

Integration of a Rotating MEMS-Based Measurement System for Condition Monitoring of Wire Race Bearings in CT Systems

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Introduction

A brief introduction and overview of the presentation

Aalen University in figures

- 4,300 students
- 60 degree programs
- 150 professorships
- 550 members of staff

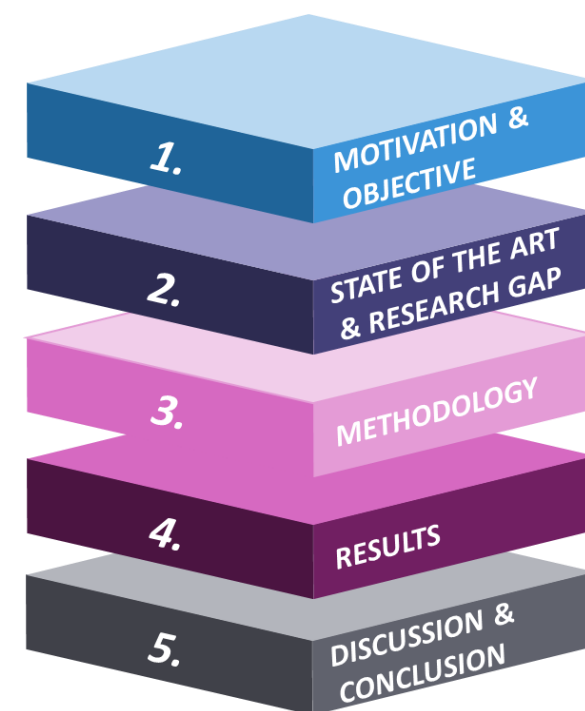


Institute of Drive Technology – IAA

RESEARCH AND DEVELOPMENT AREAS

- ▶ **Development and Design:** Drive technology, electric machines and methodology development
- ▶ **Experimental testing:** Test bench technology, testing procedure and system validation
- ▶ **Condition monitoring and predictive maintenance:** System analysis, sensor concept, DAQ, digital twin and AI-based models

“Integration of a Rotating MEMS-Based Measurement System for Condition Monitoring of Wire Race Bearings in CT Systems”



1. Motivation & Objective

Condition monitoring of a wire race bearing in CT scanners



Development of a rotating sensor system for condition monitoring of a wire race bearing. Measuring the vibrations with an acceleration sensor directly on the rotating inner ring.

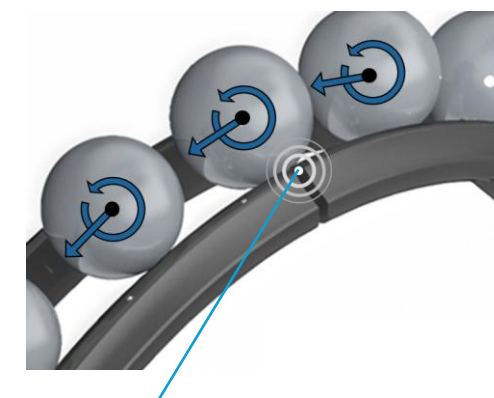
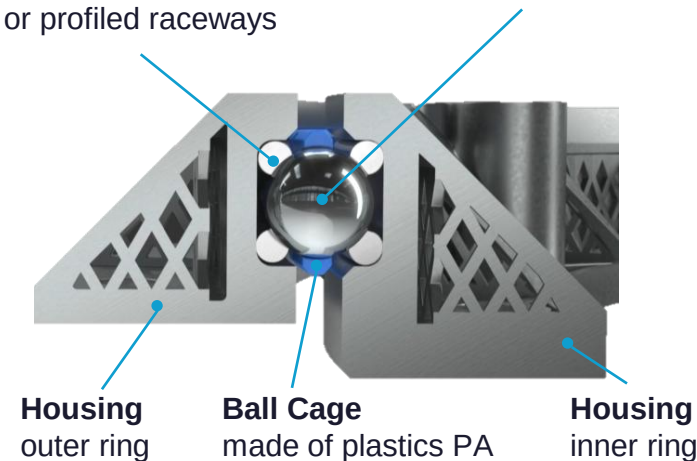
Rotation speed
up to 300 rpm



Radial load
of approx. 800 kg
from the X-ray unit

Wire race rings
from hardened steel with
ground or profiled raceways

Rolling Elements



Structure-borne sound

Bending the wires to form the race rings creates a gap (contact point) between the two ends. When the balls roll over this gap, an impact occurs which propagates as sound.

1. Motivation & Objective

Requirements for the measurement system derived from the operating conditions

Requirement	Value	Derived from
Measuring range	$\geq 50 \text{ g}$	Centripetal acceleration plus reserve
Rotational speed	250 1/min	Operating range of the CT scanner
Bandwidth	$\geq 8 \text{ kHz}$	Defect-related high-frequency content
Sampling rate / resolution	16 kHz / 16 bit	Nyquist criterion for the diagnostic signal
Measuring axes	3	Radial, axial and tangential acceleration
Measurement interval	Every 15 minutes	Slow damage progression; battery life
Measurement duration	5 seconds	Approx. 20 revolutions for averaging
Data availability	After each measurement	Transfer cycle by cycle rather than in batches
Installation space	$\leq 160 \times 45 \text{ mm}$	Adapter envelope at the inner ring
Operating time until recharging	2–4 weeks	Maintenance-free operation

KEY FACTOR – CENTRIPETAL ACCELERATION



The sensor system on the inner ring rotates in a circular path and is constantly subjected to centripetal acceleration:

$$a_m = \omega^2 \cdot r \quad \text{with} \quad \omega = 2 \cdot \pi \cdot f$$

$$r = 0.5 \text{ m}, \quad f = 4.17 \text{ s}^{-1} \rightarrow \approx 32 \text{ g}$$

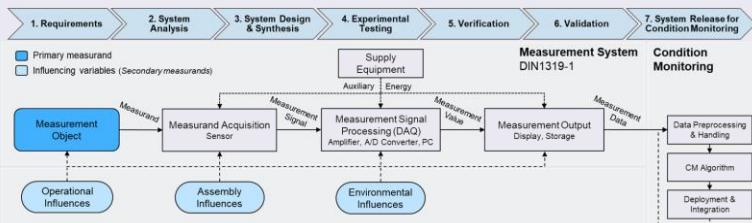
This affects the measurement range and the design of the measurement system.

