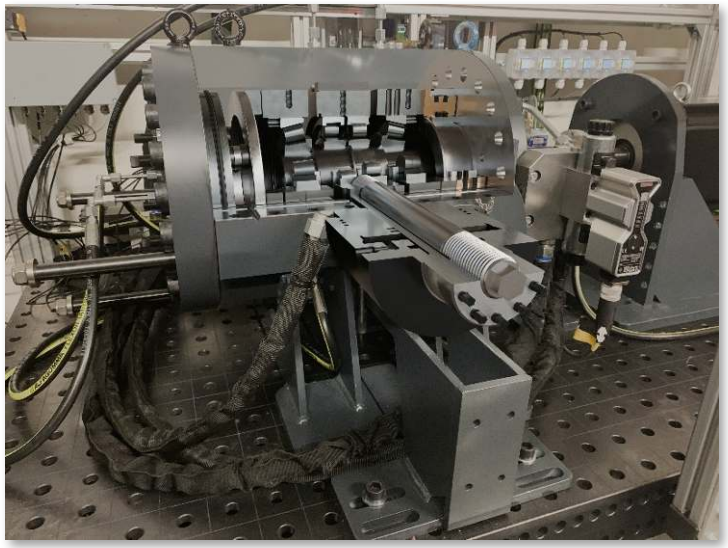
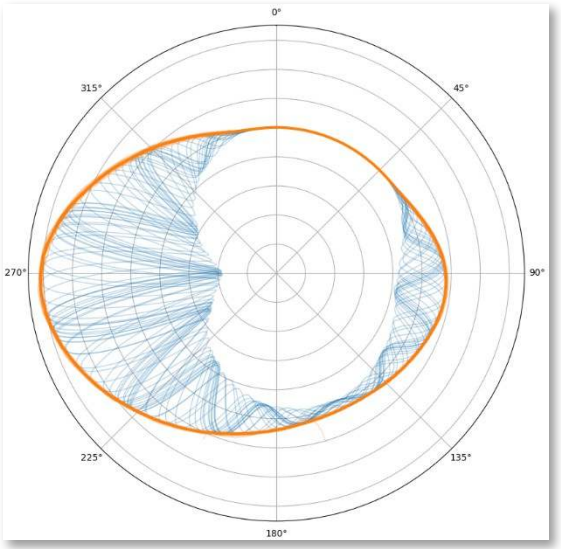
Investigation of the slip and load-carrying behavior of a tapered roller bearing using roller-integrated measurement technology

Martin-Christopher Noll, i4M technologies GmbH
Prof. Dr. Matthias Stammler, Fraunhofer IWES
Tomek Gerber, B.Sc., Fraunhofer IWES

7th VDI Conference on Damage Mechanisms in Bearings 2026, 16.04.2026, Aachen







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Outline

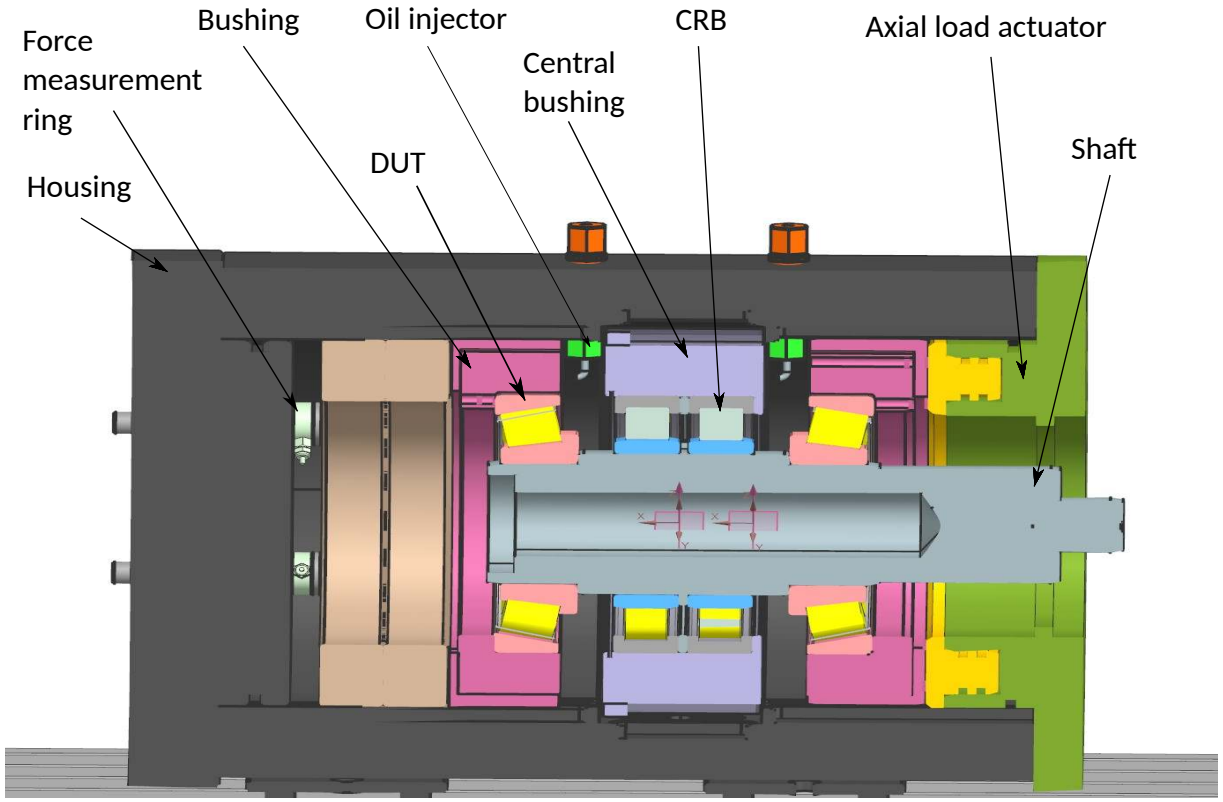
1. Introduction, overview, and motivation
2. Test bench setup and bearings
3. Rolling element-integrated measurement technology
4. Data and analysis methods
5. Results
6. Summary and outlook

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Introduction: Dy-rex Project

- **“Dy**namische **Re**gelung einer a**x**ialen Lastsuperposition“ (Dynamic control of axial load superposition)
- Reduction of harmful rolling element slip while maintaining fatigue life
- Application in critical operating situations such as fault ride through
- Motivation: Reduction of WEC



Introduction: Dy-rex Project

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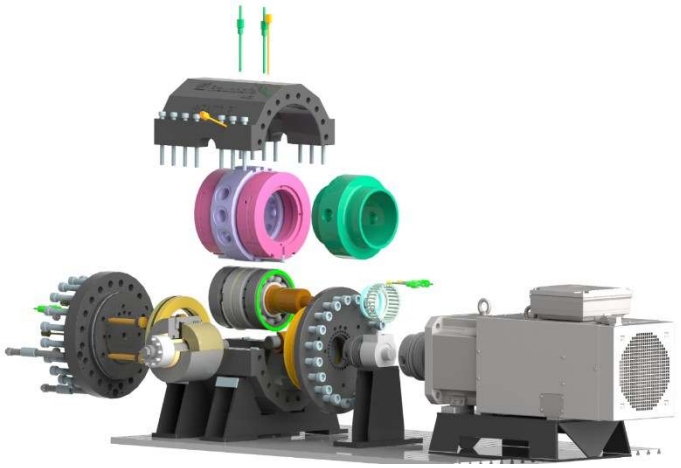


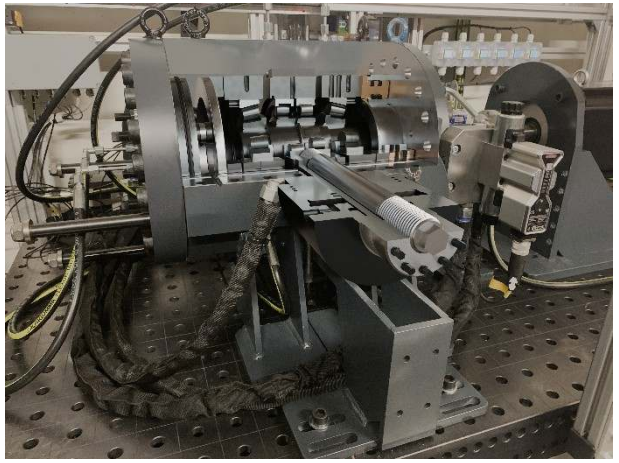
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Test bench setup & storage

- Test bench BEAT0. 3
- Designed for high load and speed dynamics
- Possible roller bearings: 30318, 7318, as well as four-point types
- Ten adjustable oil feeds
- Bearing bushes as hydrostatic plain bearings
- Radial force applied by two tension cylinders controlled by a valve
- **Load is applied on horizontal axis**





Parameter	Value	Unit
Max. RPM	3000	rpm
RPM-Dynamic	500	rpm/s
Max. Axial Force	140	kN
Axial Force Dynamic	1120	kN/s
Max. Radial Force	250	kN
Radial Force Dynamic	500	kN/s
Max. outer diameter of test bearing	220	mm
Max. flow rate for oil lubrication	60	l/min

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Outline

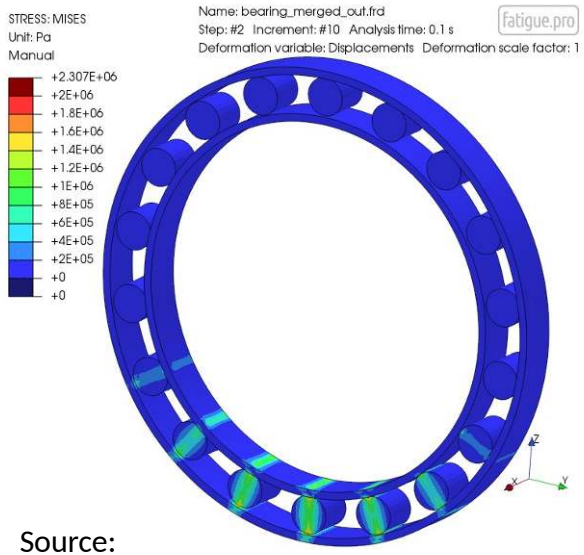
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Motivation of Smart Roller Integration

- High relevance for design and reliability calculations
  - How is the load distributed among the various rolling elements in the orbit of a rolling bearing?
  - At which points and in which operating conditions does harmful slip occur?
  - What happens to the calculated pre-tension under real operating conditions?
- Reliability is a dominant issue, especially in the field of wind energy
- Simulations only reflect reality to a limited extent; measurements are always necessary for validation
- Measurements of load distribution and slip in rolling bearings are technically challenging, a robust, precise and bearing-manufacturer independent solution is needed



Source: Schaeffler



Source: fatigue.pro

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Rolling element integrated measurement technology / i4M Smart Roller

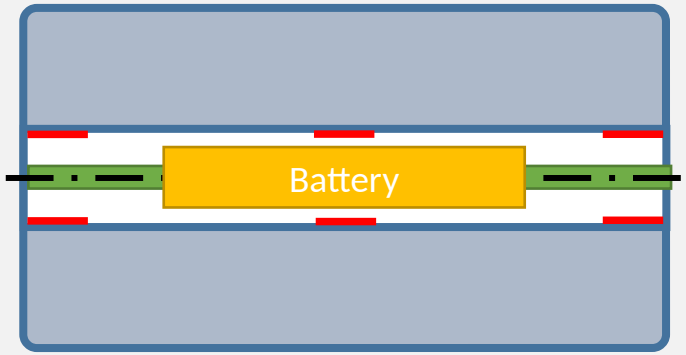
- Different Smart Roller Options

Electronics — Strain Gage — Battery

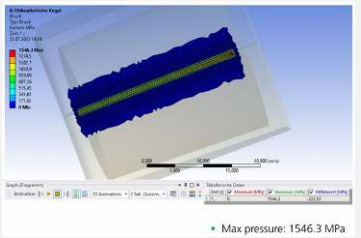
- Smaller Rollers (< 40 mm in diameter)
  - Rechargeable / non-rechargeable
  - No big central hole possible
  - Recesses at front faces for electronics and strain gages

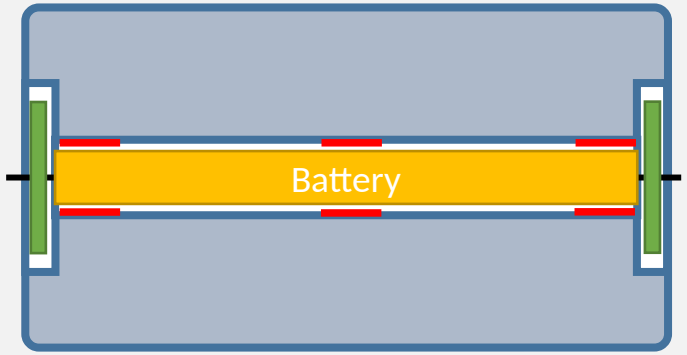


- Bigger Rollers (≥ 40 mm in diameter)
  - Rechargeable / non-rechargeable
  - Energy Harvesting possible

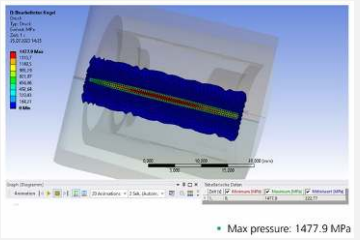


+ uniform contact pressure





+ more battery runtime



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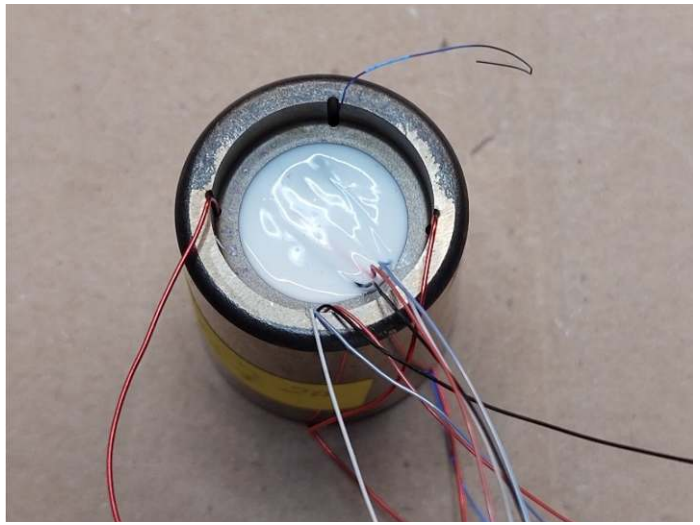
Rolling element integrated measurement technology / i4M Smart Roller

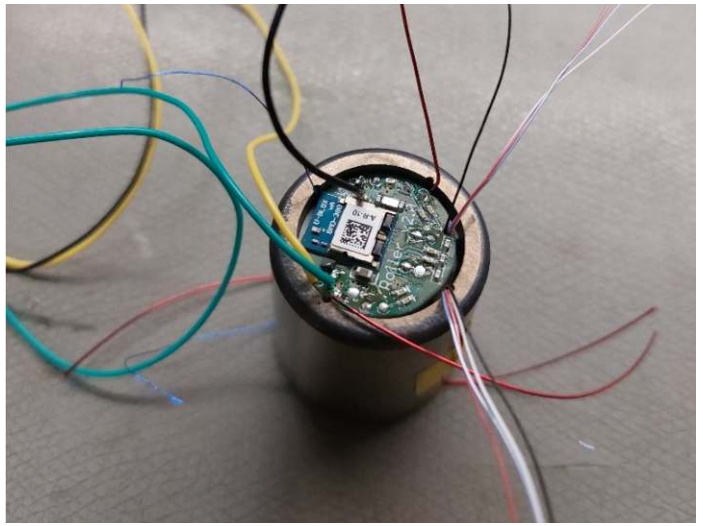
- Rolling element with integrated sensor technology for load (strain gauges) and rotational movement (MEMS IMU)
- **Rolling element diameter approx. 23 mm**
- **Shaft speeds up to 1500 rpm**
- Highly compact, battery-powered radio telemetry (proprietary i4M protocol)
- Integrated load measurement technology
  - Applied to the front faces, no central hole
  - 24-bit resolution, low noise, **2 kHz sampling rate**
- Integrated motion measurement technology
  - MEMS-based inertial measurement unit (IMU)
  - Triaxial acceleration sensor (accelerometer)
  - Triaxial rotation rate sensor (gyrometer)
  - 16-bit resolution, low noise, **1.6 kHz sampling rate**
- Power supply via integrated rechargeable battery, > 3 h continuous live measurement time
- Rechargeable on the test bench via contact pins

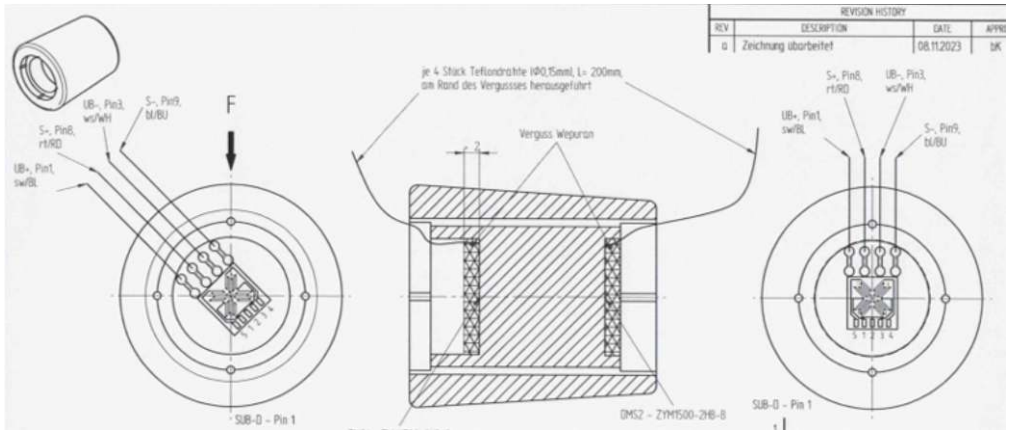


Rolling element integrated measurement technology / i4M Smart Roller

- Strain gages applied to front sides
- No through hole necessary
- Two electronics circuit boards
  - Measuring circuit board with sensors and radio telemetry
  - Power circuit board with battery and charging electronics
- Hardened rolling element manufactured using spark erosion process
- Completely encapsulated with epoxy resin



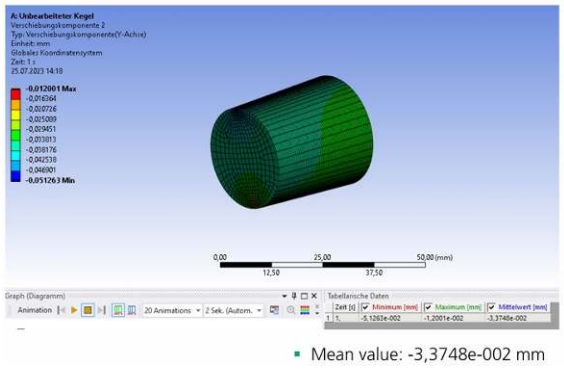


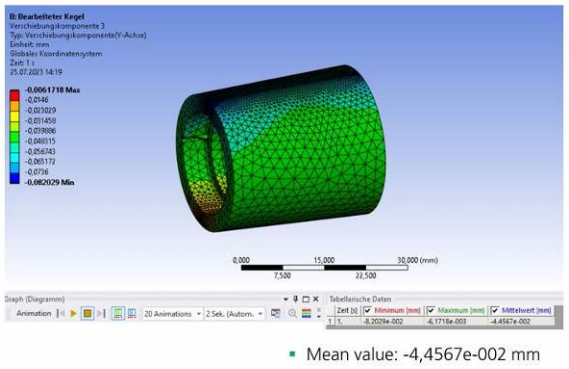


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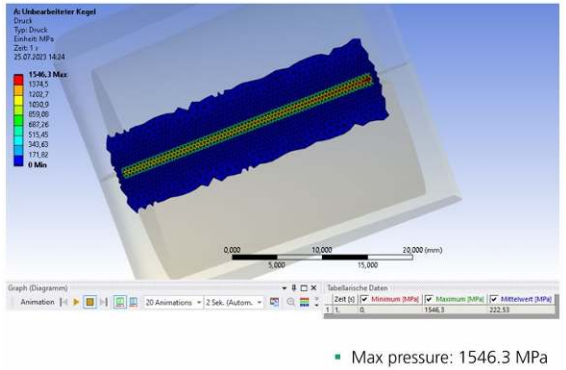
Rolling element integrated measurement technology / i4M Smart Roller

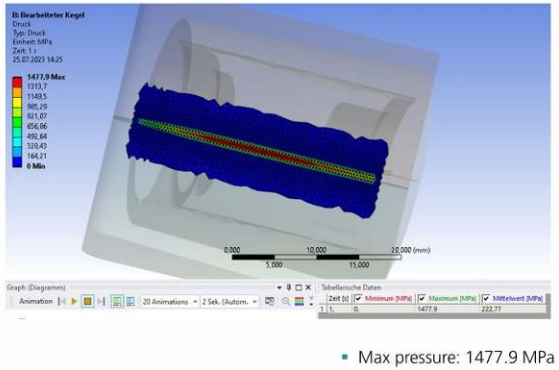
- The necessary machining of the rolling elements to integrate the measurement technology changes the system behavior
- Finite element simulations provide information about how stiffness and pressures change
- The test parameters must take these changes into account (e.g. adjustment of loads)





