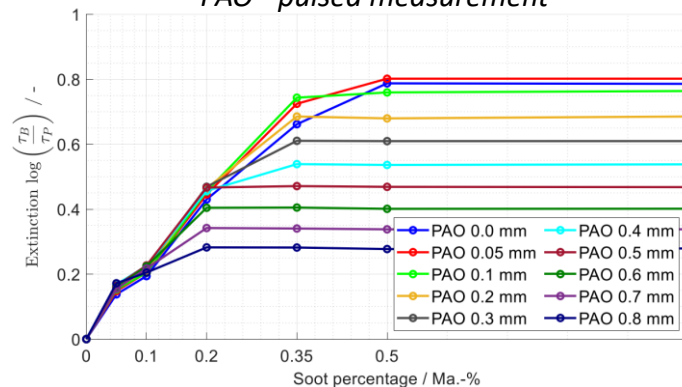
PAO - continuous measurement



PG - continuous measurement

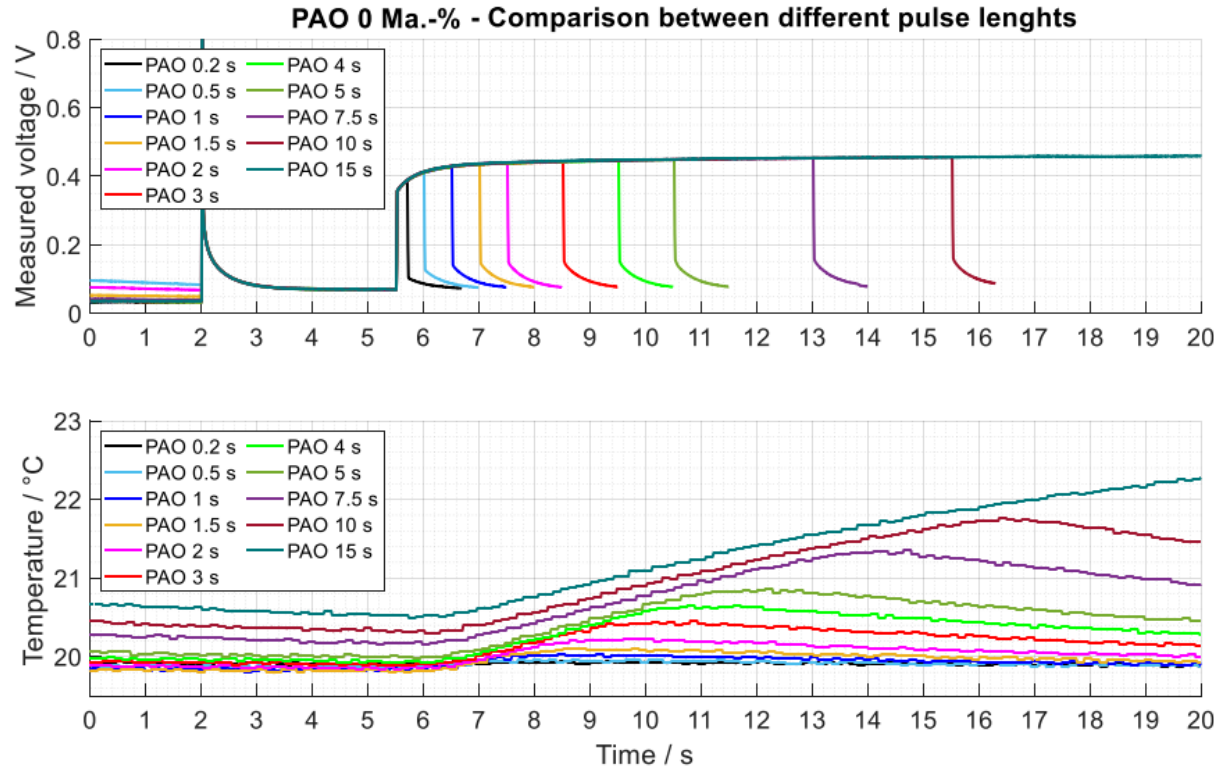


PAO - pulsed measurement