2. State of the Art

Measurement chain, on-rotor sensing and transmission under rotation

MEASUREMENT CHAIN

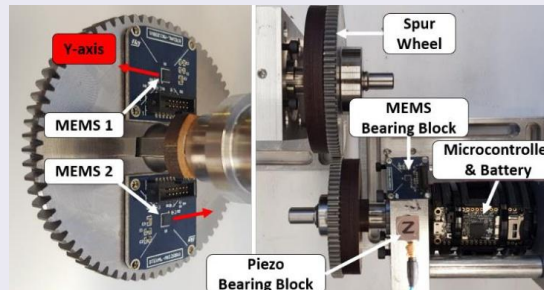
- ▶ DIN 1319-1 describes the general chain from measurement object to measurement value. The quality is shaped by operational, assembly-related and environmental influences [1].
- ▶ Measuring close to the source avoids damping in the transmission path [5].



DIN 1319-1 measurement chain [1]; general signal-flow model [4].

ON-ROTOR SENSING – ACCELERATION SENSOR

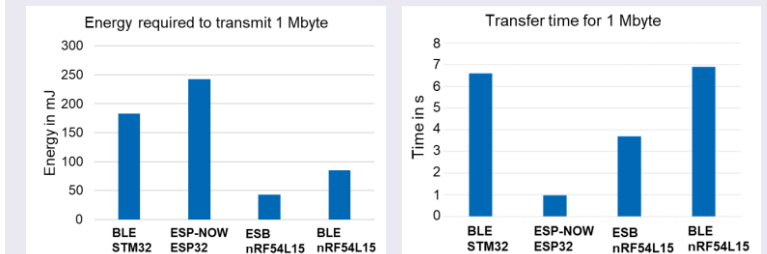
- ▶ Feasibility shown directly on rotating machine elements: gears, bearings, shafts [2, 6].
- ▶ MEMS accelerometers on a rotating gear reach SNR equal to or better than the piezo reference, with $\pm 3\%$ linearity [6].



MEMS accelerometers on a spur gear – microcontroller and battery in a rotating housing [6].

ENERGY AND DATA TRANSMISSION UNDER ROTATION

- ▶ BLE dominates recent work due to low energy demand and compact hardware.
- ▶ Rotation-induced shadowing, multipath and fading are reported qualitatively.
- ▶ Microcontrollers handle on-rotor data acquisition and storage.
- ▶ Energy transmission via slip ring or battery.

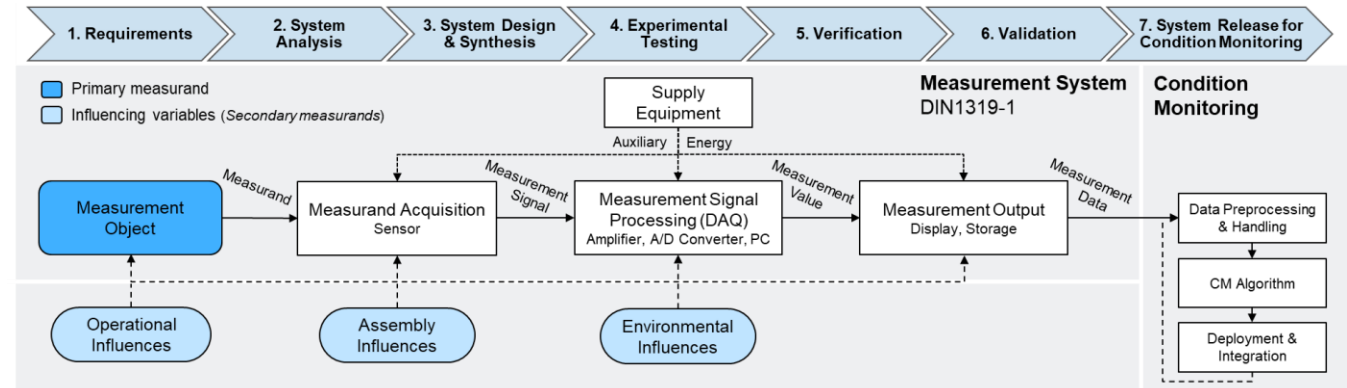
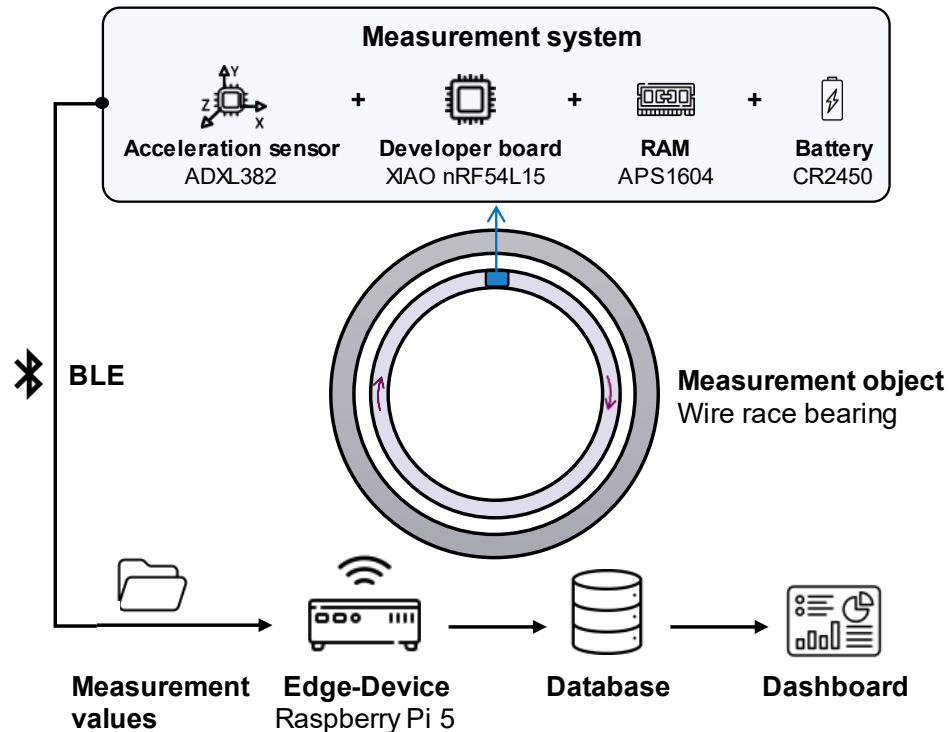