Change in the stiffness of the rolling element





Change in contact pressures

Source: FE simulations provided by Fraunhofer IWES

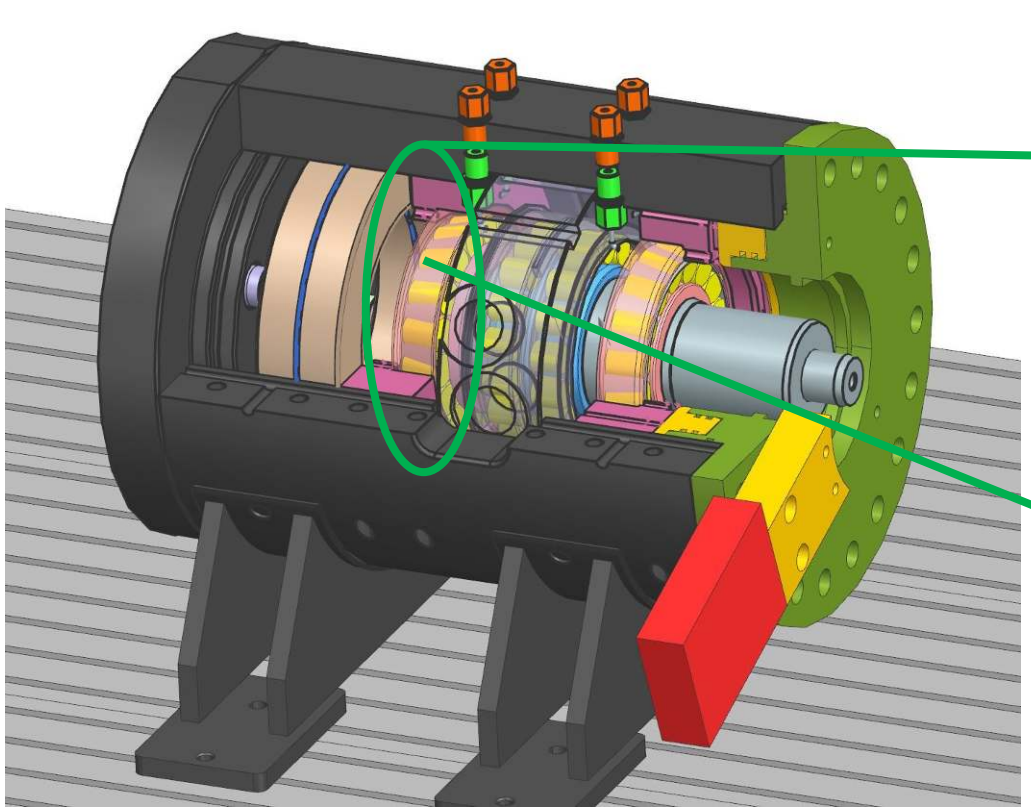
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Outline

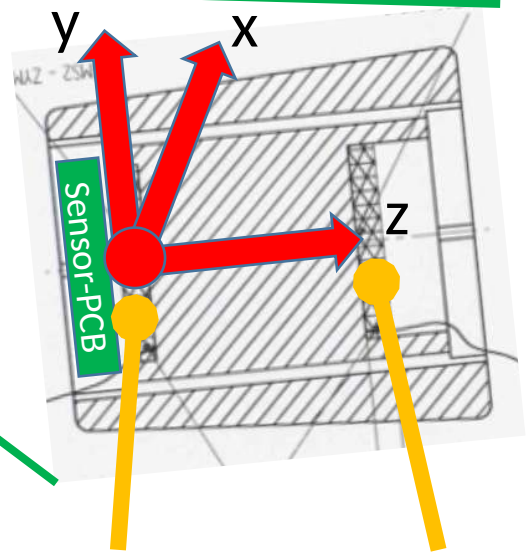
1 Introduction, overview, and motivation
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Data & Analysis Methods

- Definition of the coordinate system of the rolling element-integrated motion sensor technology
- X and Y lie in the plane of the rolling element end faces, Z lies on the rolling element axis of rotation
- Strain gauge channel 1 is located under the measuring PCB (smaller end face),
  strain gauge channel 2 is located under the power PCB (larger end face)



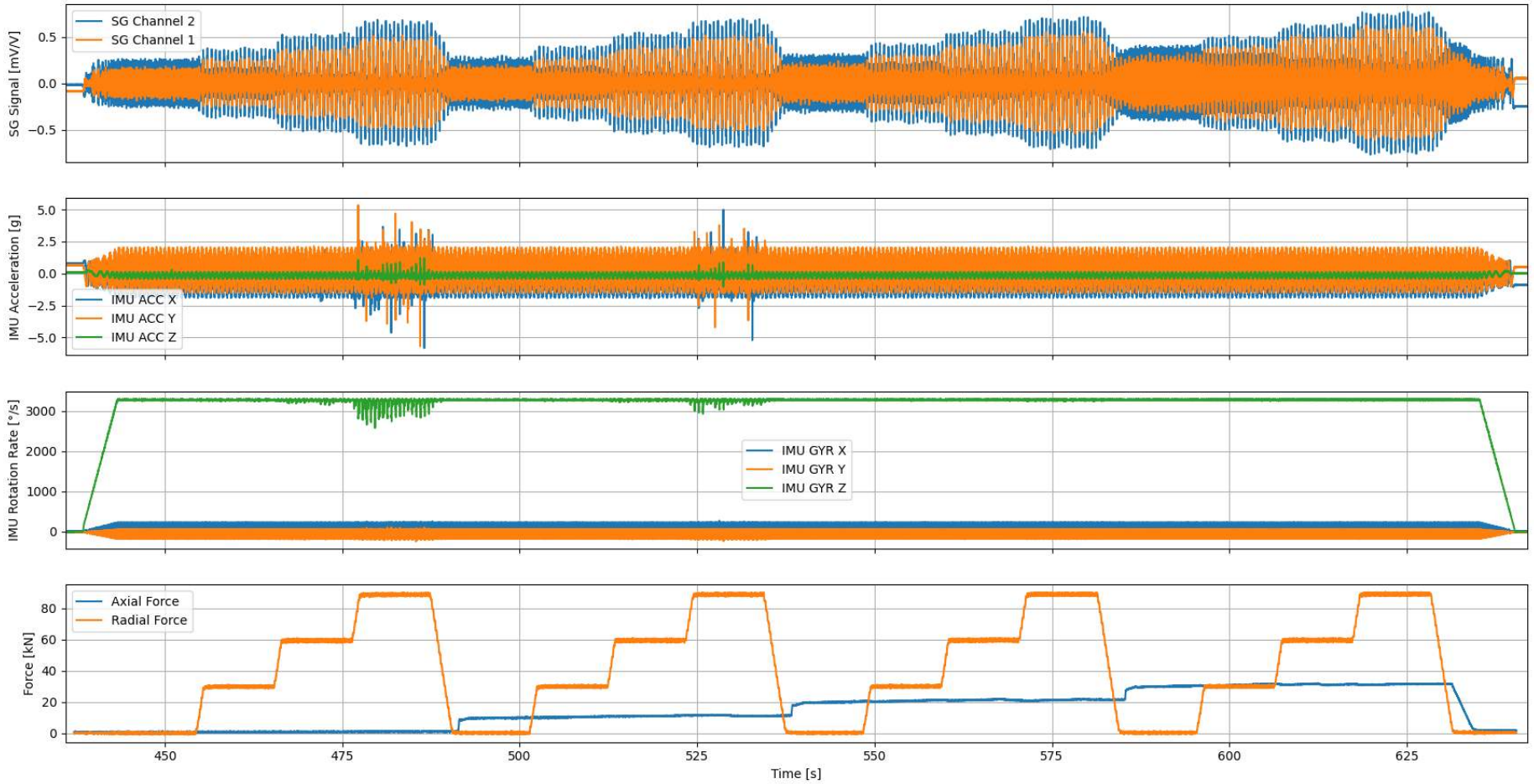




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Data & Analysis Methods

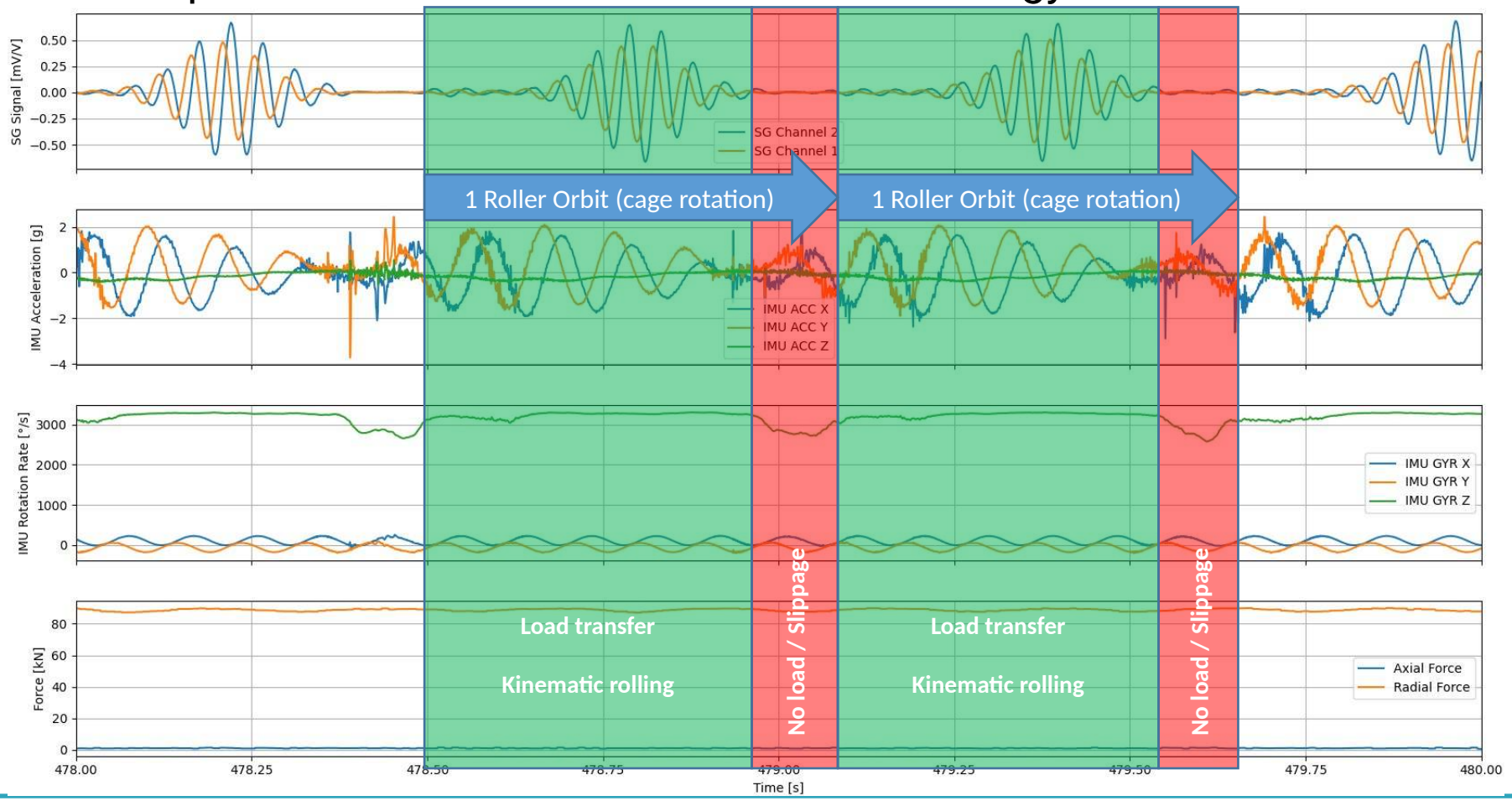
- Discussion of the delivered data using an example (250 shaft-rpm)
- Load variation on test bench: Increase in radial force 0 to 90 kN / axial force 0 to 30 kN



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Data & Analysis Methods

- Discussion of the delivered data using an example (250 shaft-rpm, 90 kN rad. / 0 kN ax. Detail)
- Identification of slip conditions based on accelerometer and gyrometer data

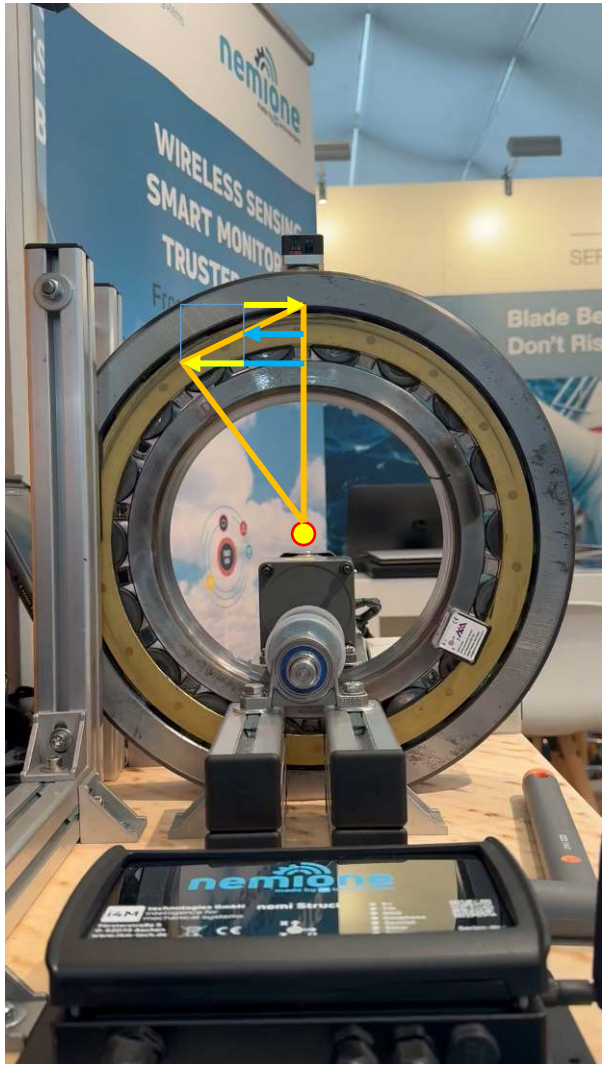


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Data & Analysis Methods

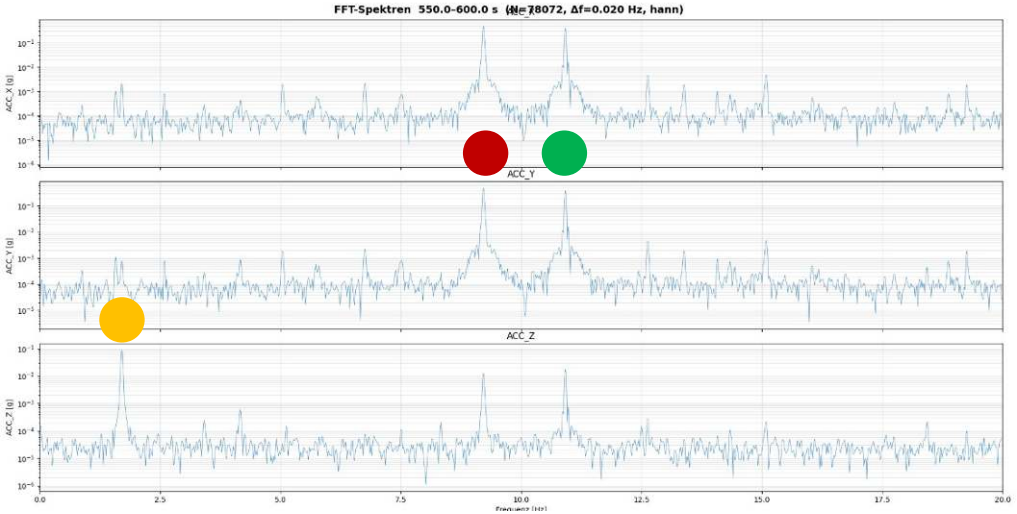
- Kinematic relationships can be derived from an analysis of the Instantaneous centers of rotation
- The rotational movement of the rolling elements is a superposition of two individual rotational movements
  - Rotation of the rolling element about the central shaft axis together with the cage and the entire set of rolling elements, in this case anticlockwise
  - Rotation of the rolling element about its own axis, in this case clockwise
- Important: The rotational frequency measured within the rolling element is the superposition / sum of these two individual rotational movements with opposite signs
- Example:
  - Shaft speed (fn): + 250 rpm
  - Cage speed (fK): + 102 rpm
  - Roller speed (fWa) - 605 rpm
  - Roller speed (measured) - 553 rpm (= 102 rpm - 605 rpm)

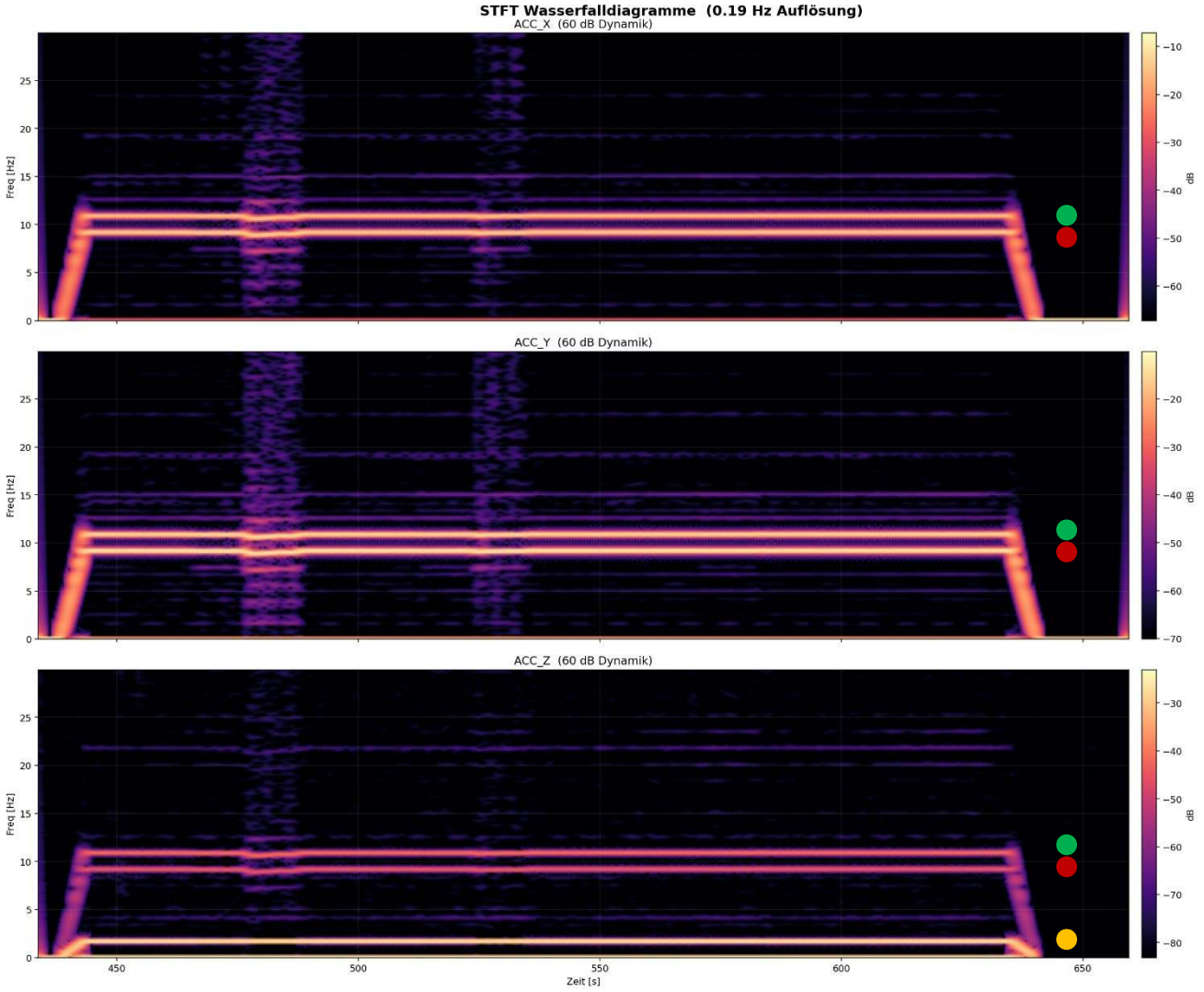
$$f_K = \frac{1}{2} f_n \left(1 - \frac{D_W}{D_T} \cos \alpha_B\right) \qquad f_{WA} = \frac{1}{2} f_n \frac{D_T}{D_W} \left[1 - \left(\frac{D_W}{D_T} \cos \alpha_B\right)^2\right]$$