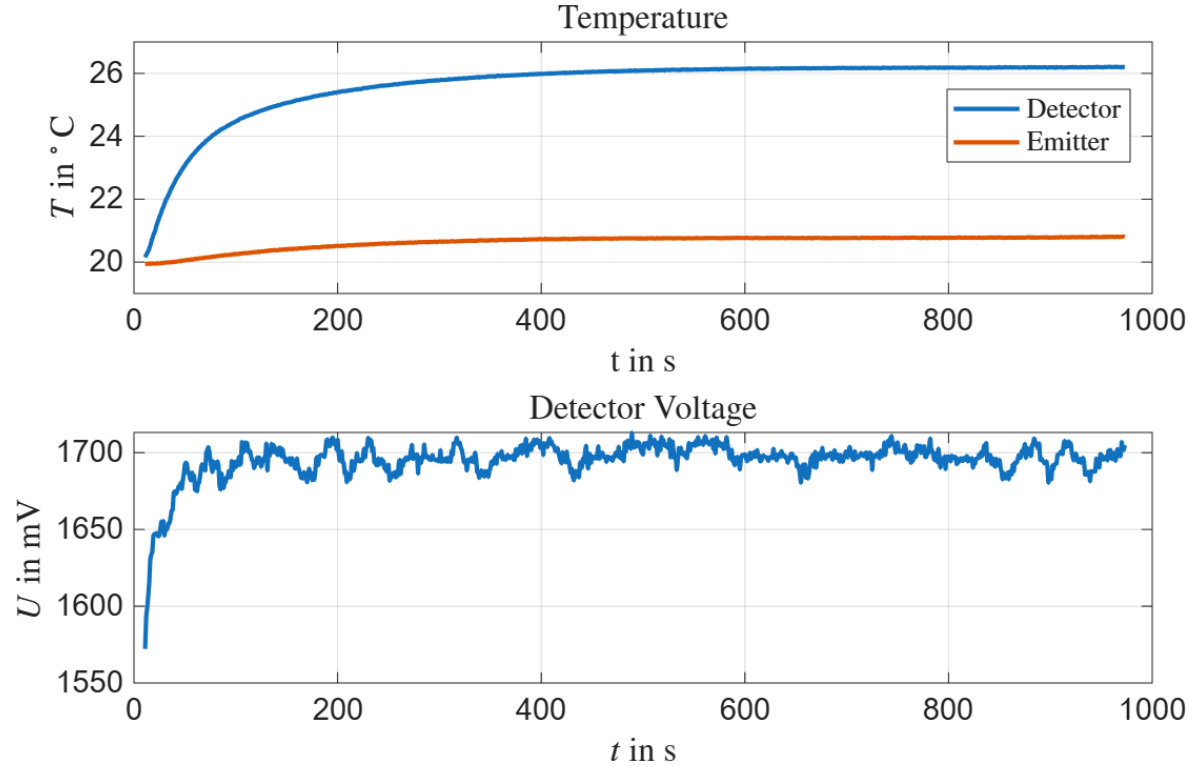


Limitations of infrared spectroscopy

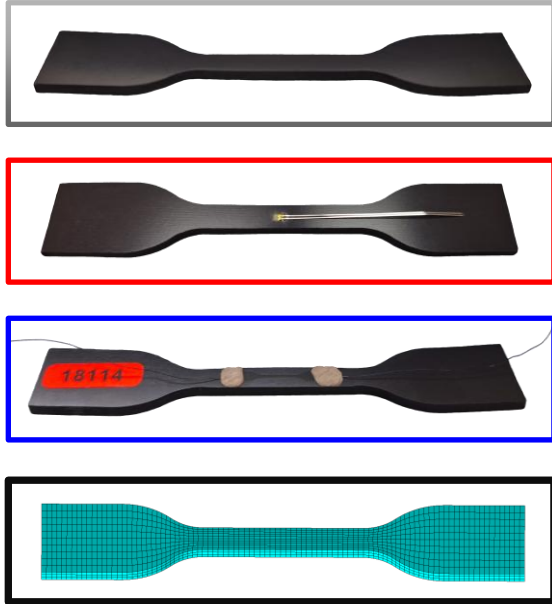
– Start-up behavior causing dampening at pulsed measurement