Transmission duration and energy requirements of different types of communication [7, 8].

The rotating measurement system is feasible in principle. What is missing is the derivation of its design from the application and a quantified assessment of the transmission under rotation [2].

3. Method

System design of the rotating measurement unit



SYSTEM DESIGN BASED ON THE MEASUREMENT CHAIN

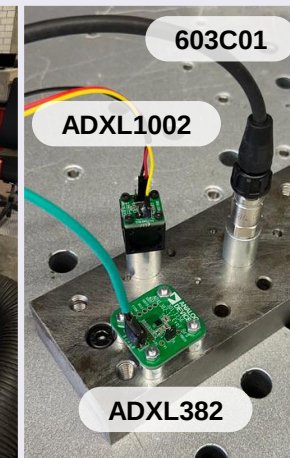
- ▶ Rotating measurement system: Sensor, DAQ, energy supply, wireless data transfer.
- ▶ Influencing variables:
 - Operational: Rotational speed checked by gyroscope value of the developer board.
 - Assembly: Installation position and alignment are checked on the basis of the signs and the range of the measured values.
 - Environmental: Ambient temperature checked by temperature sensor of the acceleration sensor.
- ▶ Edge-Device: Measurement output and condition monitoring

3. Method

Sensor selection and comparison on a shaker test rig

CANDIDATES AFTER REQUIREMENT SCREENING

	Analog Devices ADXL1002	Analog Devices ADXL382	PCB 603C01
Number of axes	1	3	1
Measurement range in g	±50	±15 / 30 / 60	±50
Bandwidth in kHz	11	8	10
Output signal type	Analog	Digital	Analog
Price in €	72	29	145
Dimensions in mm	5 × 5 × 1.80	2.9 × 2.8 × 0.87	20 × 43



Amplitude	Frequency
±0,5 g	1500 Hz
±1 g	1000 Hz
±3 g	1000 Hz
±5 g	1000 Hz
±3 g	1500 Hz
±3 g	2000 Hz

- ▶ Both MEMS candidates were available as developer boards
- ▶ The ADXL1002 has a higher bandwidth, but requires an additional A/D converter
- ▶ Both MEMS sensors were tested on a shaker test rig in comparison with a piezoelectric accelerometer
- ▶ The comparison assesses amplitude fidelity, frequency accuracy and noise behaviour under identical excitation



ADXL1002

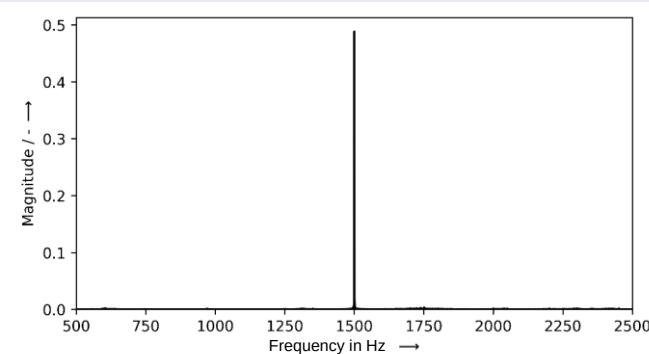
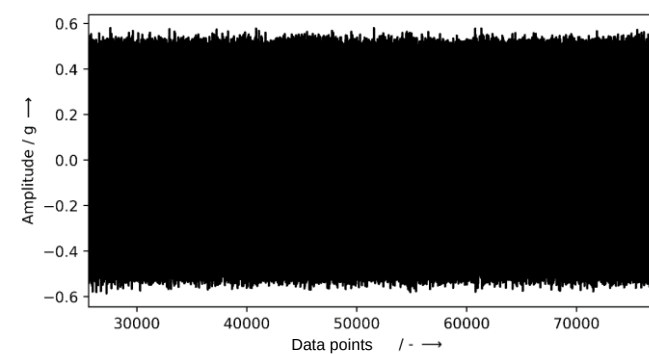


ADXL382

4. Results

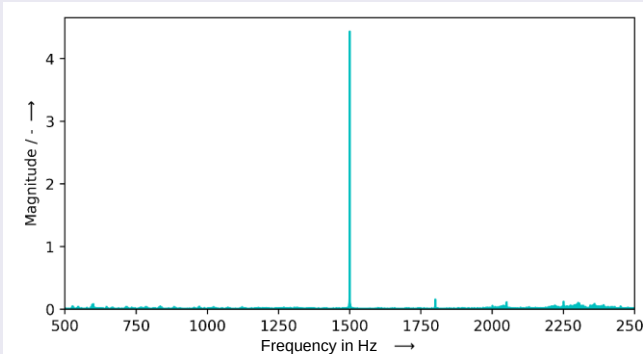
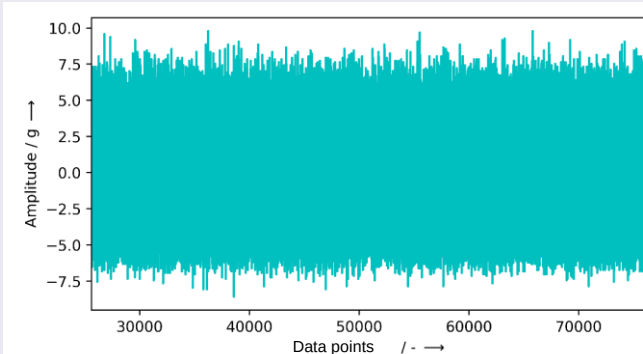
Sensor comparison at ± 0.5 g and 1500 Hz