Data & Analysis Methods

- Rotation Frequencies and Slippage in the IMU Acceleration Signals
- 250 Shaft rpm meaning following kinematic frequencies:
  - Shaft: 4.167 Hz
  - Cage: 1.706 Hz
  - Roller (w/o cage): 10.926 Hz
  - Roller (with cage): 9.220 Hz



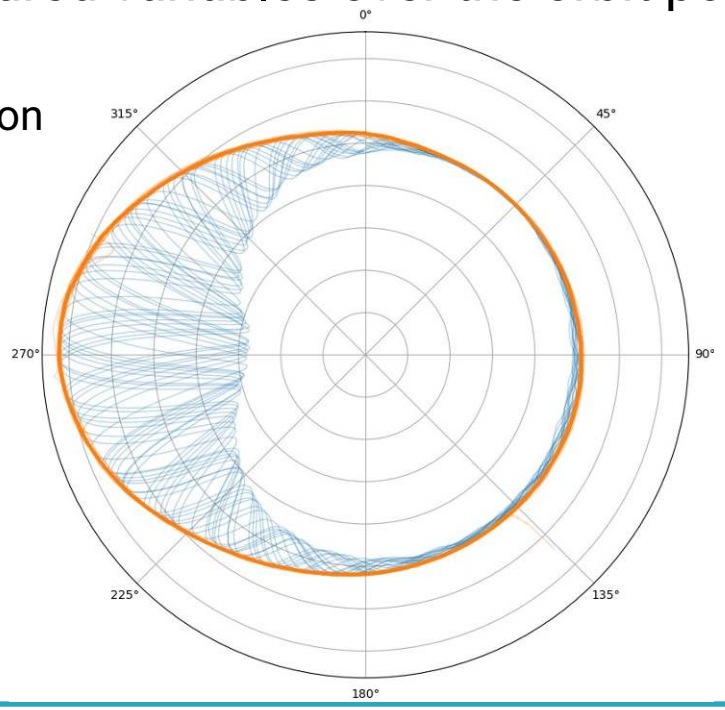


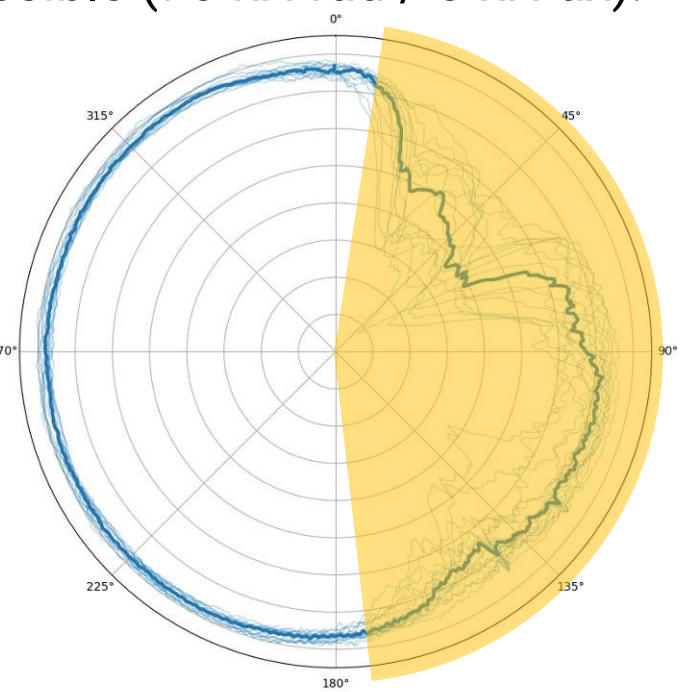
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Data & Analysis Methods

- Rotational speed of the rolling element from Z-Gyrometer (optionally zero crossings of the rolling element X/Y accelerations), rotational speed of the shaft (for kinematic reference) from test bench data
- Rolling element orbit position (= cage rotation angle and not shaft rotation angle!) from the progression of the rolling element Z acceleration
- Plots of all measured variables over the orbit possible (90 kN rad / 0 kN ax):

Roller Load Distribution (SG Channel 2)



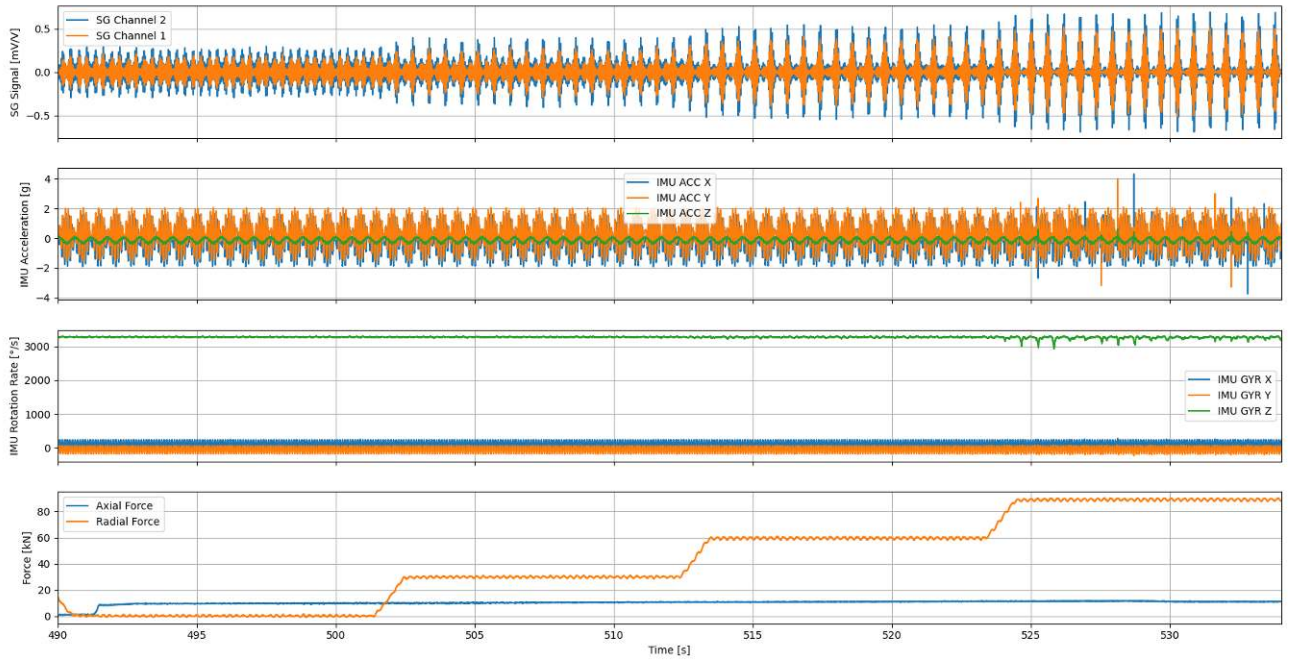


Roller Slippage

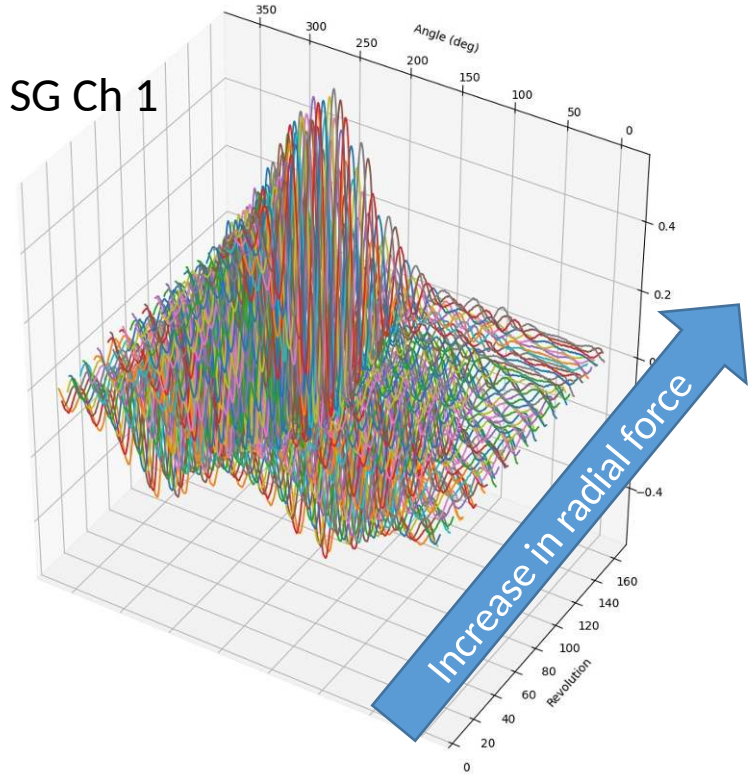
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Data & Analysis Methods

- Measurement data can be broken down into individual revolutions and temporal developments can be displayed from revolution to revolution
- Boundary condition: Increasing radial force 0 to 90 kN with constant axial force of 10 kN



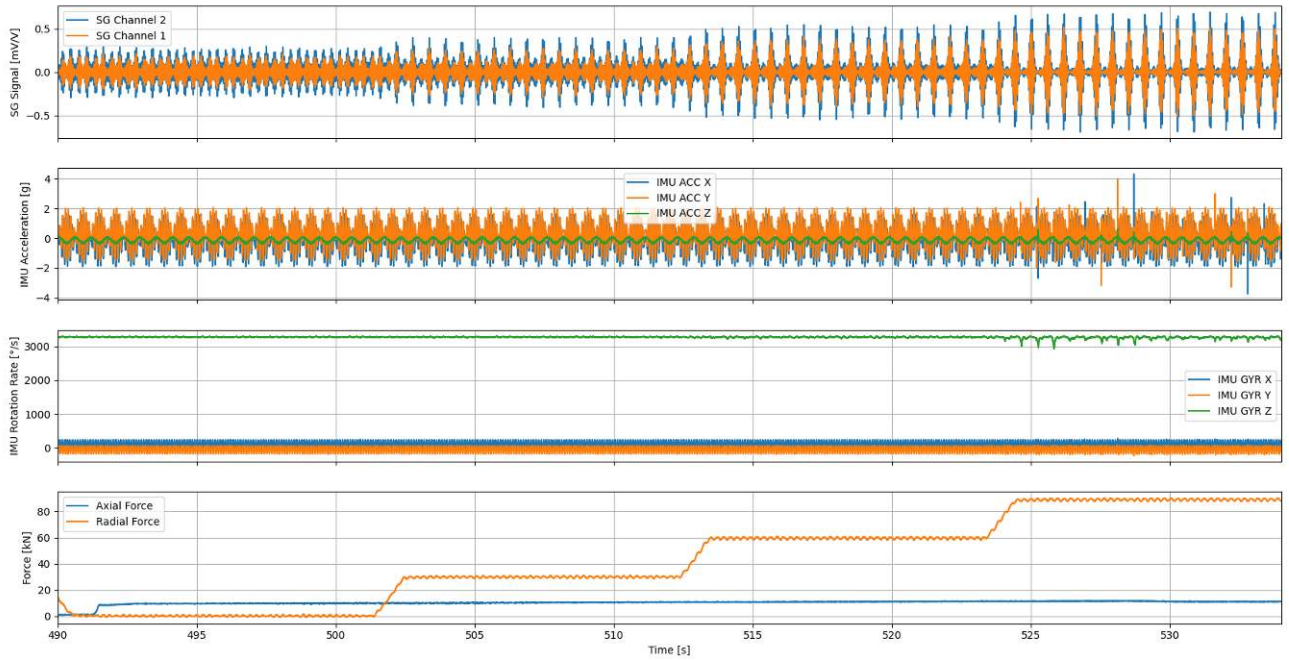
Increase in radial force



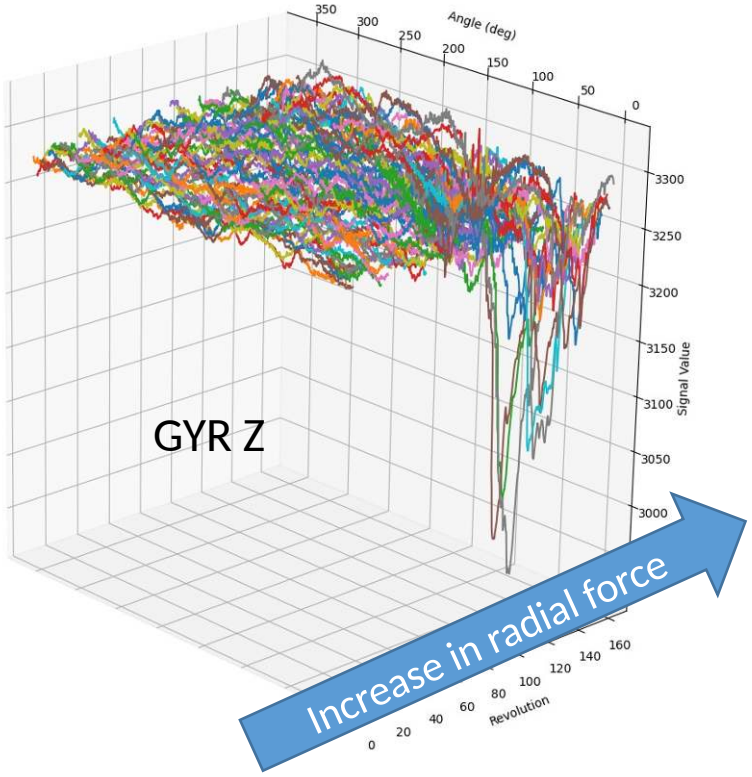
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Increase in radial force



Increase in radial force

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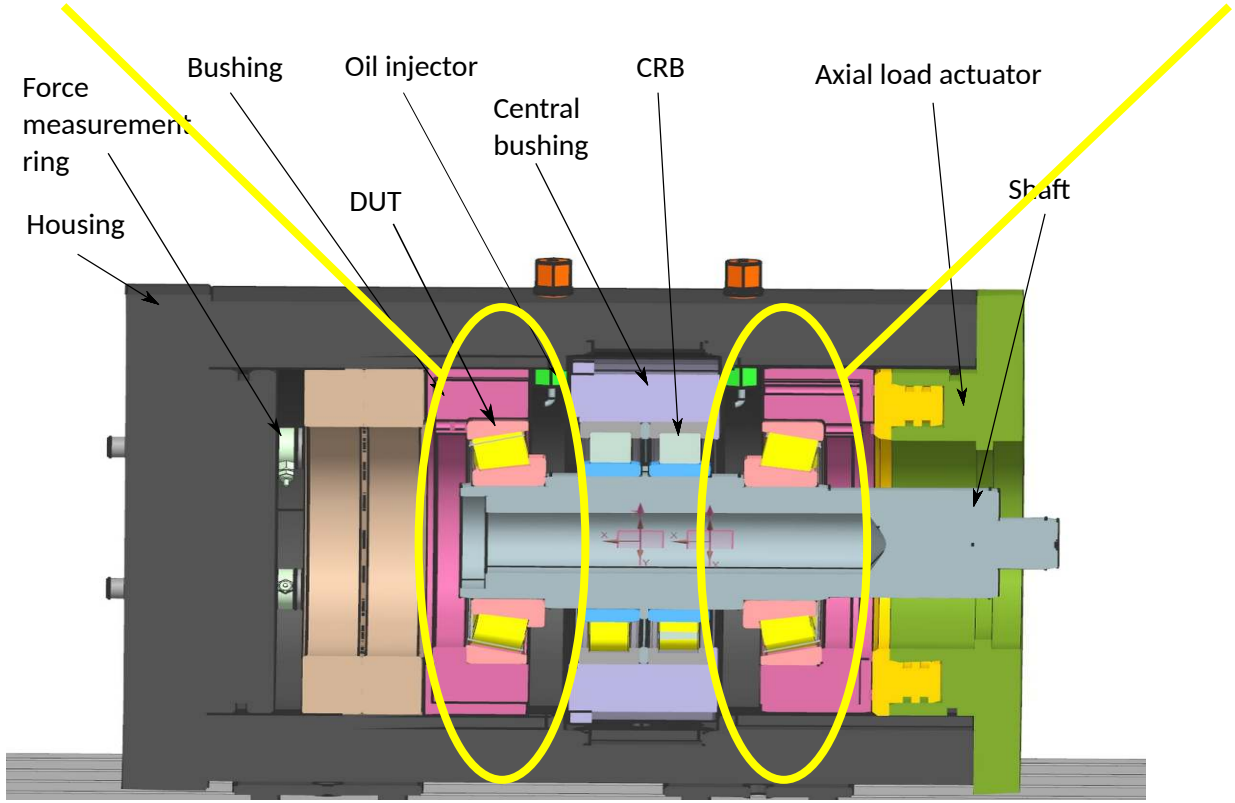
Measurement Results

“Bearing Sensor Lid“

- Further away from the point of axial force application
- Friction within the system reduces the axial force
- The effect of the axial force is reduced, so greater slippage is expected here

“Bearing Actuator“

- Directly at the point of axial force application
- Friction plays only a minor role here
- The influence of the axial force is greater, so less slippage is expected here



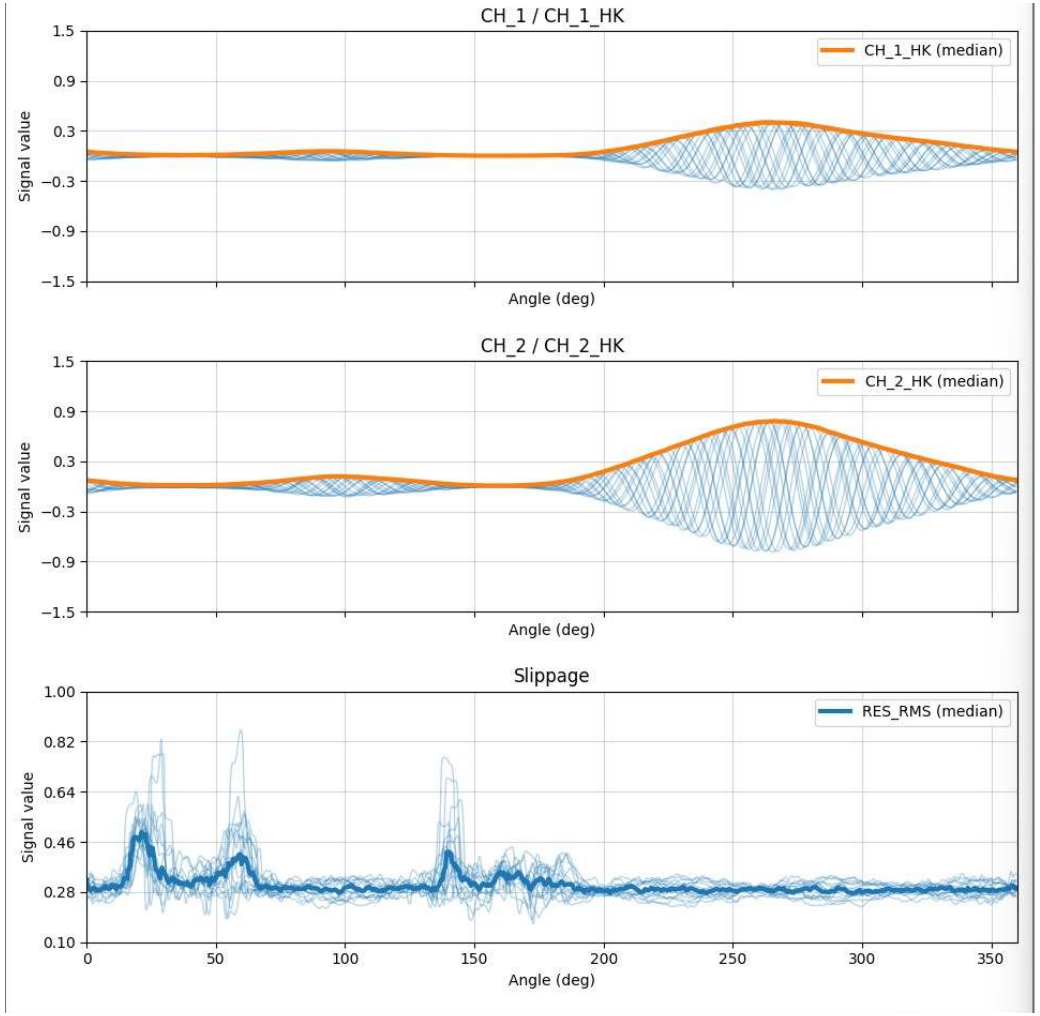
SG Channels: 1 2 2 1

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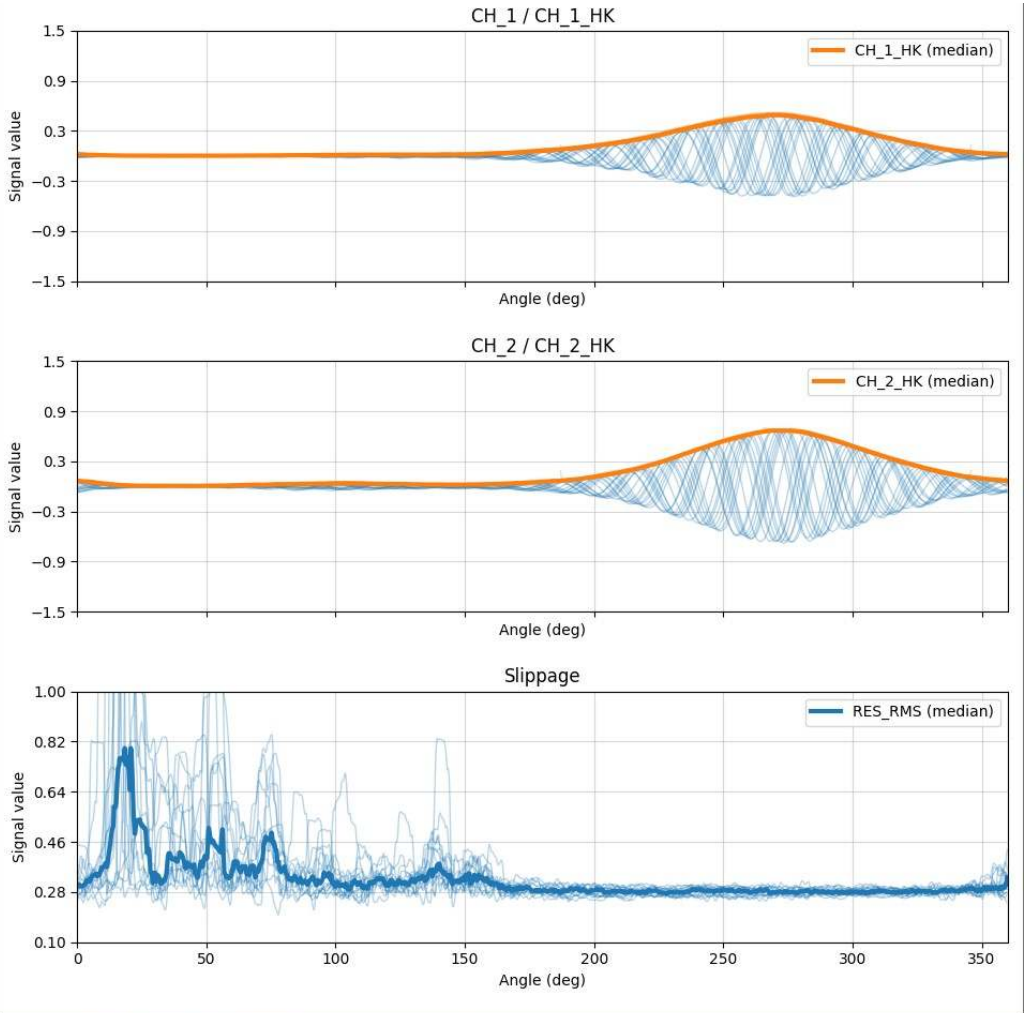
Measurement Results – load and slippage distributions