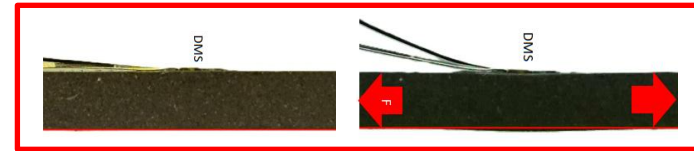
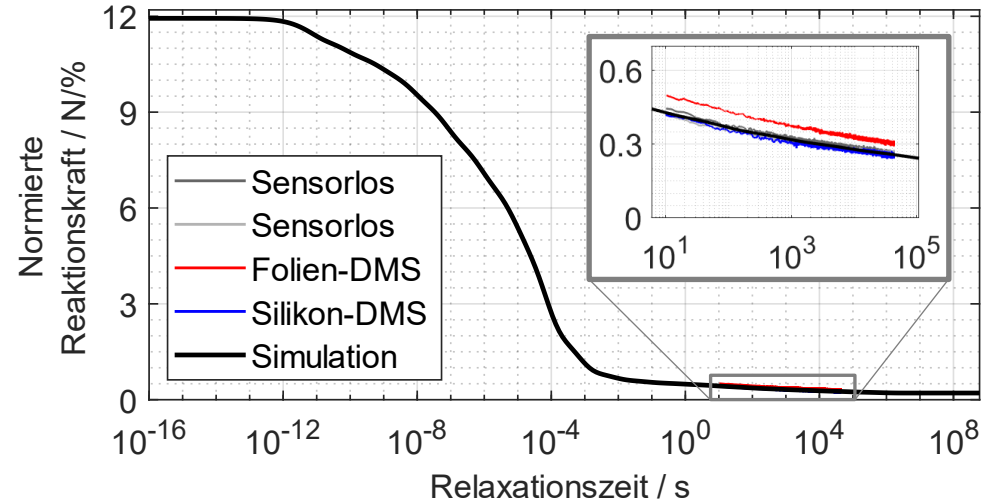
Time behavior of the measured variables