603C01 – Piezoelectric



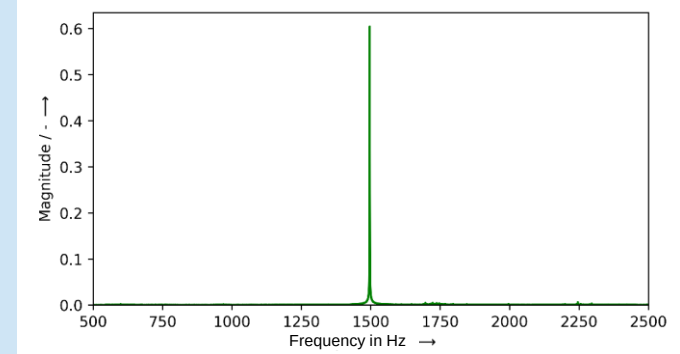
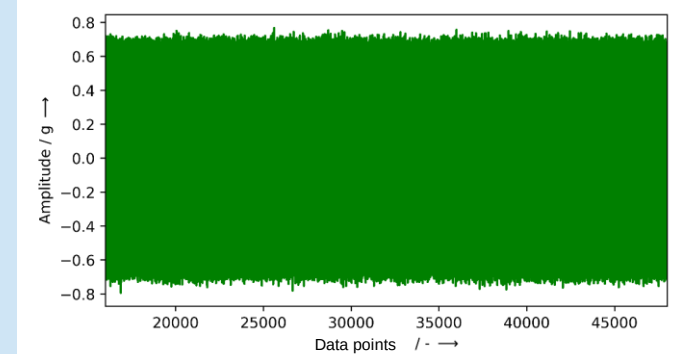
- ▶ Amplitude and frequency as set
- ▶ **Reference**

ADXL1002 – Analogue MEMS



- ▶ Amplitude approx. 20× the set value
- ▶ Additional frequency peaks above 1500 Hz
- ▶ **Not suitable**

ADXL382 – Digital MEMS

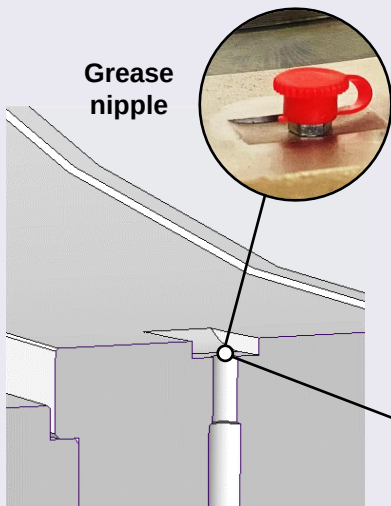


- ▶ Amplitude close to the reference
- ▶ Single frequency peak at 1500 Hz
- ▶ **Selected**

4. Results

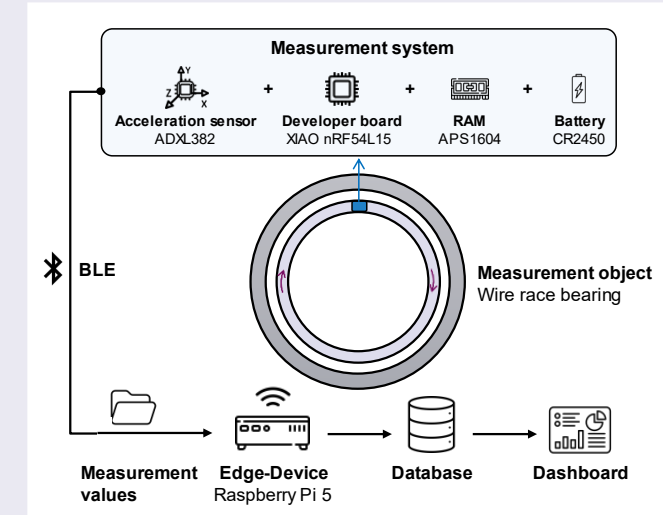
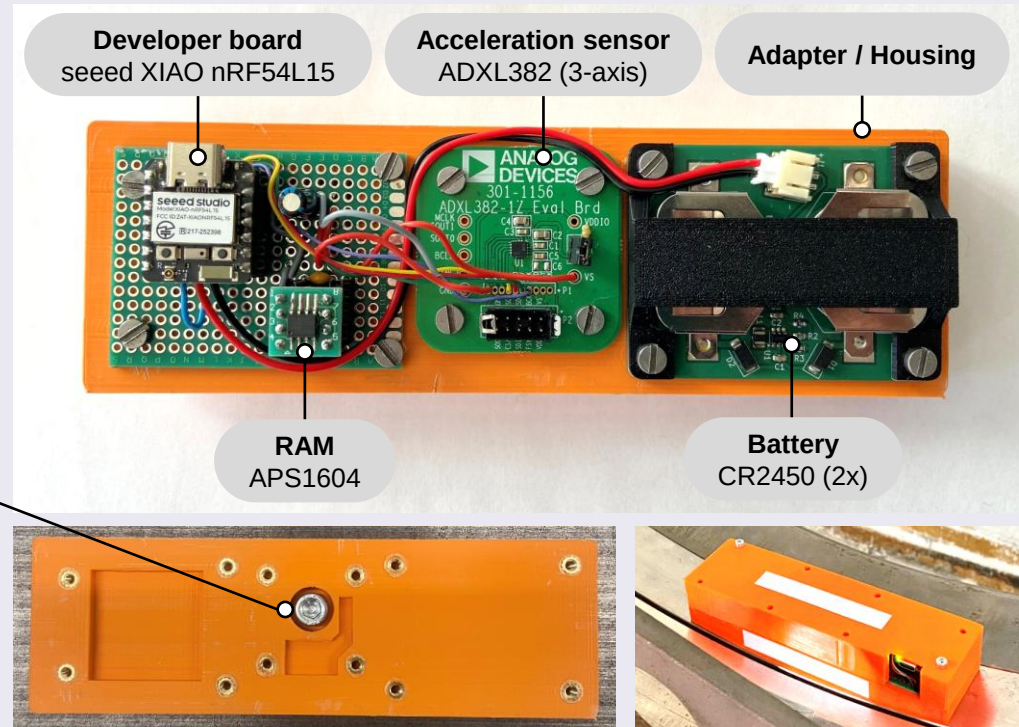
Mechanical integration of the rotating measurement unit