90 kN radial, 0 kN axial load

“Bearing Sensor Lid“



“Bearing Actuator“

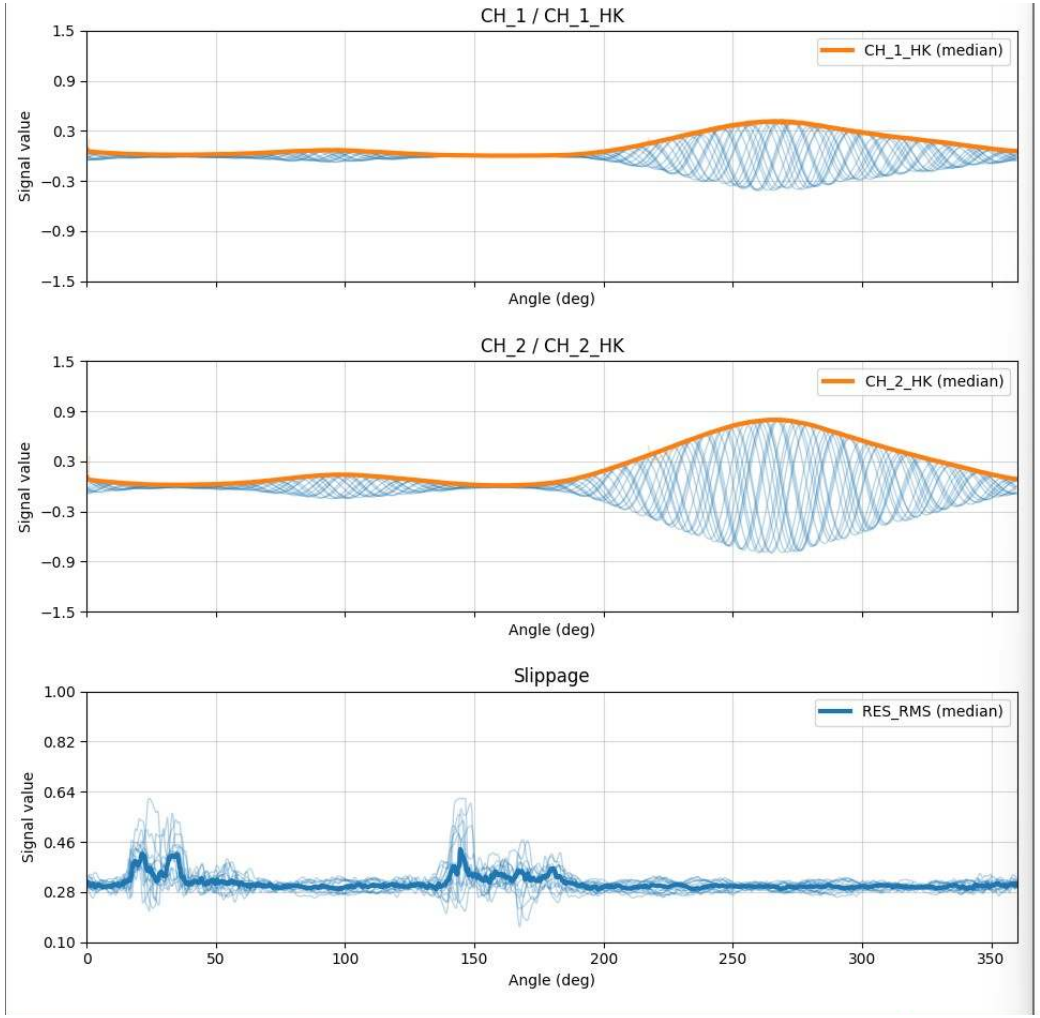


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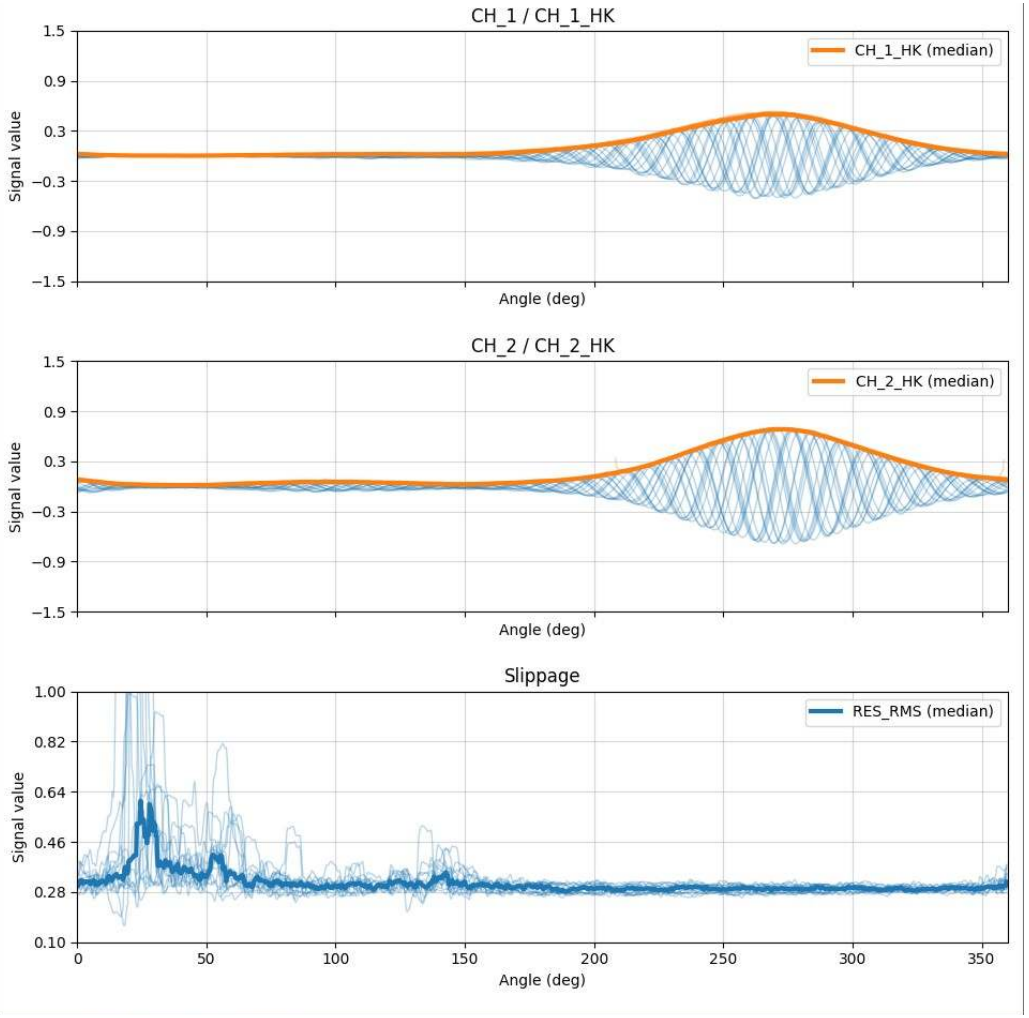
Measurement Results – load and slippage distributions

90 kN radial, 10 kN axial load

“Bearing Sensor Lid“



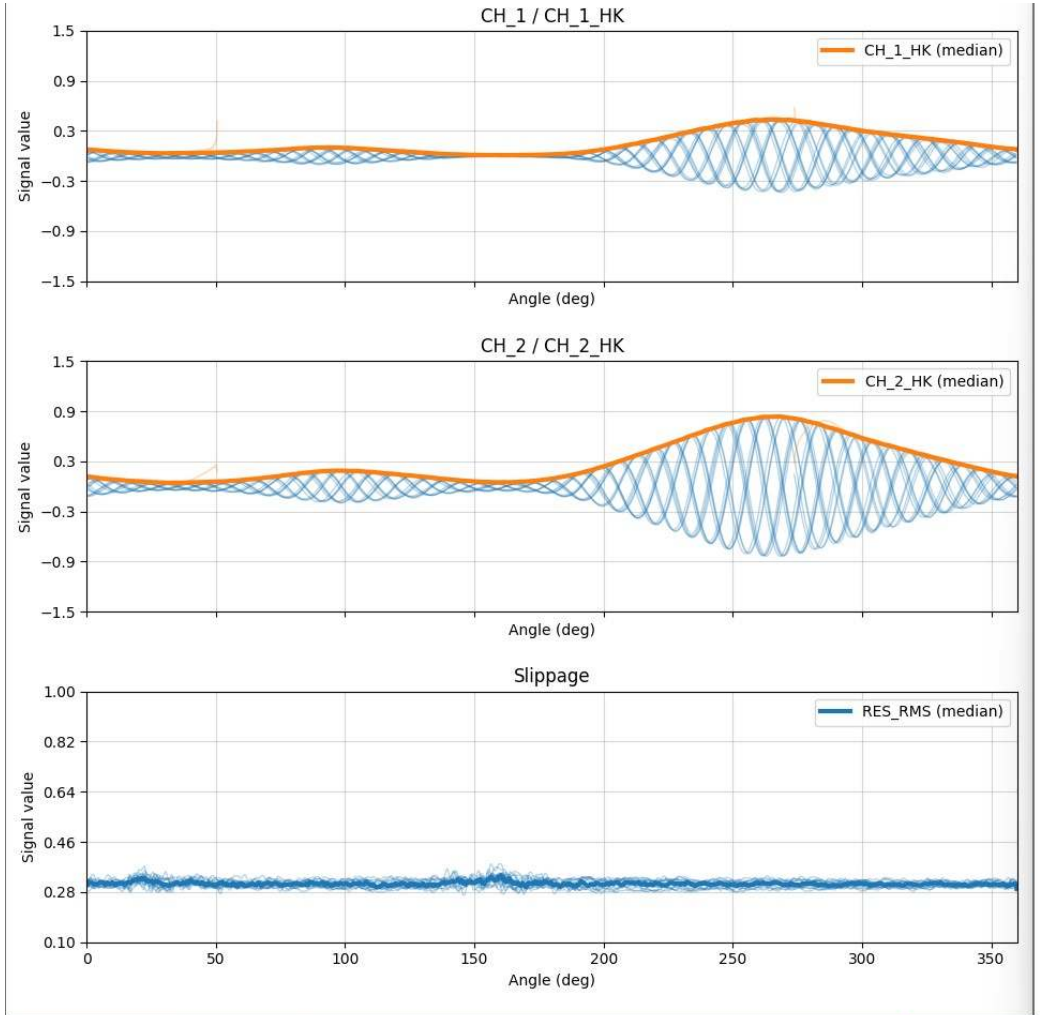
“Bearing Actuator“



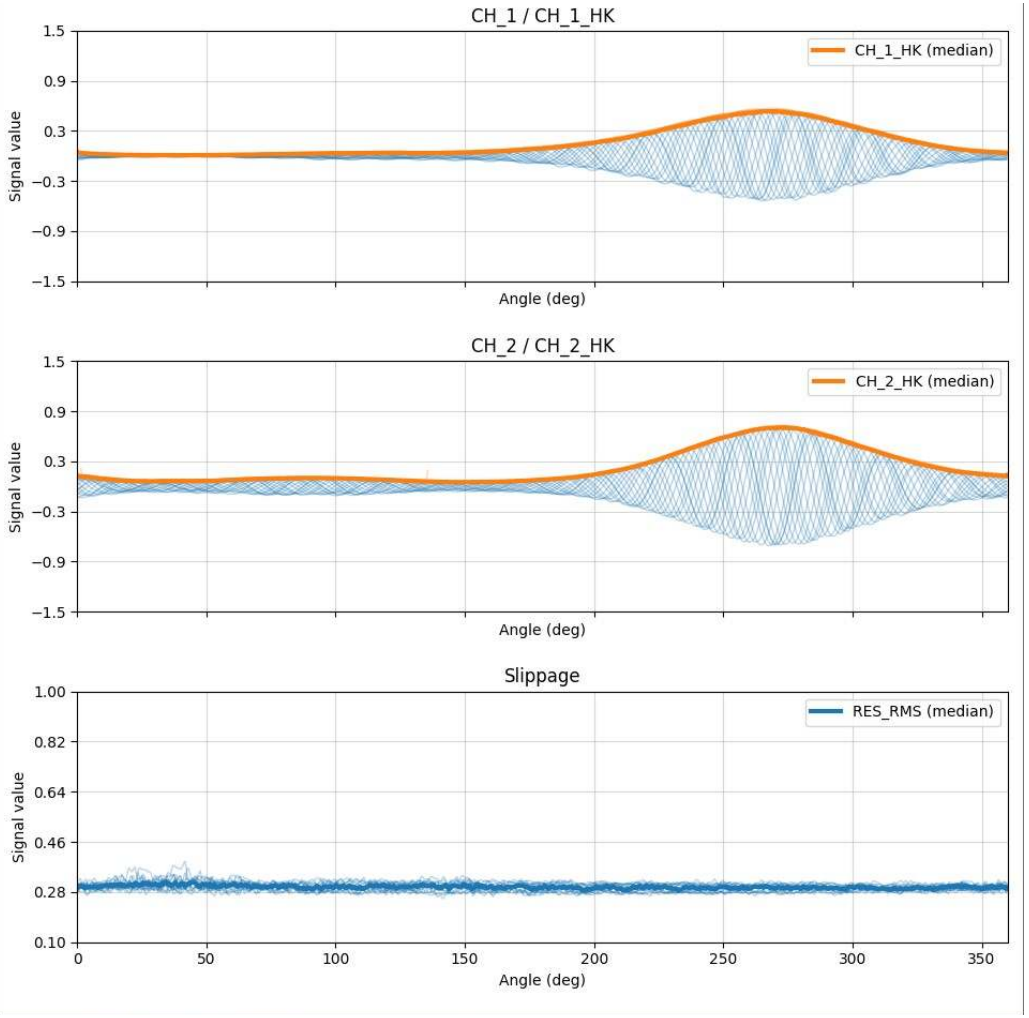
Measurement Results – load and slippage distributions

90 kN radial, 20 kN axial load

“Bearing Sensor Lid“



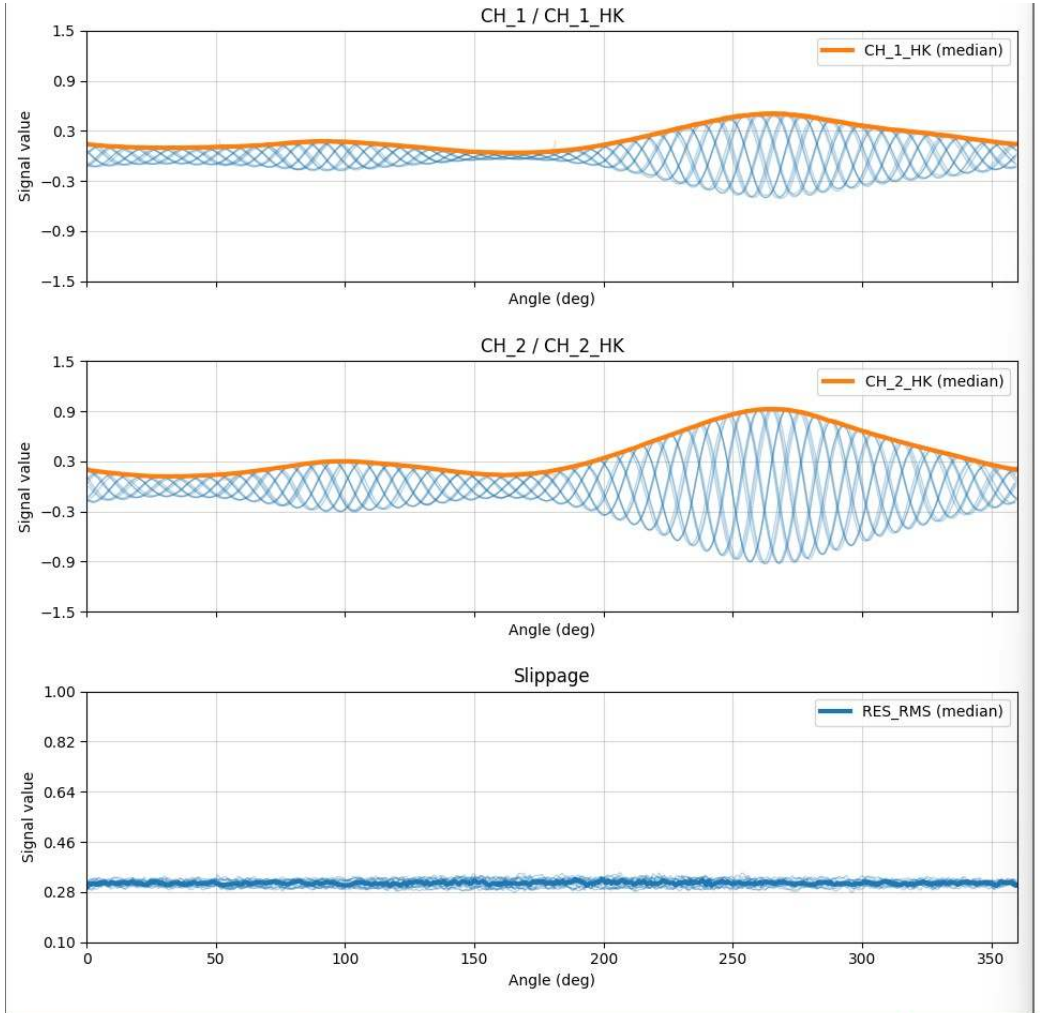
“Bearing Actuator“



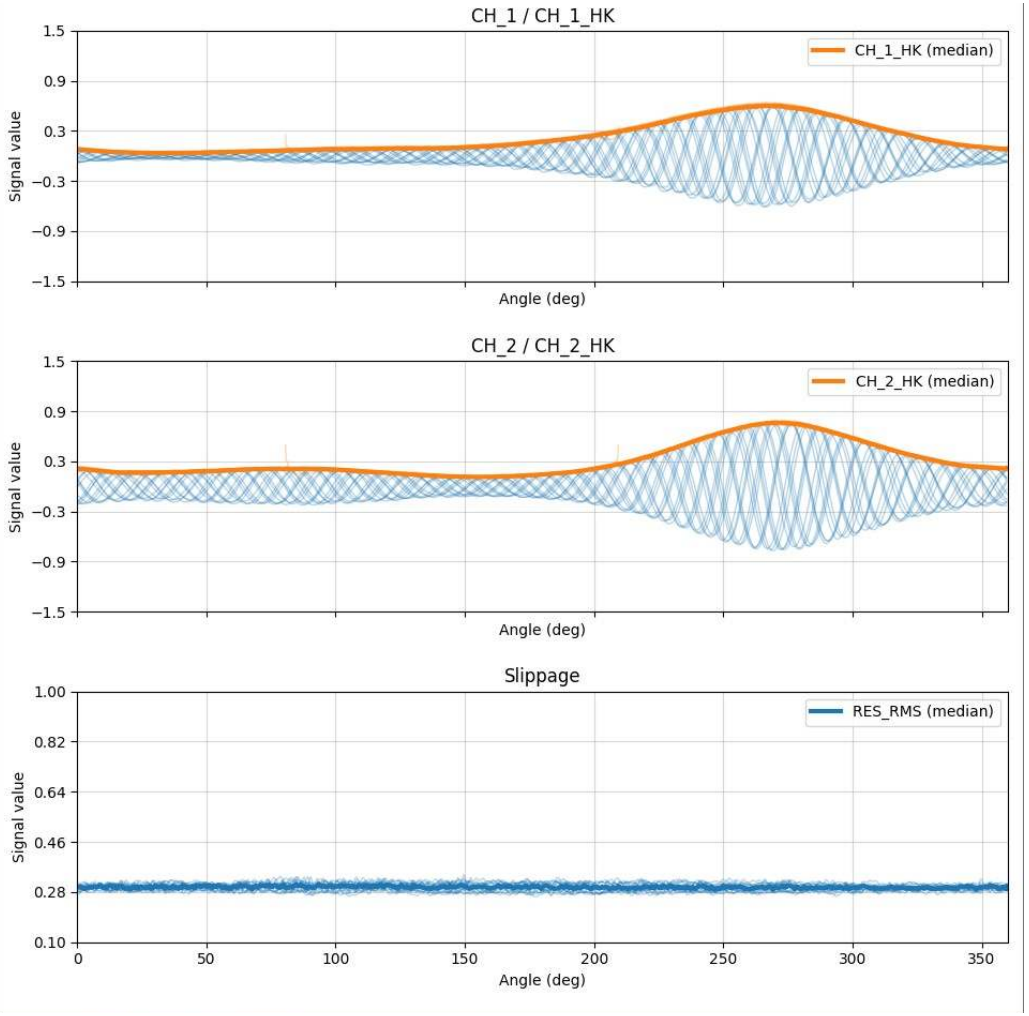
Measurement Results – load and slippage distributions