Friction torque

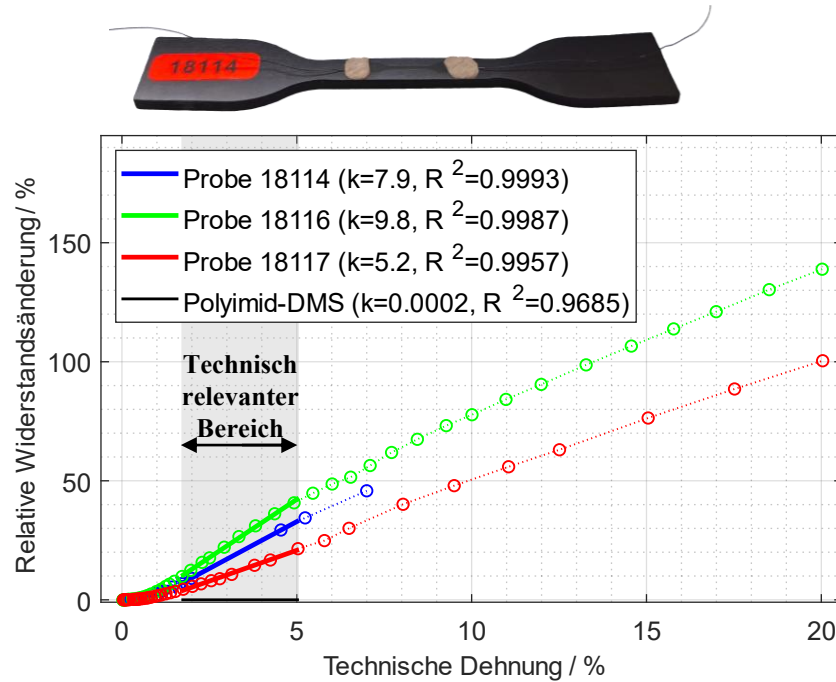


Sensor-specimen interaction in the relaxation test

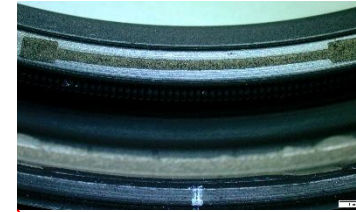


Friction torque – Implementation in progress

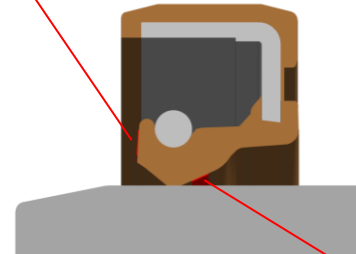
Prototype strain gauges in tensile testing



Transfer to the RSS – results pending

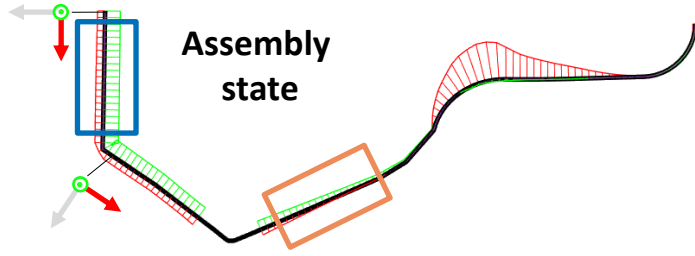


Strain gauge for preload measurement

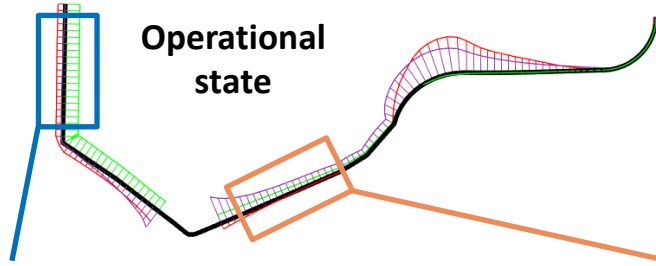


Shear strain gauge for friction torque measurement

Friction torque and preload – Measurement concept



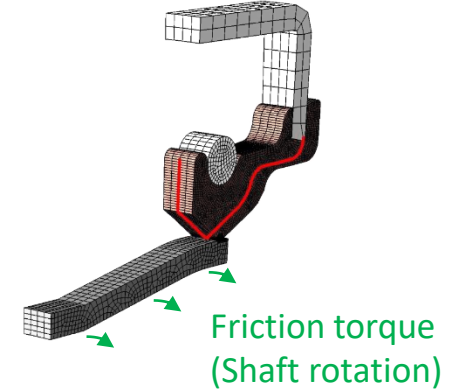
$\epsilon_{\text{Profile}}^{\text{max}}$	= 11.6%	
$\epsilon_{\text{Circumference}}^{\text{max}}$	= 4.7%	
$\epsilon_{\text{Shear}}^{\text{max}}$	= 0.1%	



$\epsilon_{\text{Profile}}^{\text{max}}$	= 11.1%	
$\epsilon_{\text{Circumference}}^{\text{max}}$	= 4.5%	
$\epsilon_{\text{Shear}}^{\text{max}}$	= 8.5%	