INTEGRATION & ASSEMBLY



- ▶ Universal fixing point for quick assembly
- ▶ No modification required

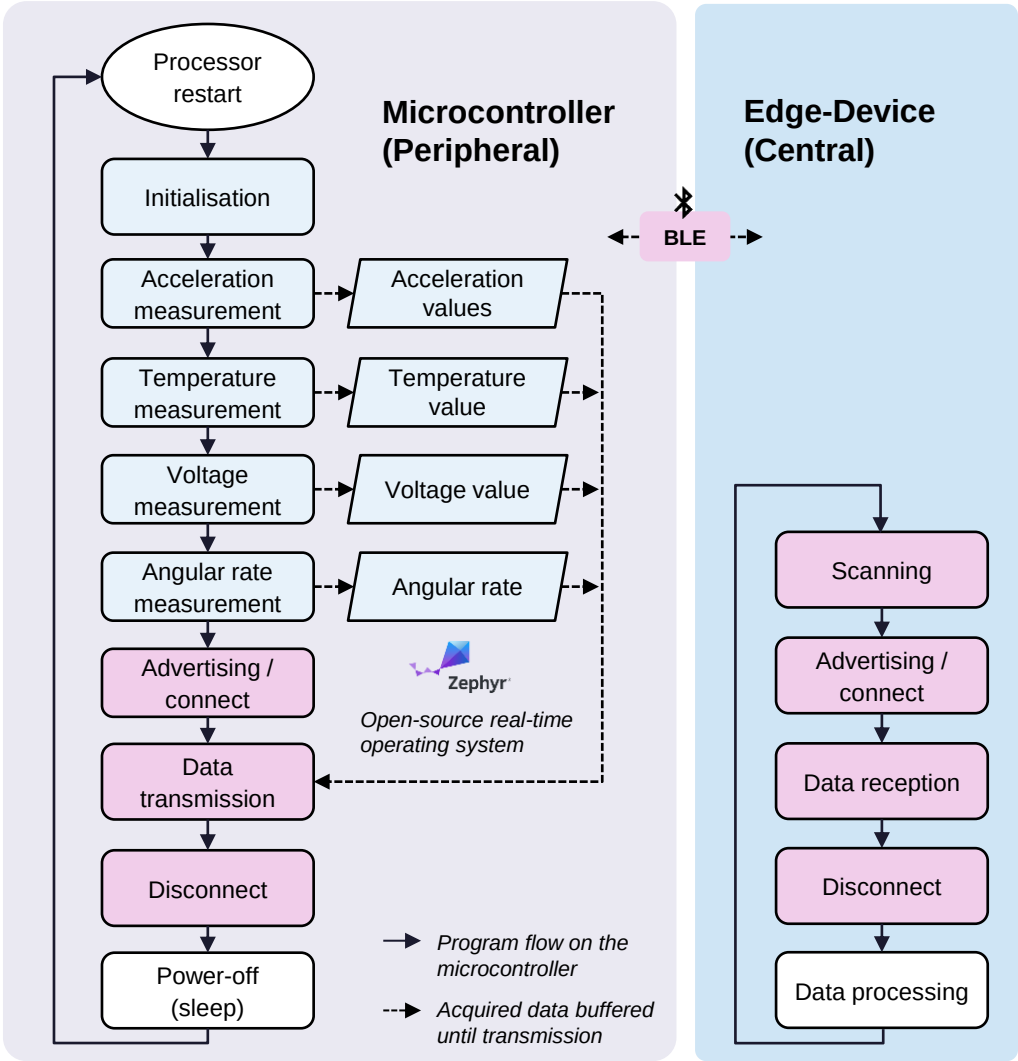
ROTATING MEASURING SYSTEM – 1st GENERATION



- ▶ Plastic adapter manufactured by additive manufacturing
- ▶ Positive fit with the bearing
- ▶ Dimensions: 160 × 45 × 35 mm
- ▶ Weight: 184 gram

4. Results

Measurement cycle, energy demand and transmission effort

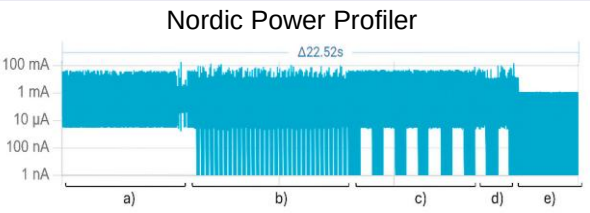


ENERGY DEMAND PER MEASUREMENT CYCLE

Phase	Duration	Mean current
Measurement (a)	5 s	5.32 mA
Advertising / connect (b)	7.64 s	1.10 mA
Payload transfer (c)	5.38 s	9.24 mA
Disconnect (d)	1.95 s	581.81 µA
Power-off (sleep) (e)	20 s	35.74 µA