90 kN radial, 30 kN axial load

“Bearing Sensor Lid“



“Bearing Actuator“



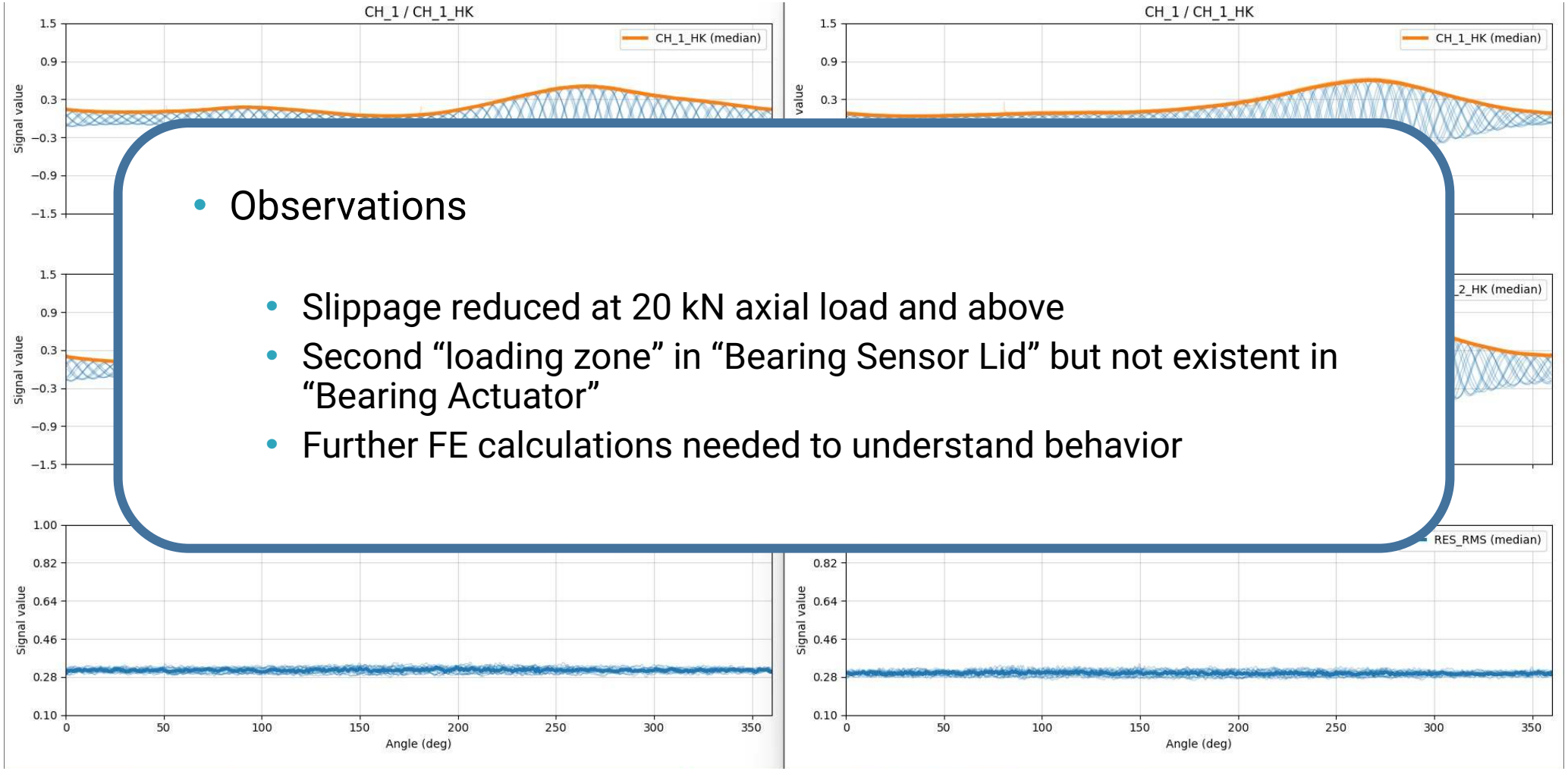
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Measurement Results

90 kN radial, 30 kN axial load

“Bearing Sensor Lid“

“Bearing Actuator“



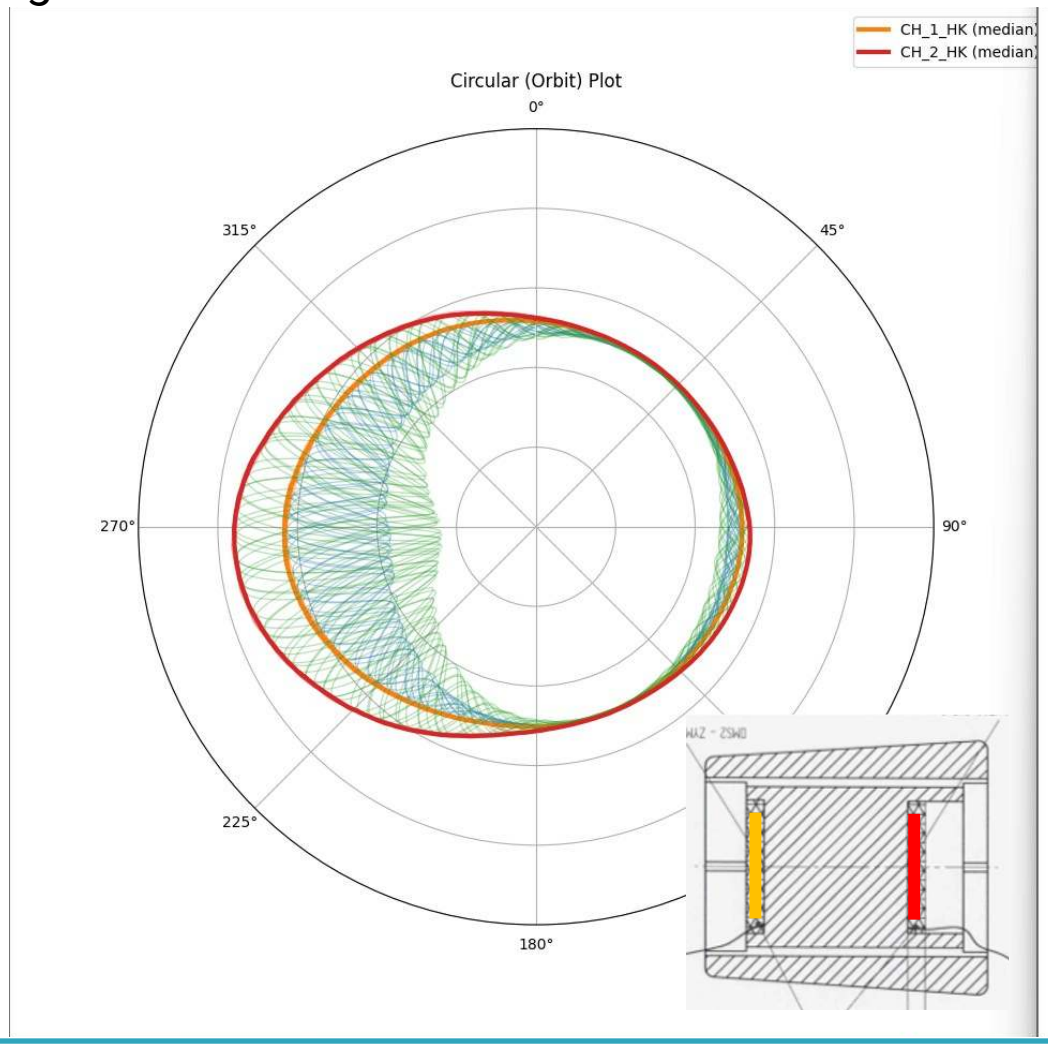
- Observations
  - Slippage reduced at 20 kN axial load and above
  - Second “loading zone” in “Bearing Sensor Lid” but not existent in “Bearing Actuator”
  - Further FE calculations needed to understand behavior

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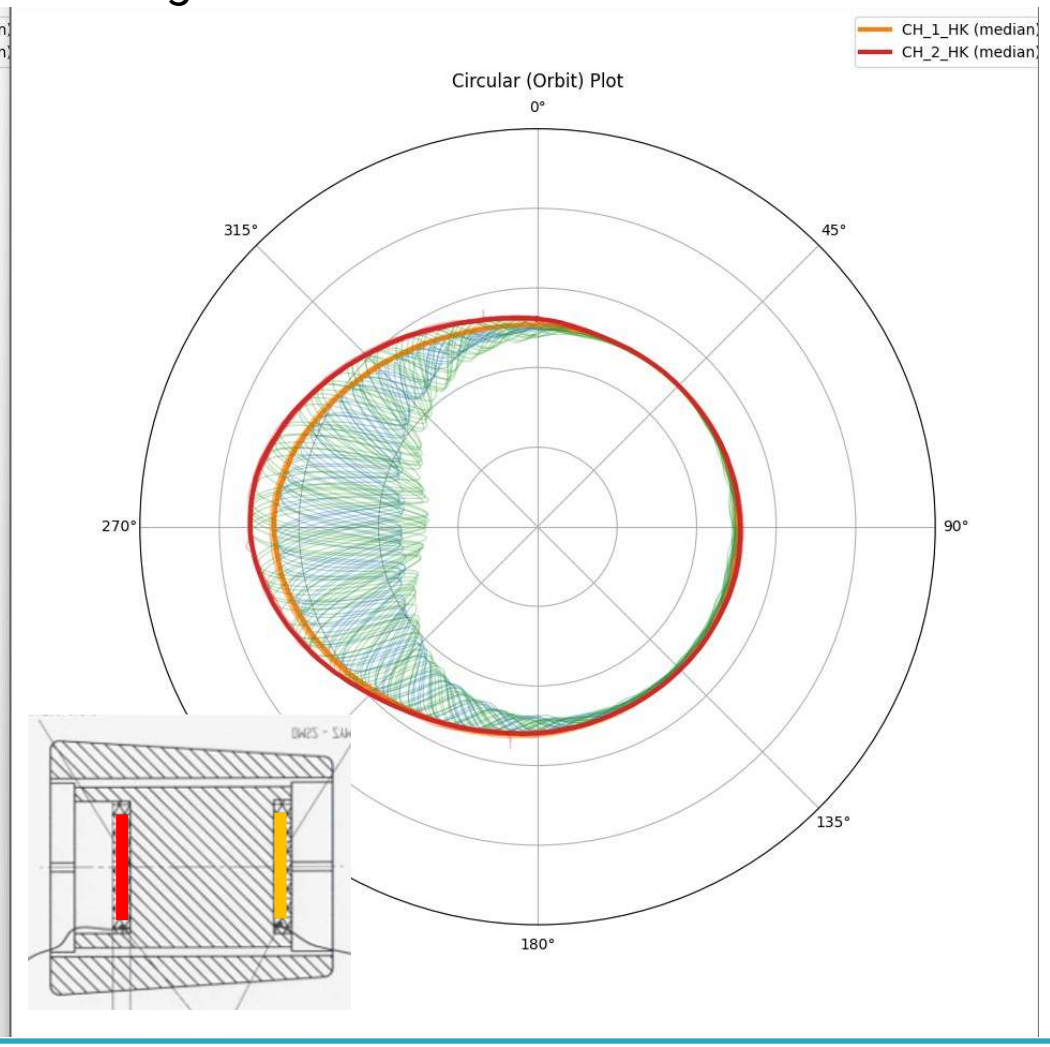
Measurement Results – load distribution orbit

90 kN radial, 0 kN axial load

“Bearing Sensor Lid“



“Bearing Actuator“

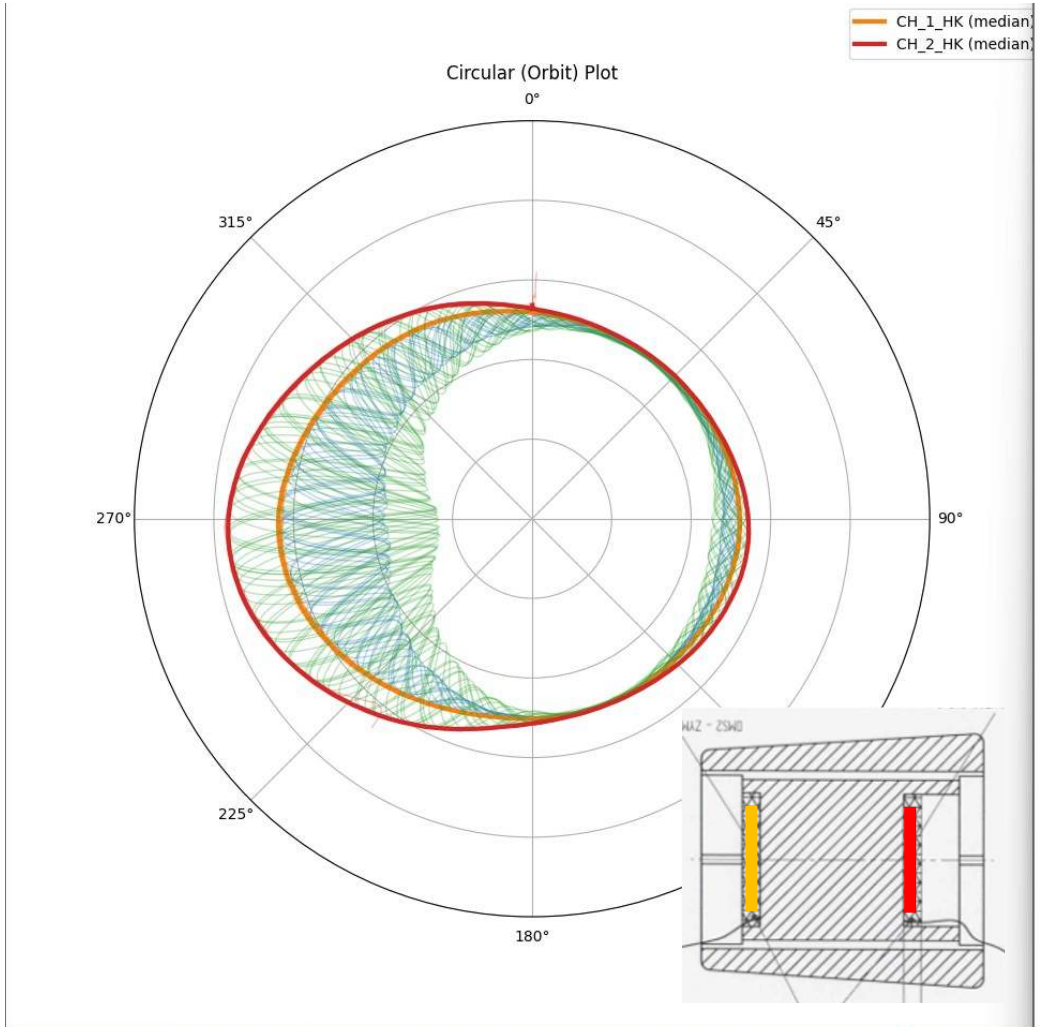


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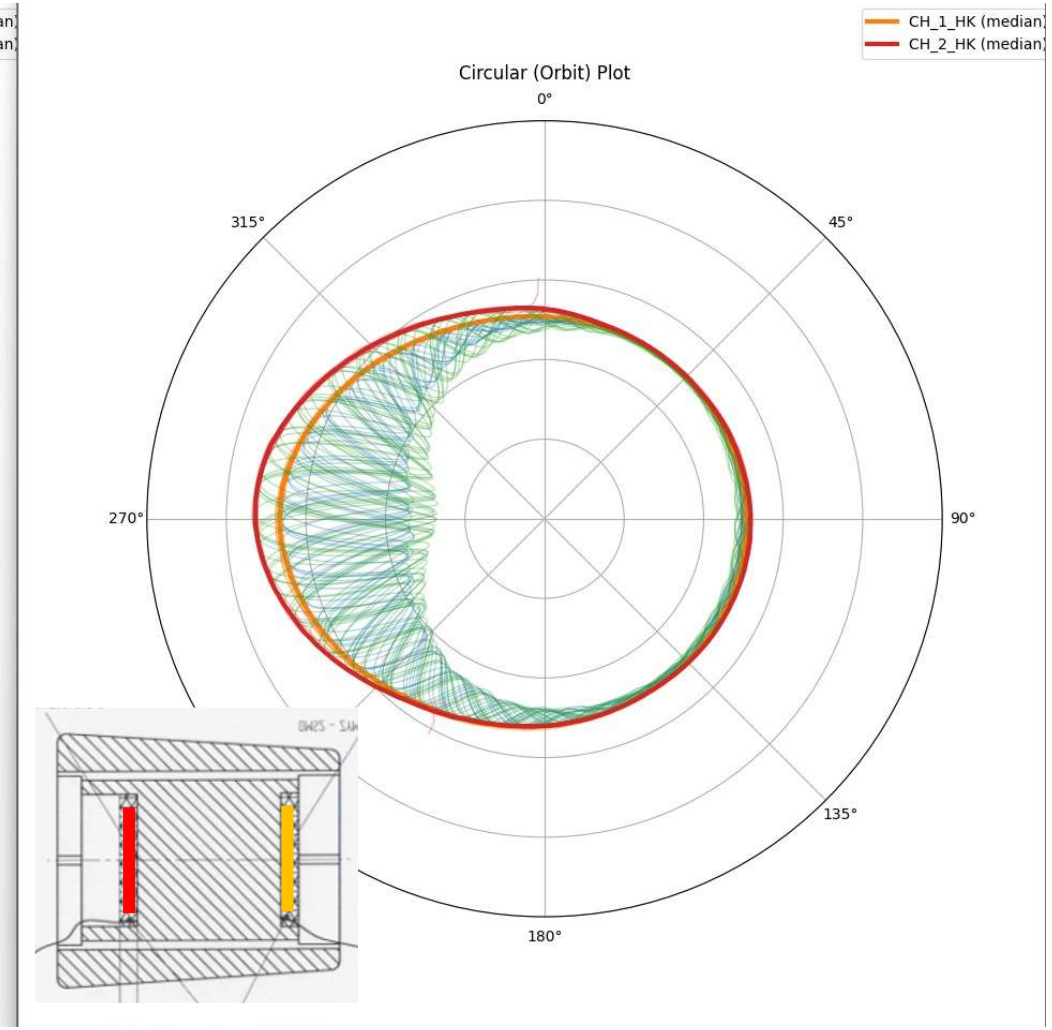
Measurement Results – load distribution orbit