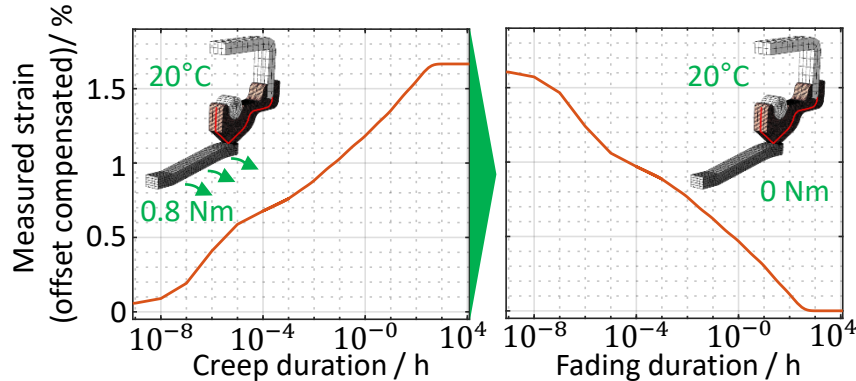
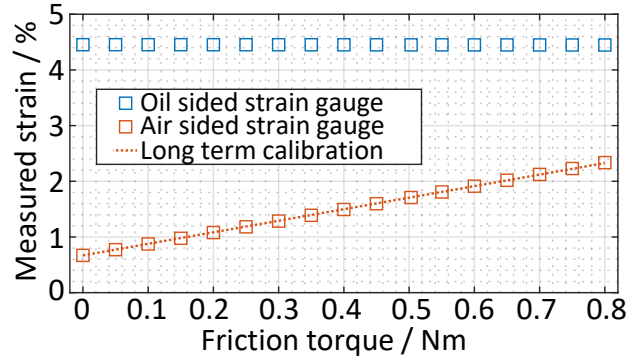
Oil sided strain gauge

Air sided strain gauge



- Normal strain due to assembly deformation
 - Mapped on **preload**
 - Connection to further measurands (Radial force, state of relaxation, etc.)
- Shear strain due to Torsion
 - Mapped on **friction torque**
- Superimposition with assembly deformation (**preload**)
 - Offset to be compensated for

Friction torque and preload – Calibration strategy: proof of function



Strain gauge measurements from simulation

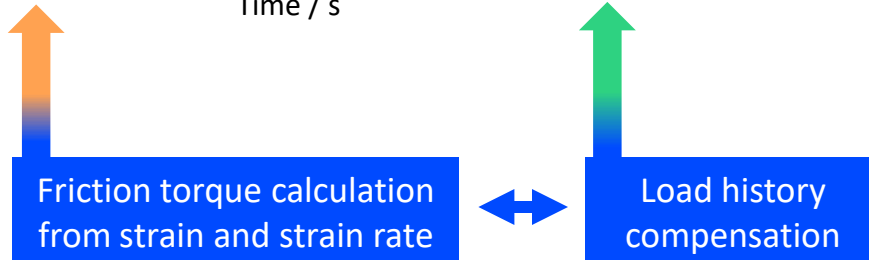
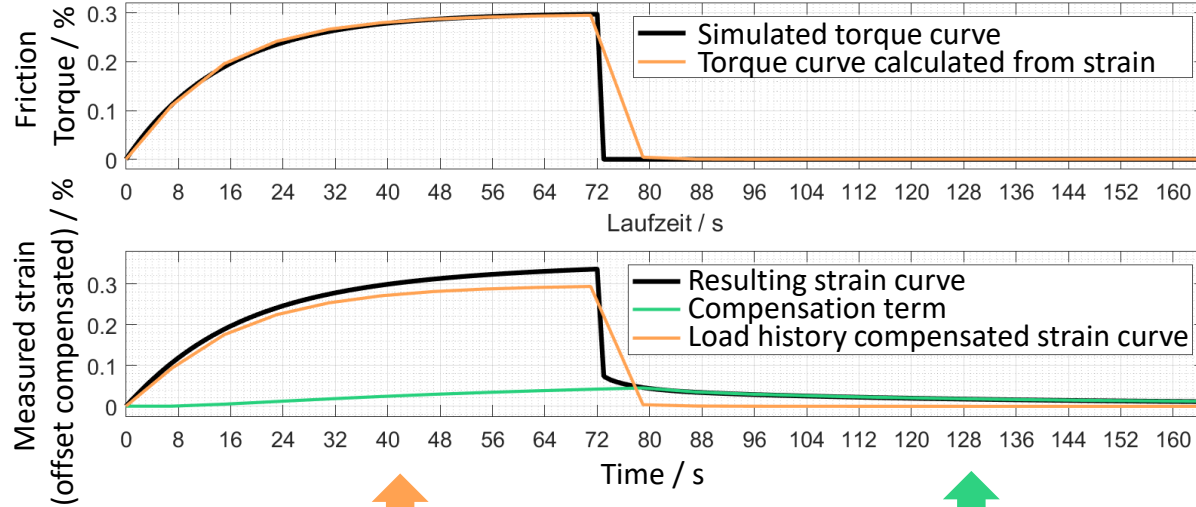
- Long-term behavior ($t \rightarrow \infty$)
 - **Preload strain:**
Constant, torque-independent
 - **Shear strain:**
Linear relationship to friction torque
- Viscoelastic behavior ($t \ll \infty$)
 - Load: Creep dominating **shear strain**
(logarithmic drift in measured strain)
 - Load relief: inverse effect
(fading measured strain)