Battery runtime (3.0 V / 1,140 mAh)

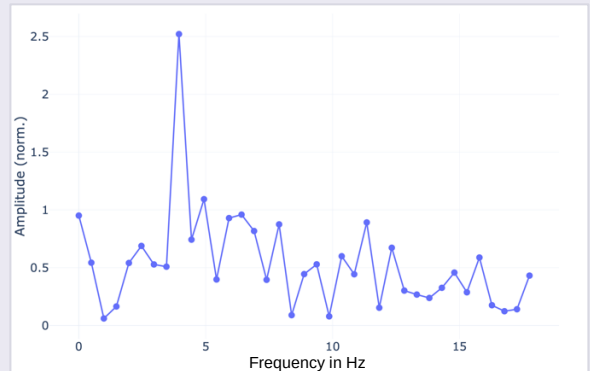
- ▶ 20 s power-off: 20 days
- ▶ 15 min power-off: 11 months



TRANSMISSION UNDER ROTATION

Metric	Rotating	Stationary (4 orientations)
Throughput	37.4 kB/s	57.2–78.6 kB/s
Transfer duration	12.9 s	6.1–8.4 s
RSSI mean	-51.5 dBm	-52.8 to -55.4 dBm
RSSI span	31.4 dB	17.0–27.0 dB

RSSI spectrum (rotating operation)



4. Results

Experimental testing – endurance test on the test bench

TEST BENCH & SETUP

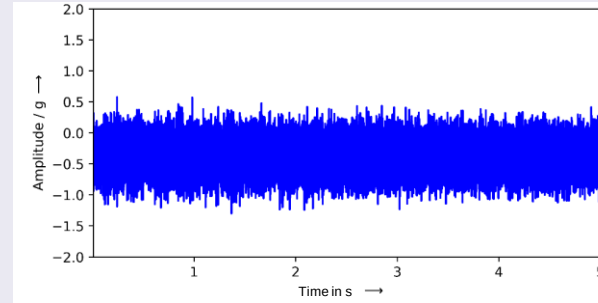
Reference measurement system



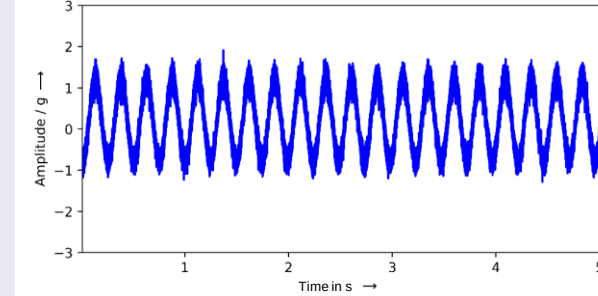
- ▶ Endurance test: Start 01.2026 → today
- ▶ Rotational speed: 250 1/min
- ▶ Measurement interval: Every 15 min
- ▶ Measurement duration: 5 seconds
- ▶ Measuring range: ± 60 g
- ▶ Measuring axes: 3
- ▶ Bandwidth: 8 kHz
- ▶ Sampling rate: 16 kHz

MEASUREMENT DATA

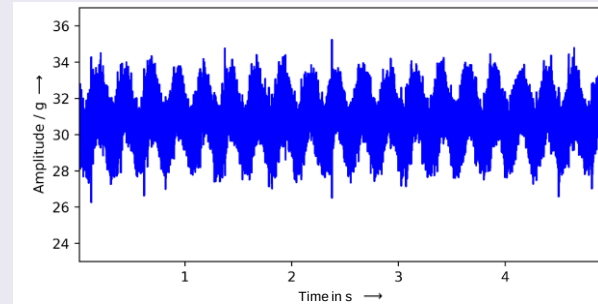
X-axis



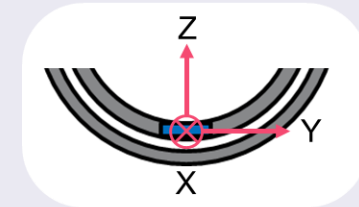
Y-axis



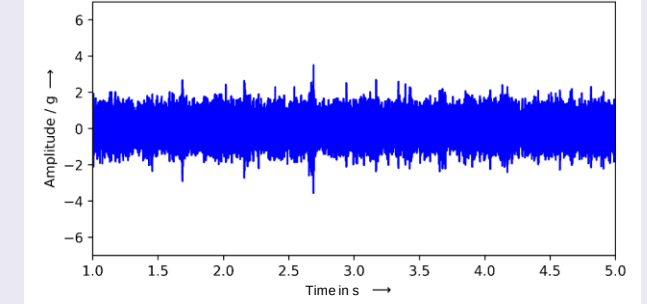
Z-axis



- ▶ The rotational frequency of about 4 Hz is clearly resolved in time and frequency domain and matches the gyroscope reading.
- ▶ The radial z-axis carries a constant offset of approximately 31 g from the centripetal load.
- ▶ Plausible and reproducible measurement data.