90 kN radial, 10 kN axial load

“Bearing Sensor Lid“



“Bearing Actuator“

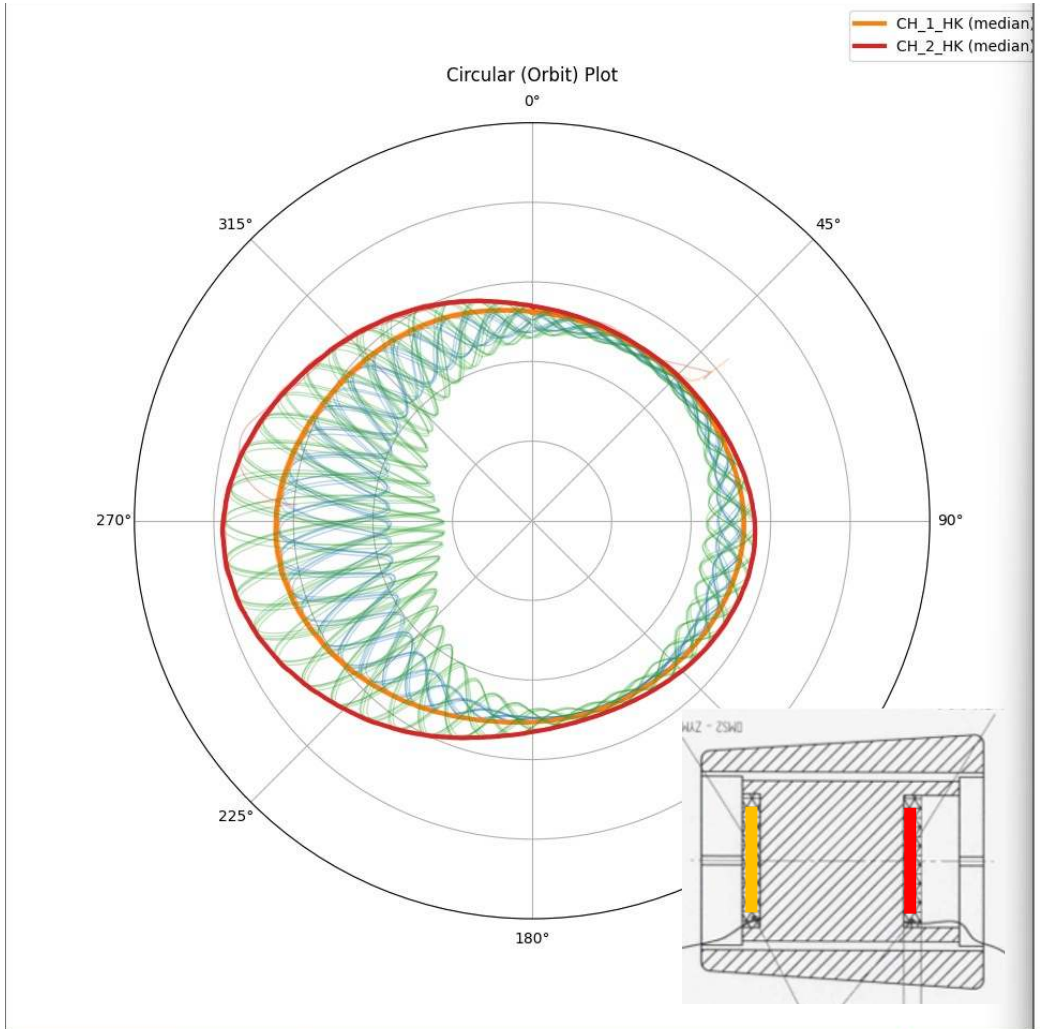


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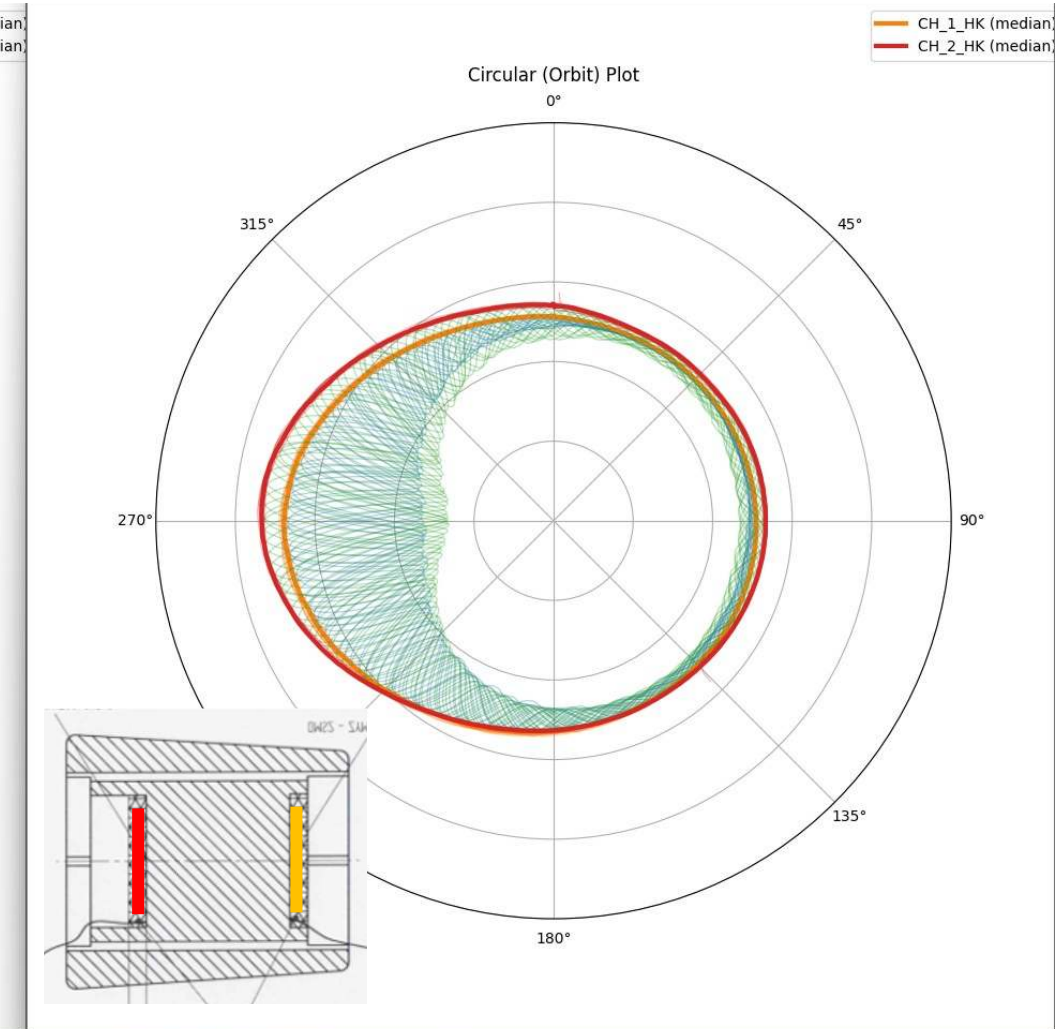
Measurement Results – load distribution orbit

90 kN radial, 20 kN axial load

“Bearing Sensor Lid“



“Bearing Actuator“

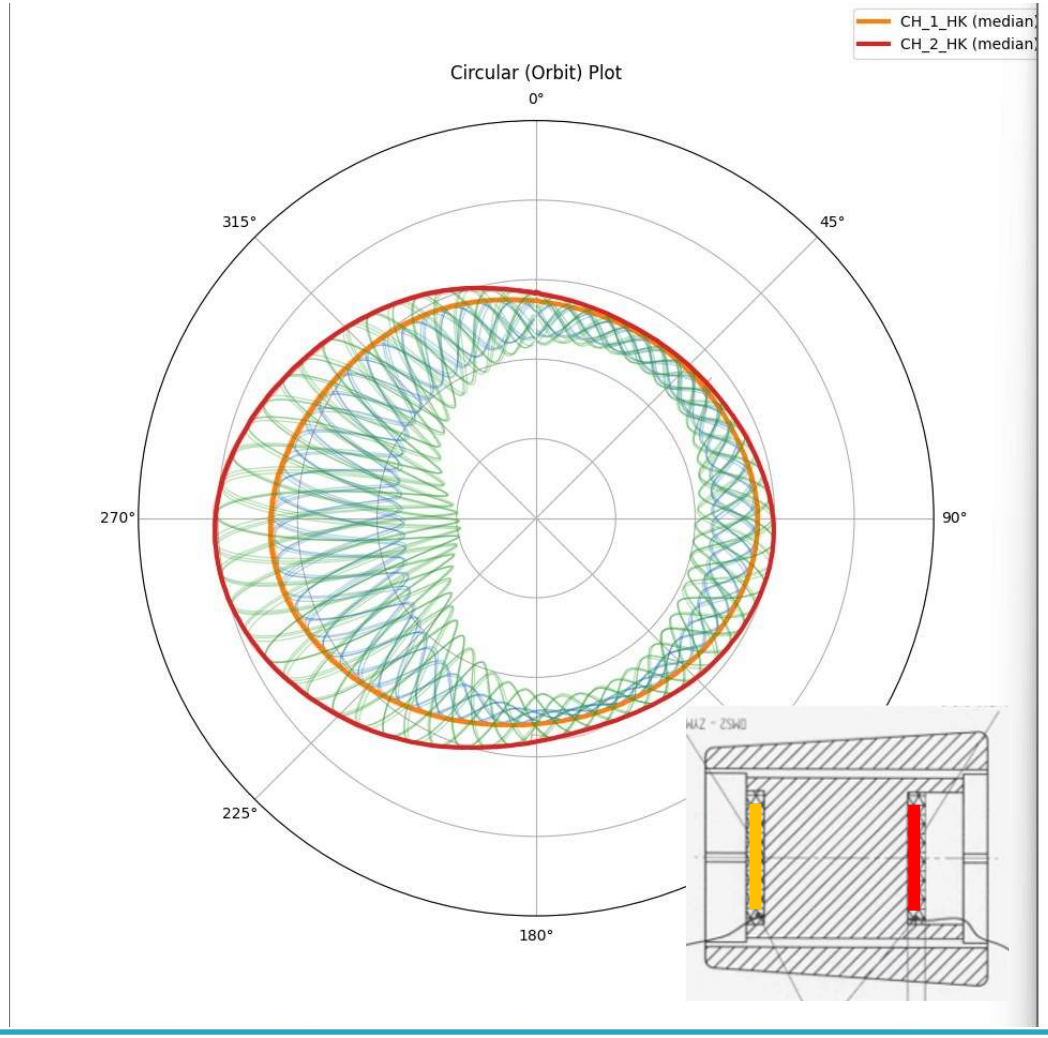


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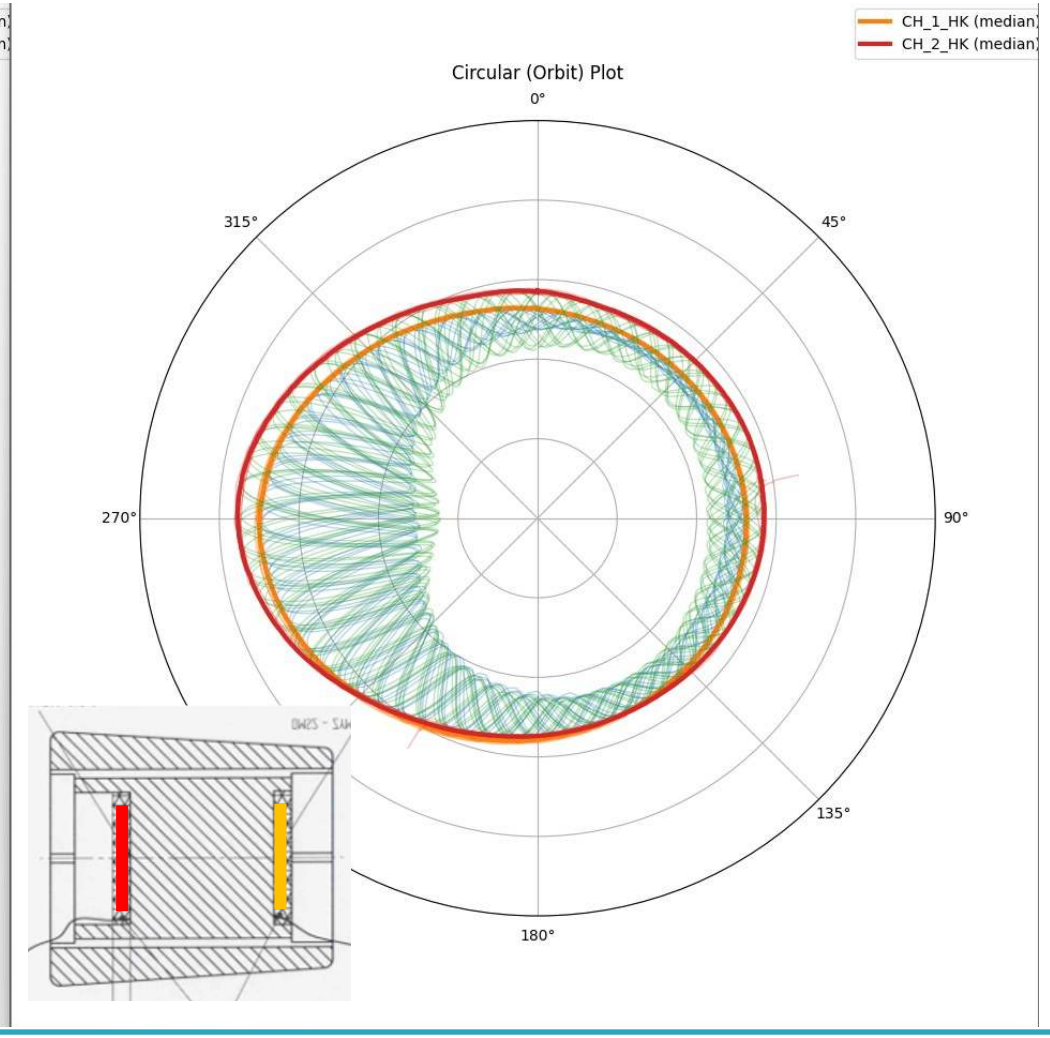
Measurement Results – load distribution orbit

90 kN radial, 30 kN axial load

“Bearing Sensor Lid“



“Bearing Actuator“



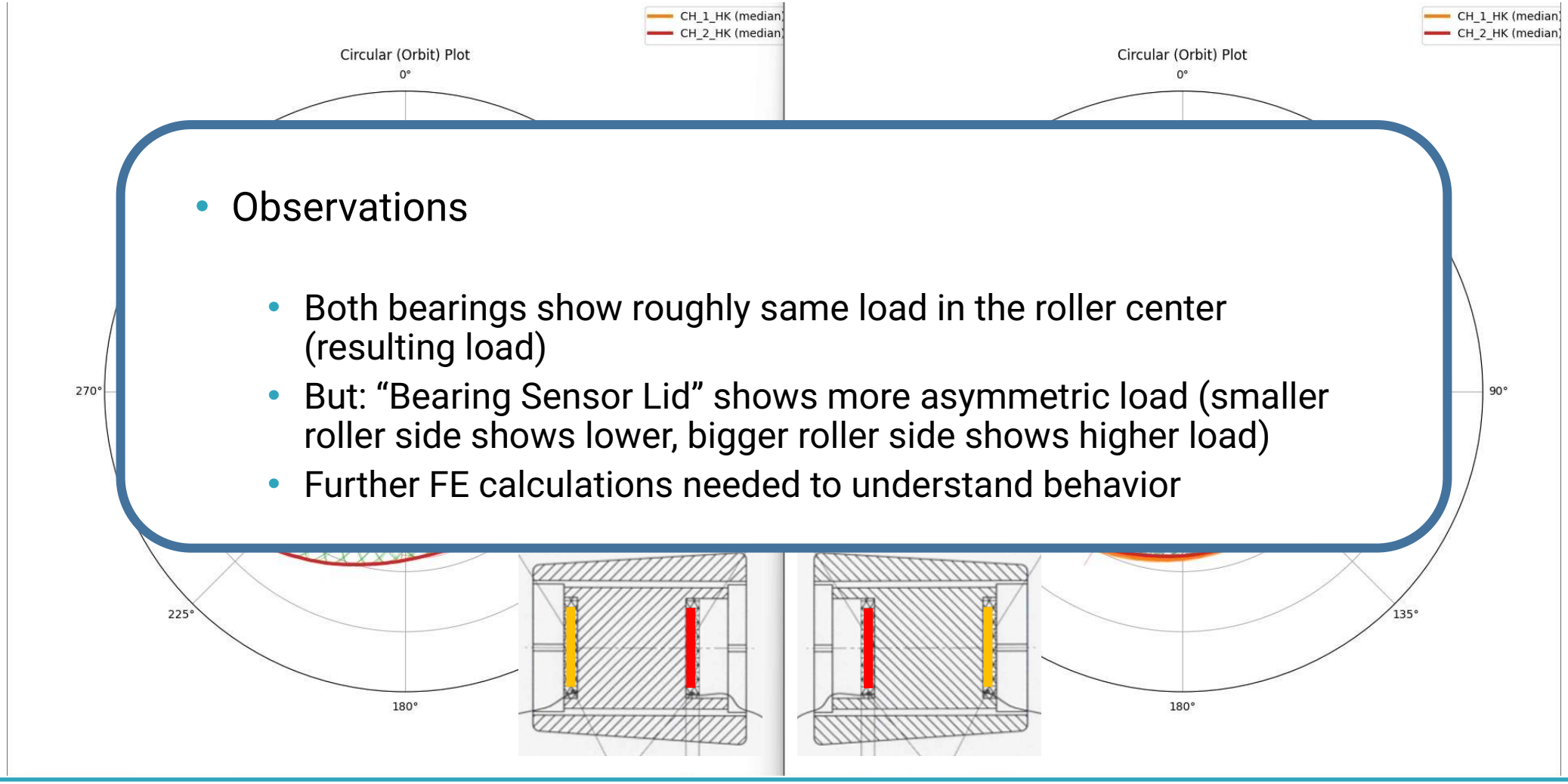
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Measurement Results – load distribution orbit

90 kN radial, 30 kN axial load

“Bearing Sensor Lid“

“Bearing Actuator“



- Observations
  - Both bearings show roughly same load in the roller center (resulting load)
  - But: “Bearing Sensor Lid” shows more asymmetric load (smaller roller side shows lower, bigger roller side shows higher load)
  - Further FE calculations needed to understand behavior

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Outline

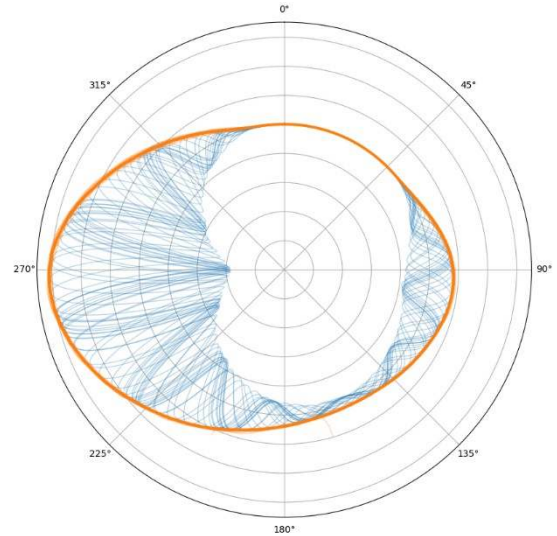
1 Introduction, overview, and motivation
2 Test bench setup and bearings
3 Rolling element-integrated measurement technology
4 Data and analysis methods
5 Results
6 Summary and outlook

Summary & Outlook

- Integration of i4M's “Smart Roller” technology possible in smaller, faster-rotating bearings
- Compact, robust, reliable solution independent of bearing manufacturer with high data rates and low energy consumption
- High-quality kinematic and load data from the rolling element
- Weakening of small rolling elements must be taken into account, usually no problem for bigger bearings



- Here: Concentrated on quasi-static operating conditions
- As expected, the introduction of axial bearing force reduces slippage
- Validation: Measured load distributions in both bearings differ significantly from theory and current state of simulation, conclusions for further improvement of the test rig can be derived



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Contact

Thank you very much for your attention!