Friction torque calculation
from strain and strain rate



Load history
compensation

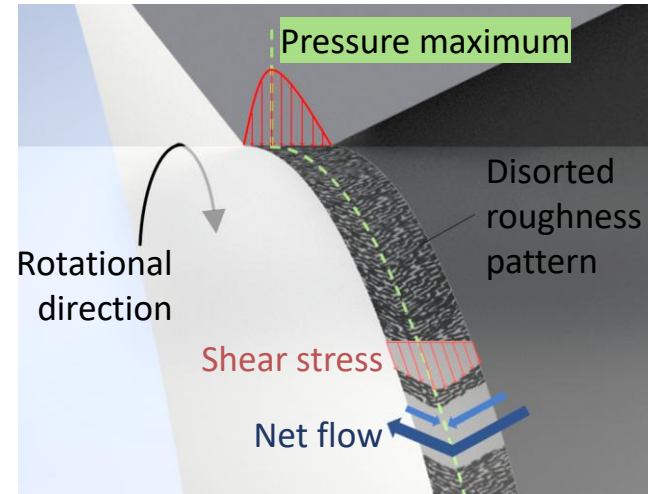
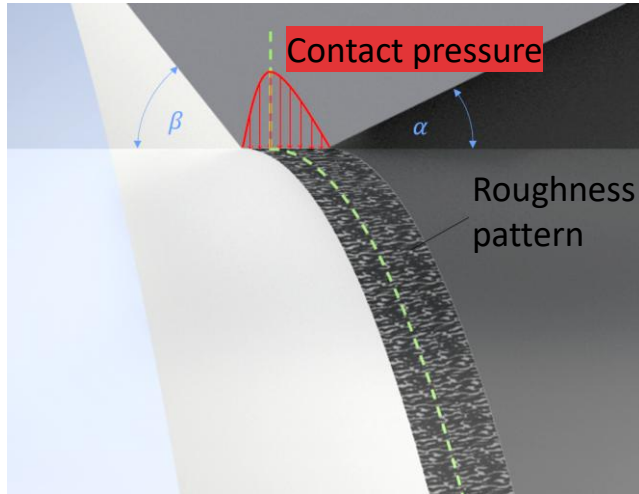
Friction torque – Calibration strategy: simulative proof of function



RSS

Seal mechanism

- Primary function of RSS



Disortion principle (Kammüller, 1986), schematic