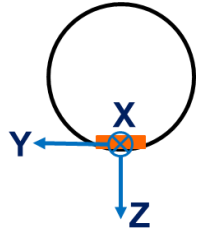


Z-axis (after signal pre-processing)



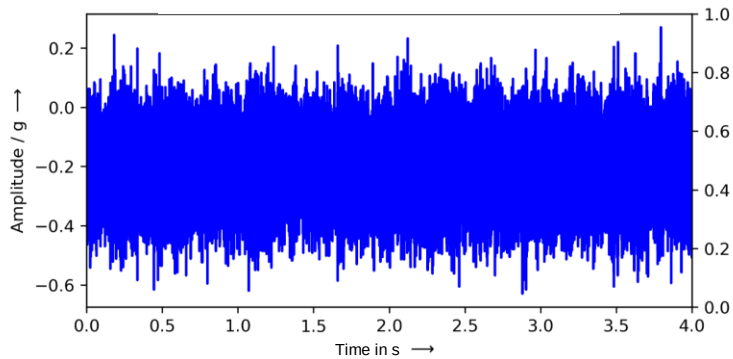
4. Results

Experimental testing – end-of-line testing, time signals

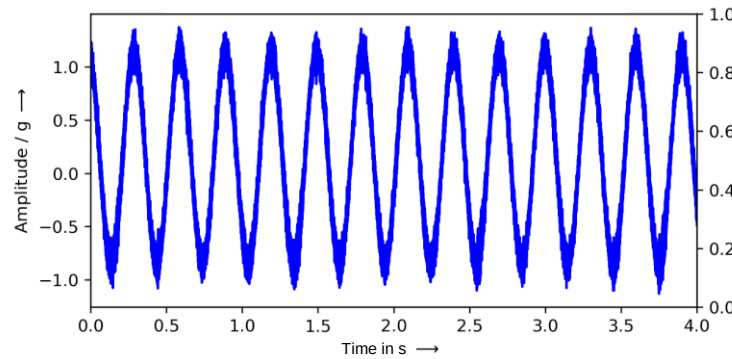


OK

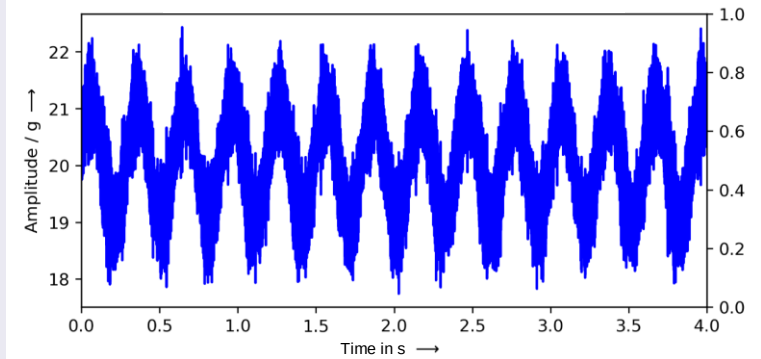
X-axis



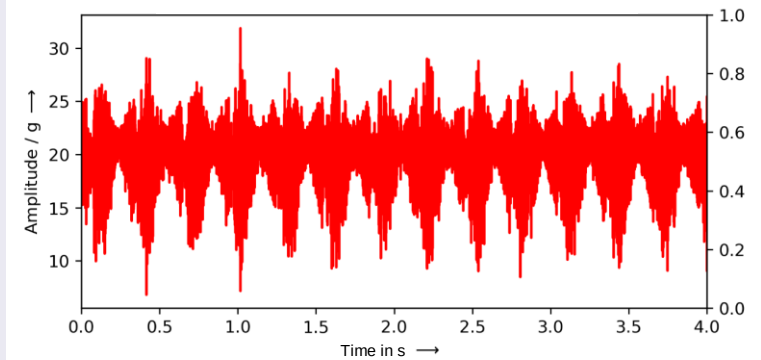
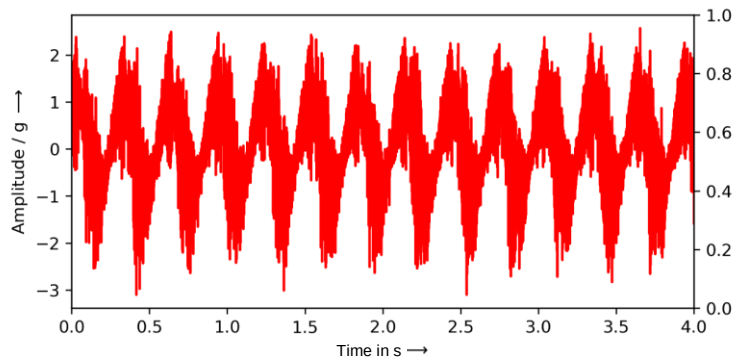
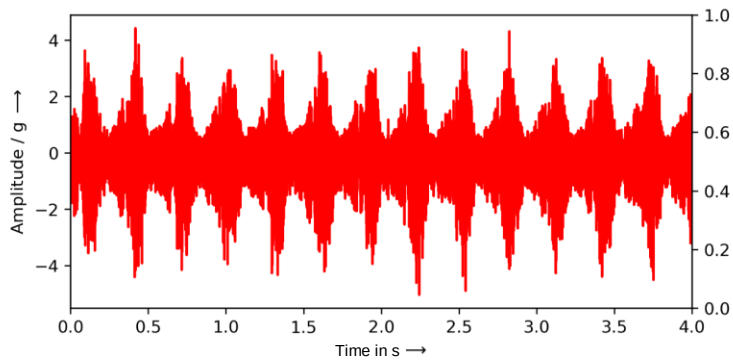
Y-axis