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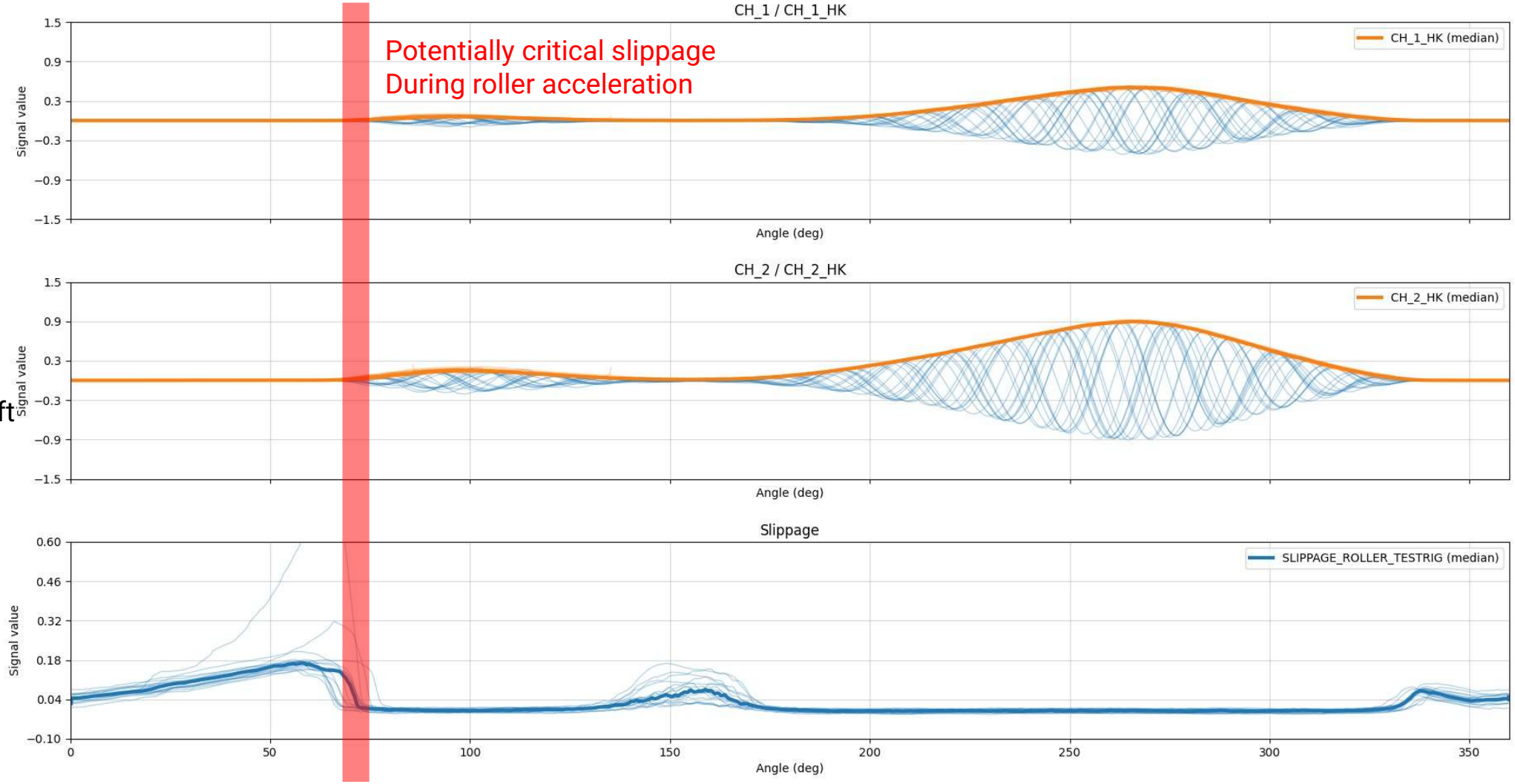
Tel.: +49 (0) 471 14290-522

www.iwes.fraunhofer.de

Backup

Results and evaluation – Influence of axial load under quasi-static conditions

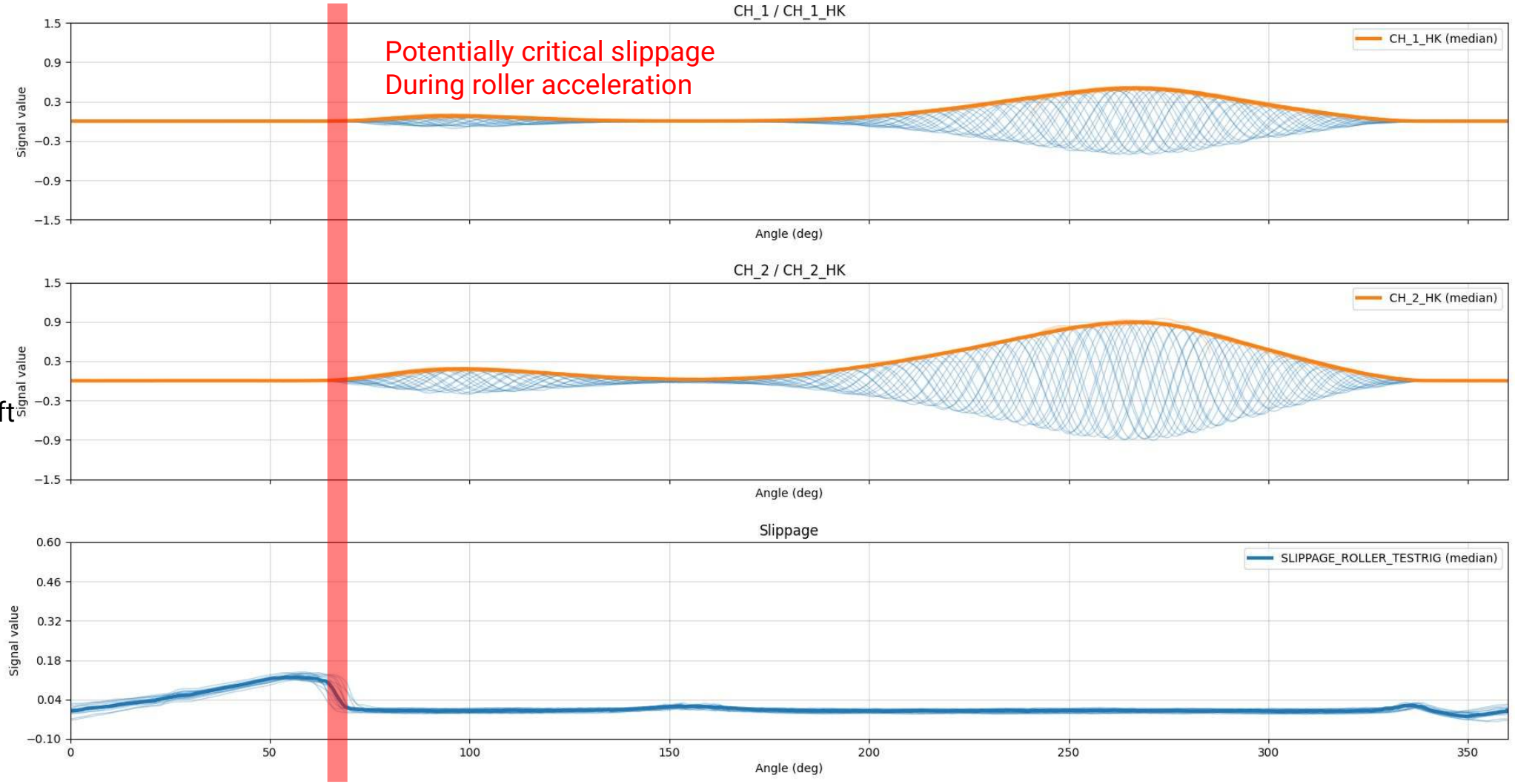
Radial: 90 kN
Axial: 0 kN
250 rpm Shaft



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Results and evaluation – Influence of axial load under quasi-static conditions

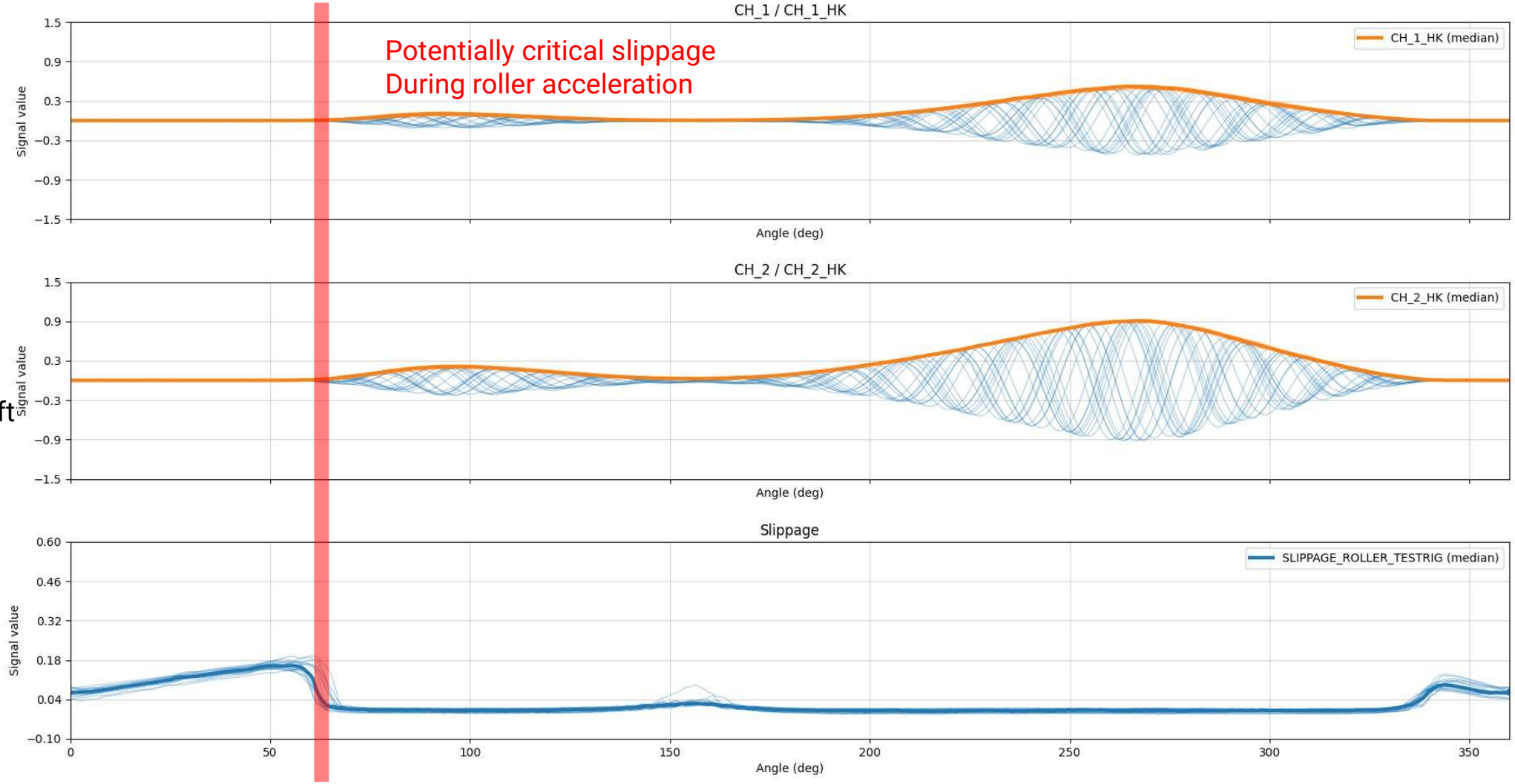
Radial: 90 kN
Axial: 10 kN
250 rpm Shaft



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Results and evaluation – Influence of axial load under quasi-static conditions

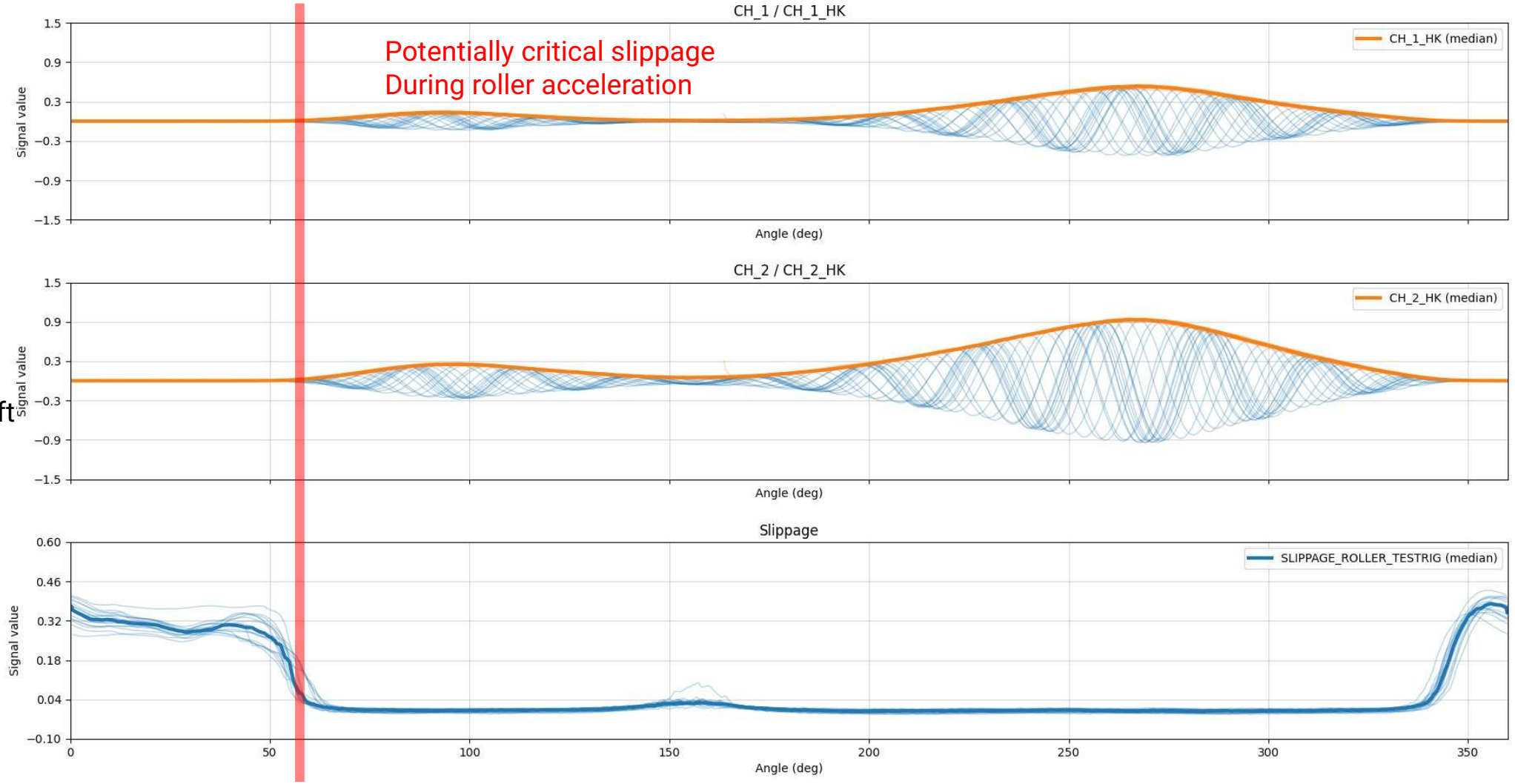
Radial: 90 kN
Axial: 20 kN
250 rpm Shaft



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Results and evaluation – Influence of axial load under quasi-static conditions

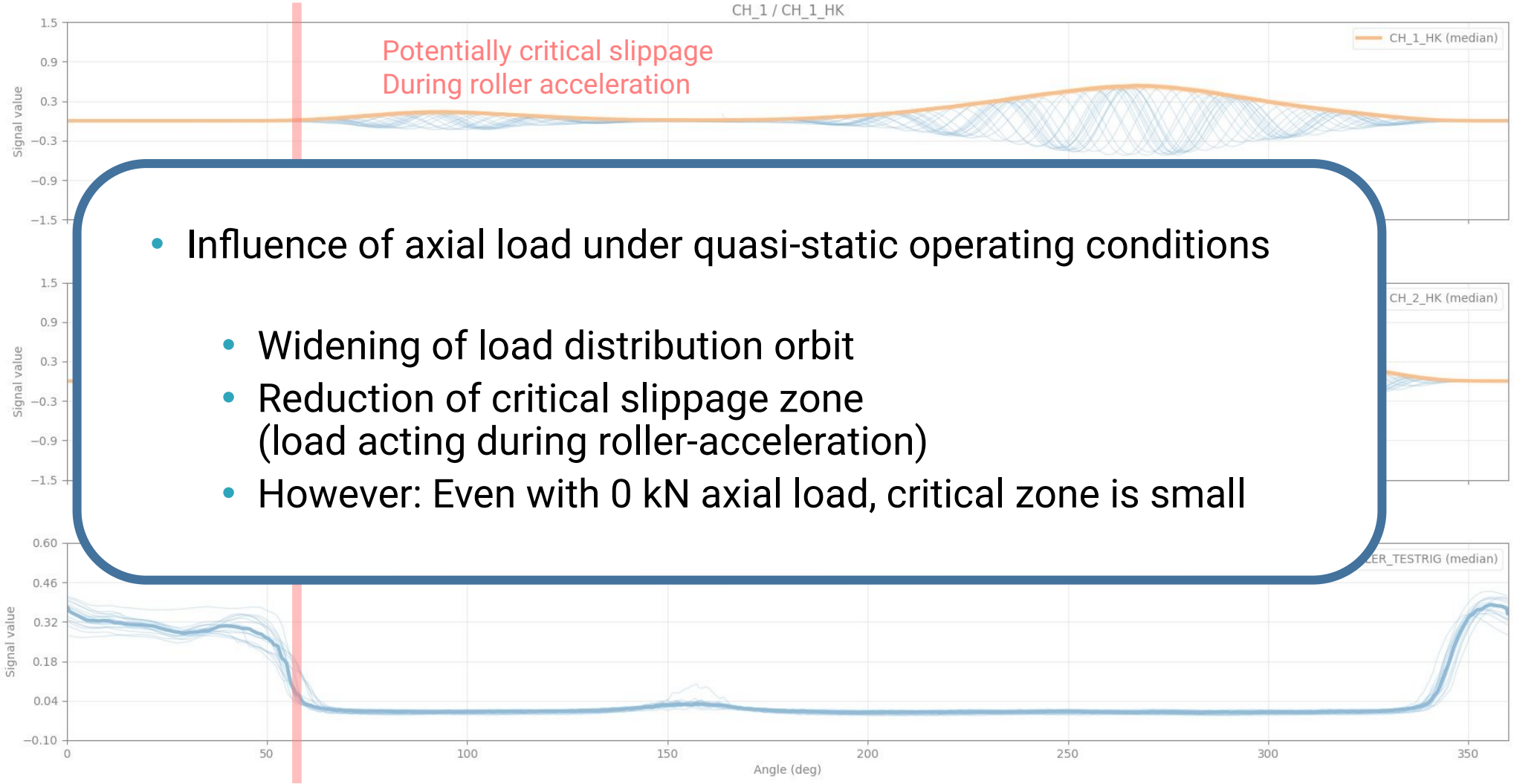
Radial: 90 kN
Axial: 30 kN
250 rpm Shaft



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Results and evaluation – Influence of axial load under quasi-static conditions

Radial: 90 kN
Axial: 30 kN



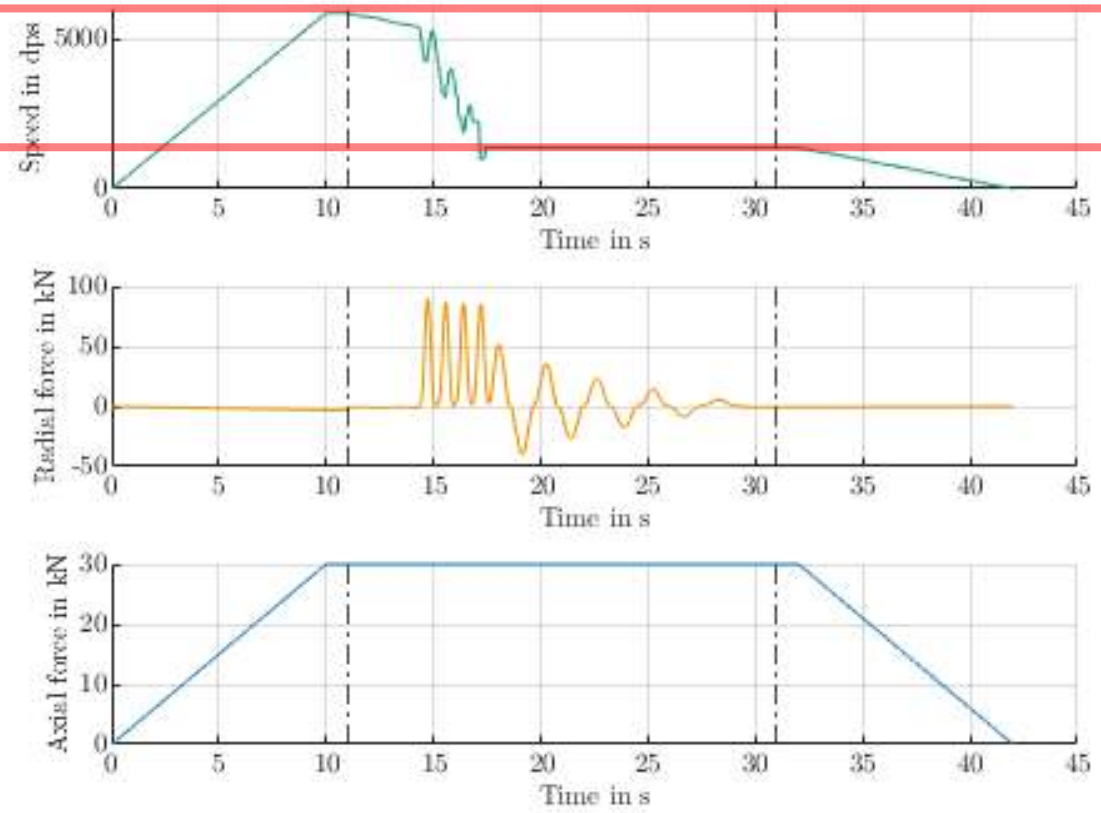
- Influence of axial load under quasi-static operating conditions
  - Widening of load distribution orbit
  - Reduction of critical slippage zone (load acting during roller-acceleration)
  - However: Even with 0 kN axial load, critical zone is small

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Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event

Start Shaft Rotation-Rate: 5800 °/s = 967 rpm
Start Roller Rotation-Rate: **15200 °/s** = 2532 rpm



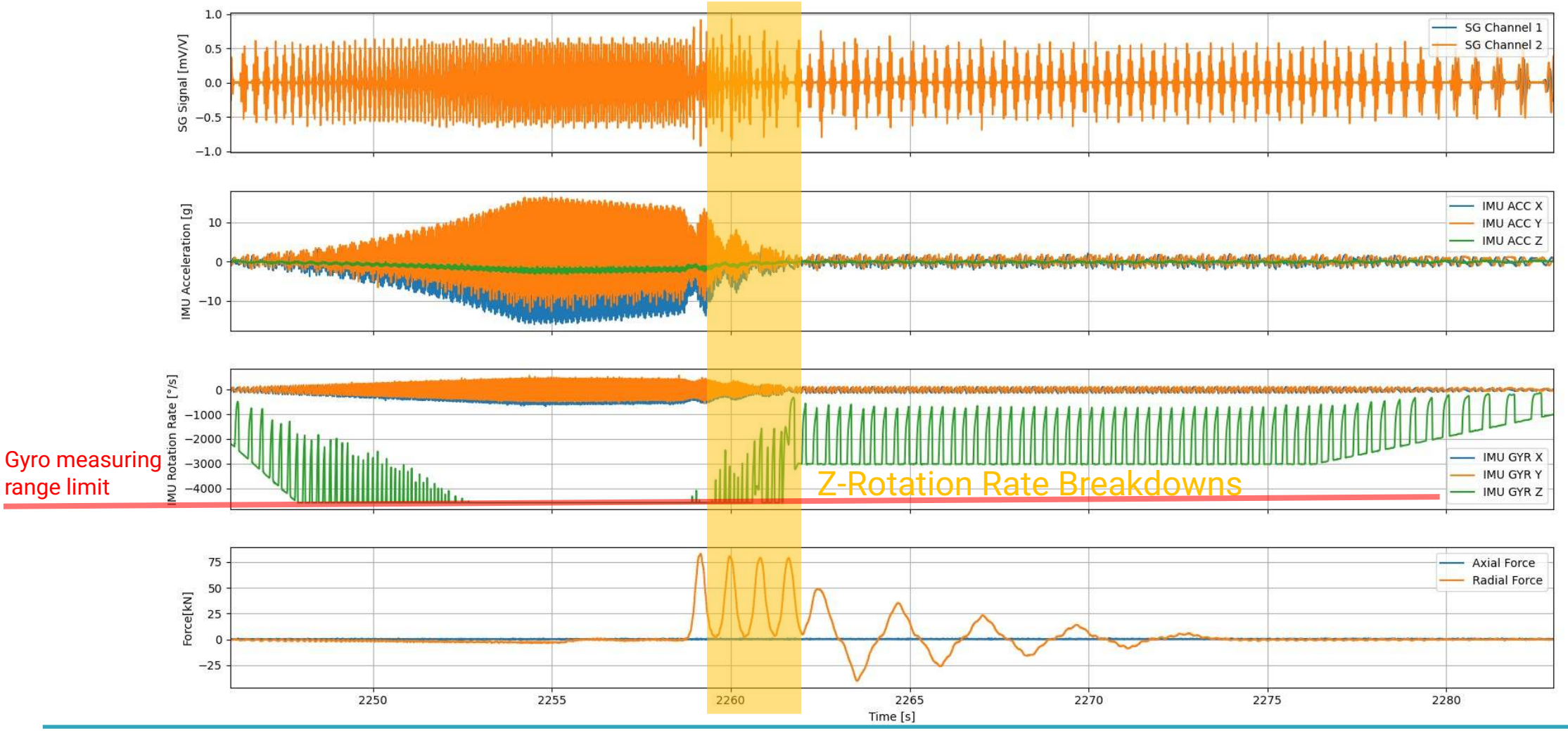
End Shaft Rotation-Rate: 1305 °/s = 218 rpm
End Roller Rotation-Rate: **3420 °/s** = 570 rpm

Z-Gyro Range of the used roller is max. ca. ± 4500 °/s
Current Smart Rollers can measure higher rotation rates
X/Y Accelerations can be used as an alternative to calculate Roller RPM up to higher speeds but with reduced time-resolution

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Results and evaluation – Analyzing dynamic Events

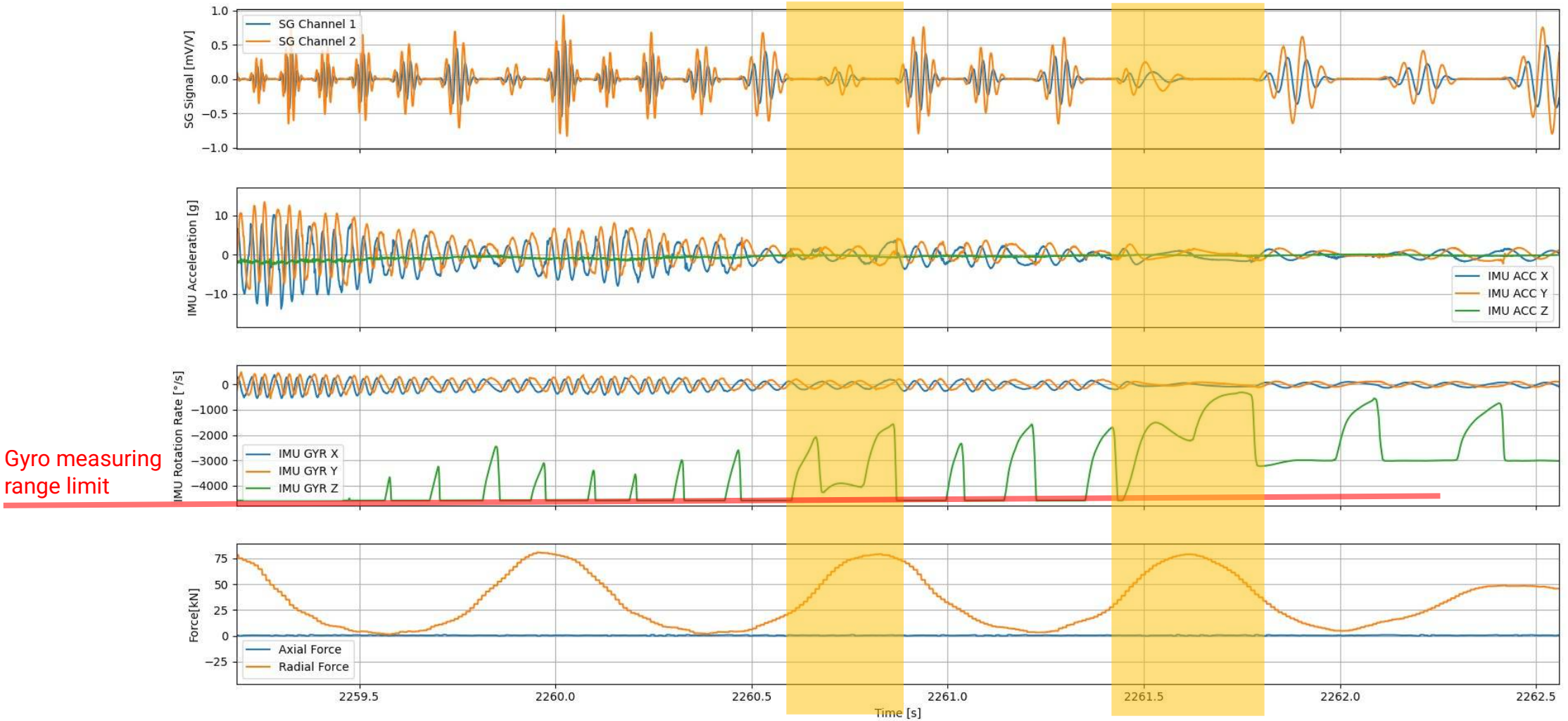
- Simulated Grid Disconnect Event, no axial load



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Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, Detail, no axial load

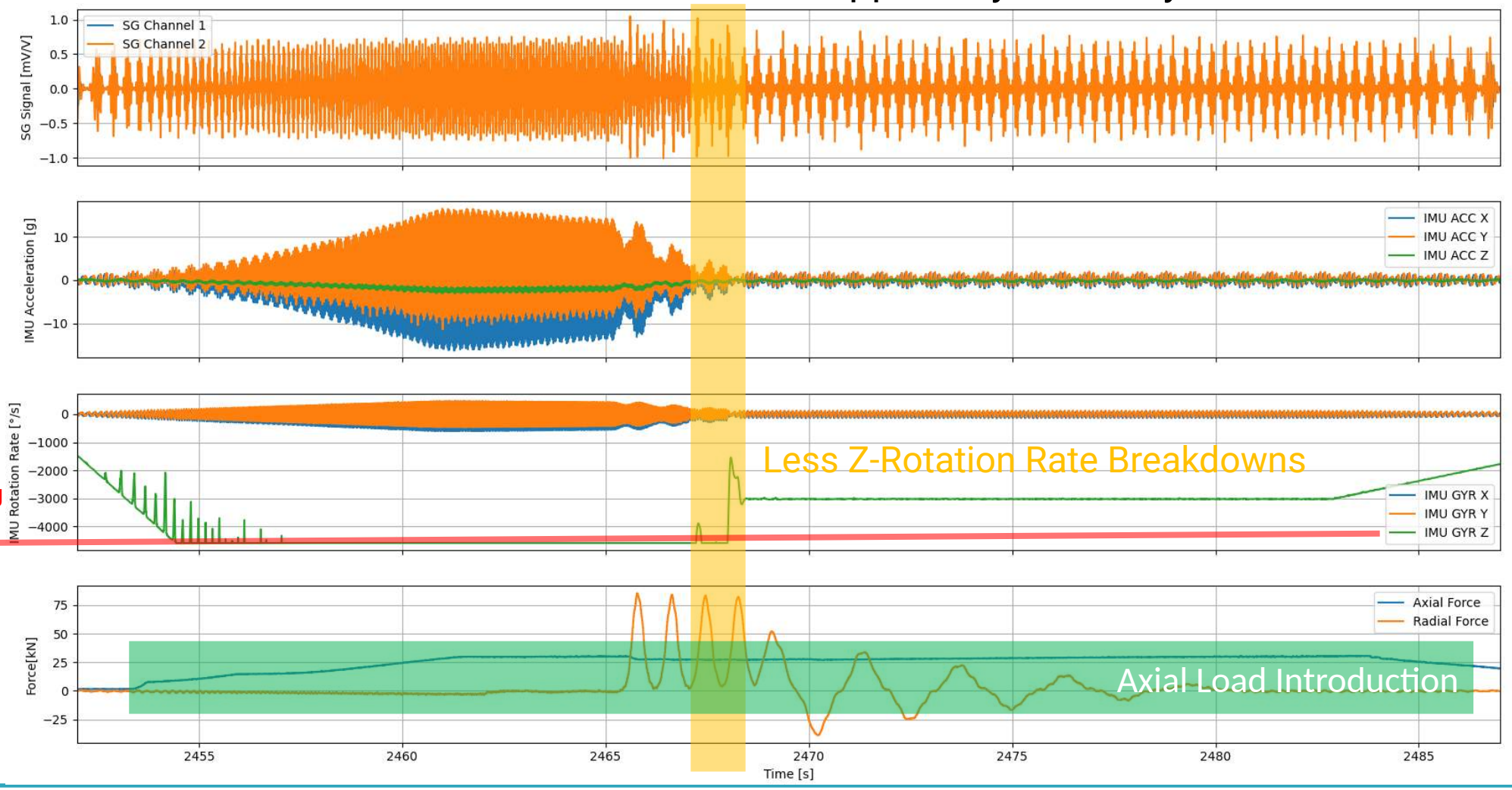


Gyro measuring range limit

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Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, 30 kN axial load applied dynamically

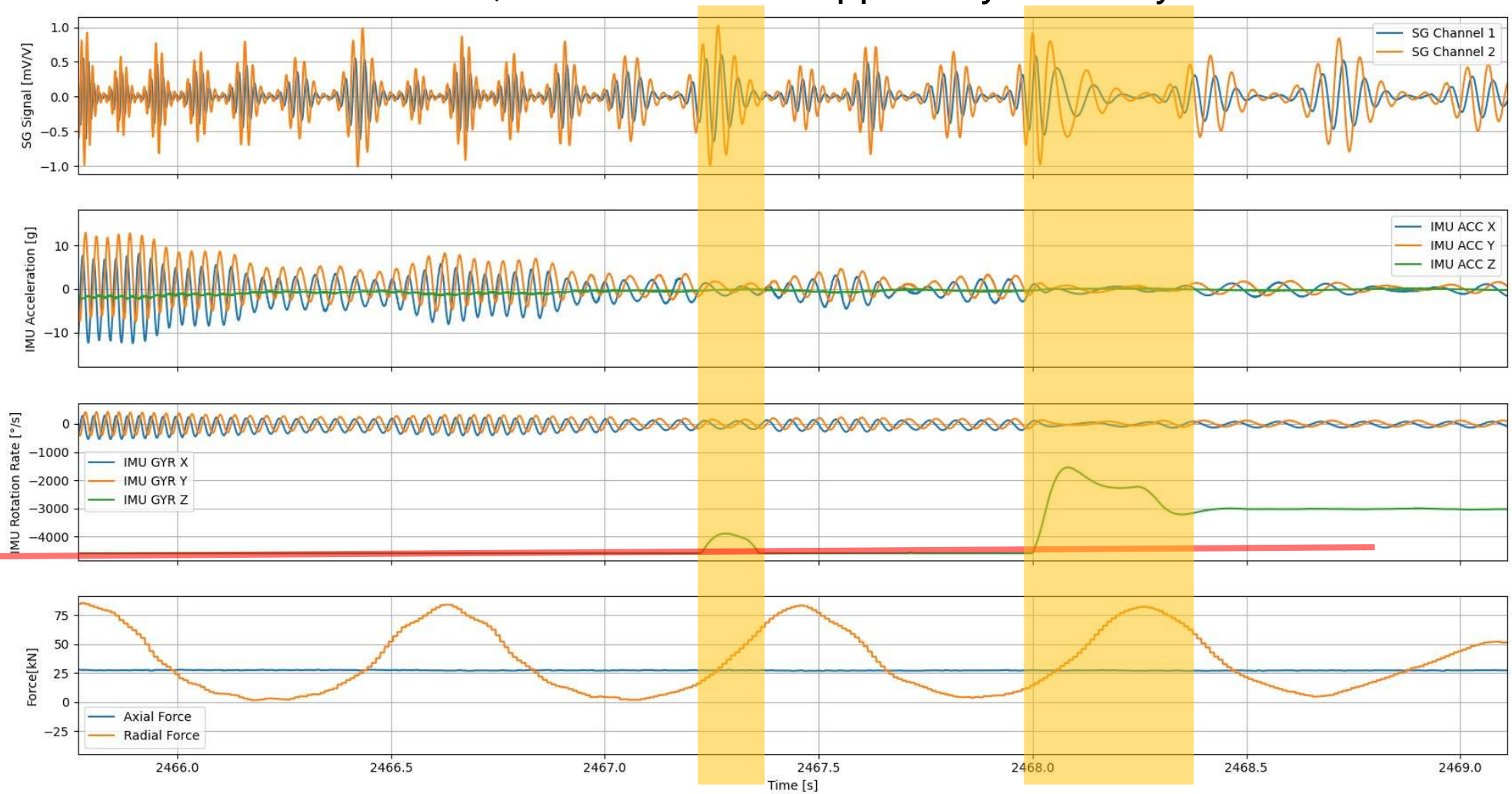


Gyro measuring range limit

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Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, 30 kN axial load applied dynamically

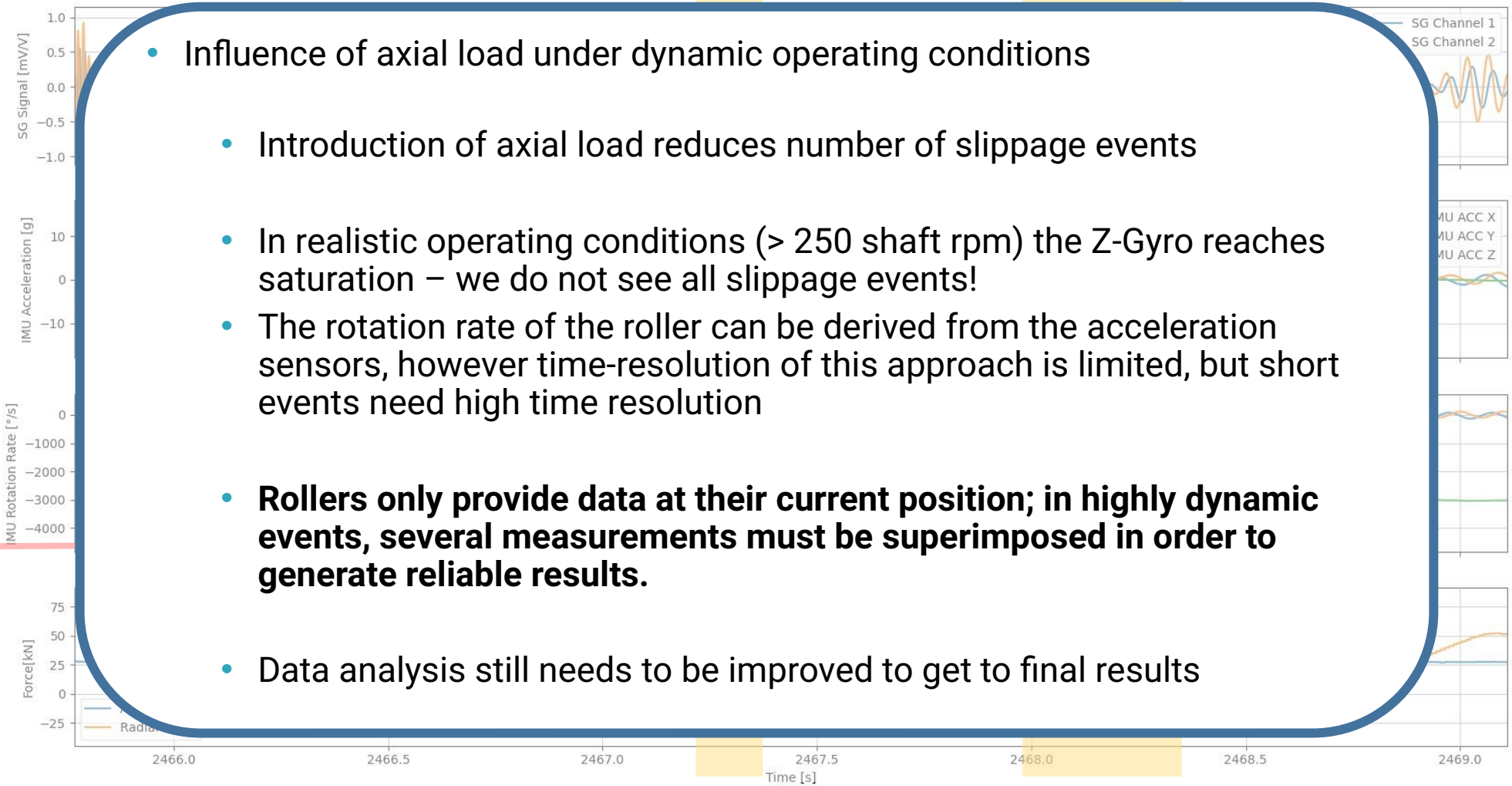


Gyro measuring range limit

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Results and evaluation – Analyzing dynamic Events

- Simulated Grid Disconnect Event, 30 kN axial load



- Influence of axial load under dynamic operating conditions
  - Introduction of axial load reduces number of slippage events
  - In realistic operating conditions (> 250 shaft rpm) the Z-Gyro reaches saturation – we do not see all slippage events!
  - The rotation rate of the roller can be derived from the acceleration sensors, however time-resolution of this approach is limited, but short events need high time resolution
  - **Rollers only provide data at their current position; in highly dynamic events, several measurements must be superimposed in order to generate reliable results.**
  - Data analysis still needs to be improved to get to final results

Gyro measuring range limit

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