Z-axis

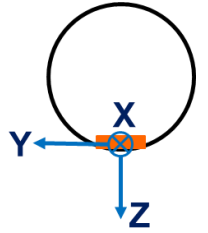


Not OK



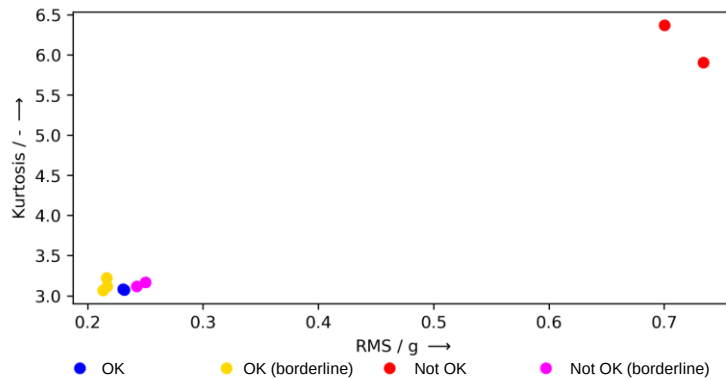
4. Results

Experimental testing – end-of-line testing, feature separation

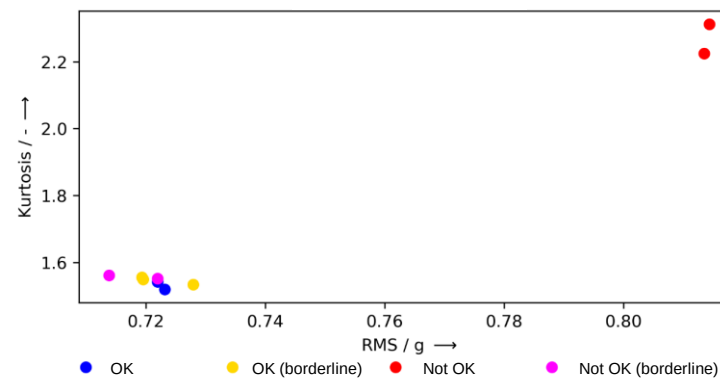


Kurtosis over RMS

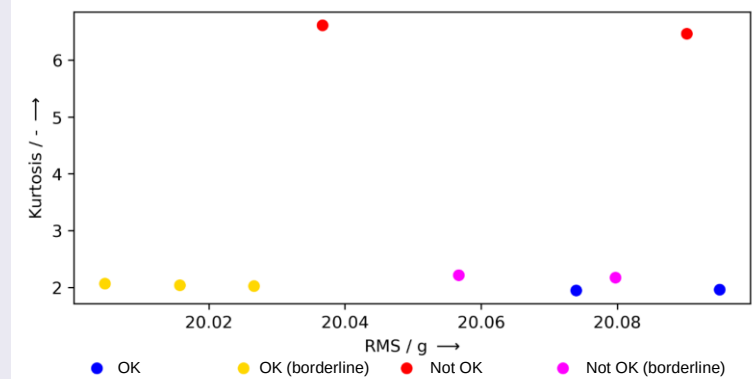
X-axis



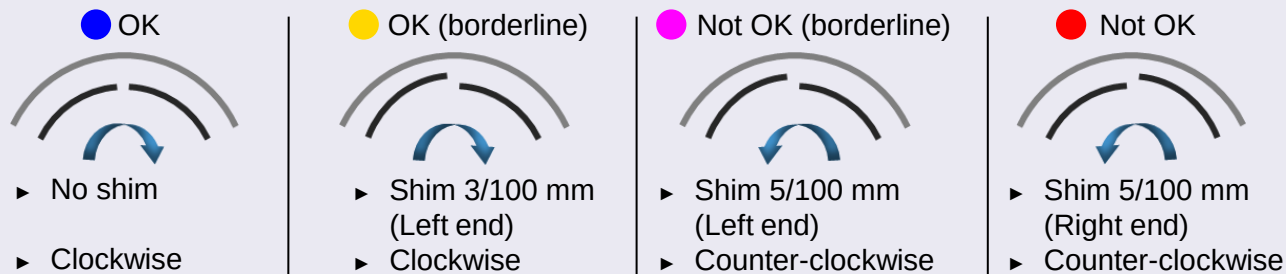
Y-axis



Z-axis



► Four conditions set on the same bearing, measured at 200 rpm



- Two measurements per condition, three for OK (borderline).
- Repeated measurements under a single condition are close to one another. RMS and kurtosis clearly separate the defective states on the radial x- and y-axis.
- Borderline states cluster close to the acceptable ones.
- The z-axis is dominated by the centripetal offset and contributes little to the separation.

5. Discussion & Conclusion

What the system delivers, where it does not, and what comes next

STRENGTHS

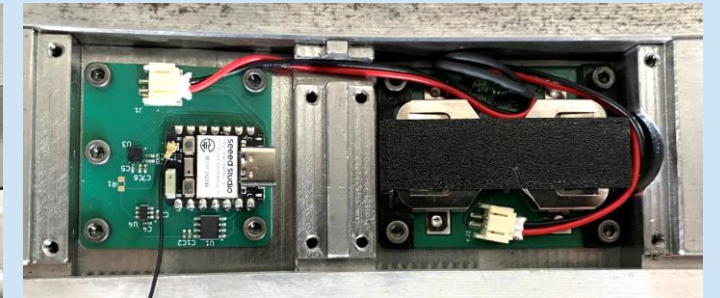
- ▶ Acquisition, buffering, energy supply and wireless communication co-rotate on the inner ring.
- ▶ Local buffering decouples the constant sampling rate from the varying radio channel.
- ▶ Measuring on the rotating inner ring avoids the damped path through housing and damping element.
- ▶ Rotation measurably degrades the transmission, but not the acquisition.
- ▶ Defined bearing conditions can be distinguished under rotation.

LIMITATIONS

- ▶ Clear defects separate reliably, but borderline states require further signal preprocessing.
- ▶ The required bandwidth of 8 kHz could not be verified – the shaker rig reaches 3 kHz.
- ▶ The printed adapter introduces a compliant interface in the transmission path and its influence has not yet been quantified yet.
- ▶ Rotation halves the throughput and the cause cannot be resolved from RSSI alone.
- ▶ No end-to-end acknowledgement of stored data – individual cycles can be lost undetected.

NEXT STEPS

- ▶ Comparative measurement of the directly coupled second generation
- ▶ Signal preprocessing to separate borderline condition states
- ▶ Extension of the end-of-line dataset towards classification
- ▶ Full paper for the SiME-Kongress Collection in Engineering Research





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Thank you for your attention!



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