EXPERIMENTAL INVESTIGATION OF THE ROLLING CONTACT FATIGUE BEHAVIOR OF TOROIDAL BEARINGS USING ACOUSTIC EMISSION

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INSTITUTE OF MACHINE AND INDUSTRIAL DESIGN

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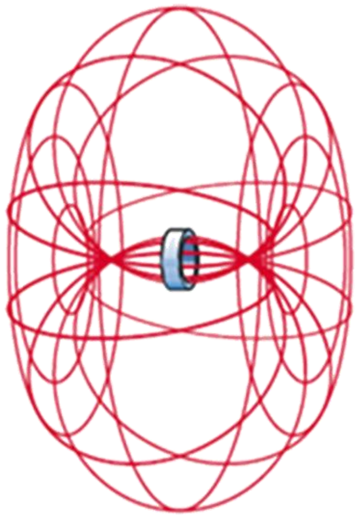
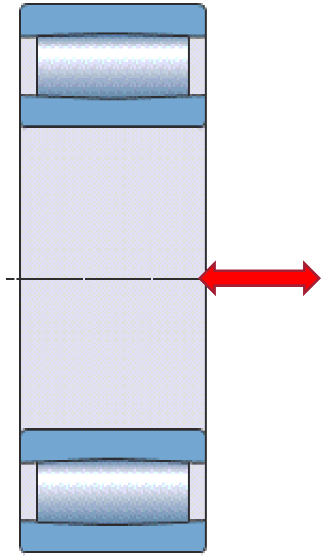
CONTENTS

Introduction

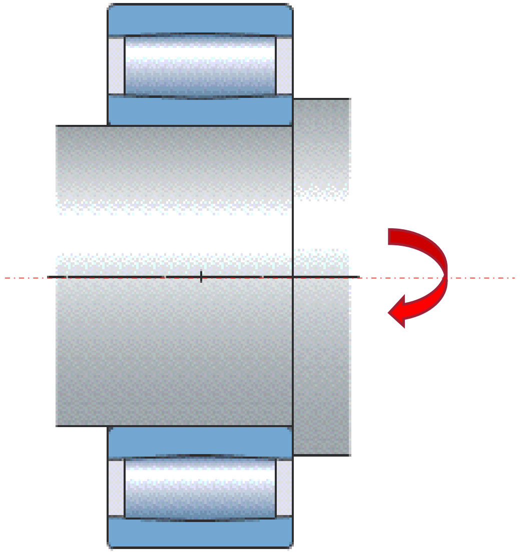
<u>Toroidal bearings</u> special design combines the **self-aligning** capability with the **axial displacement** ability.



Inner and outer raceways are parts of a **torus**



Ability to adapt to axial misalignment



Ability to adapt to angular misalignment

Torus equation

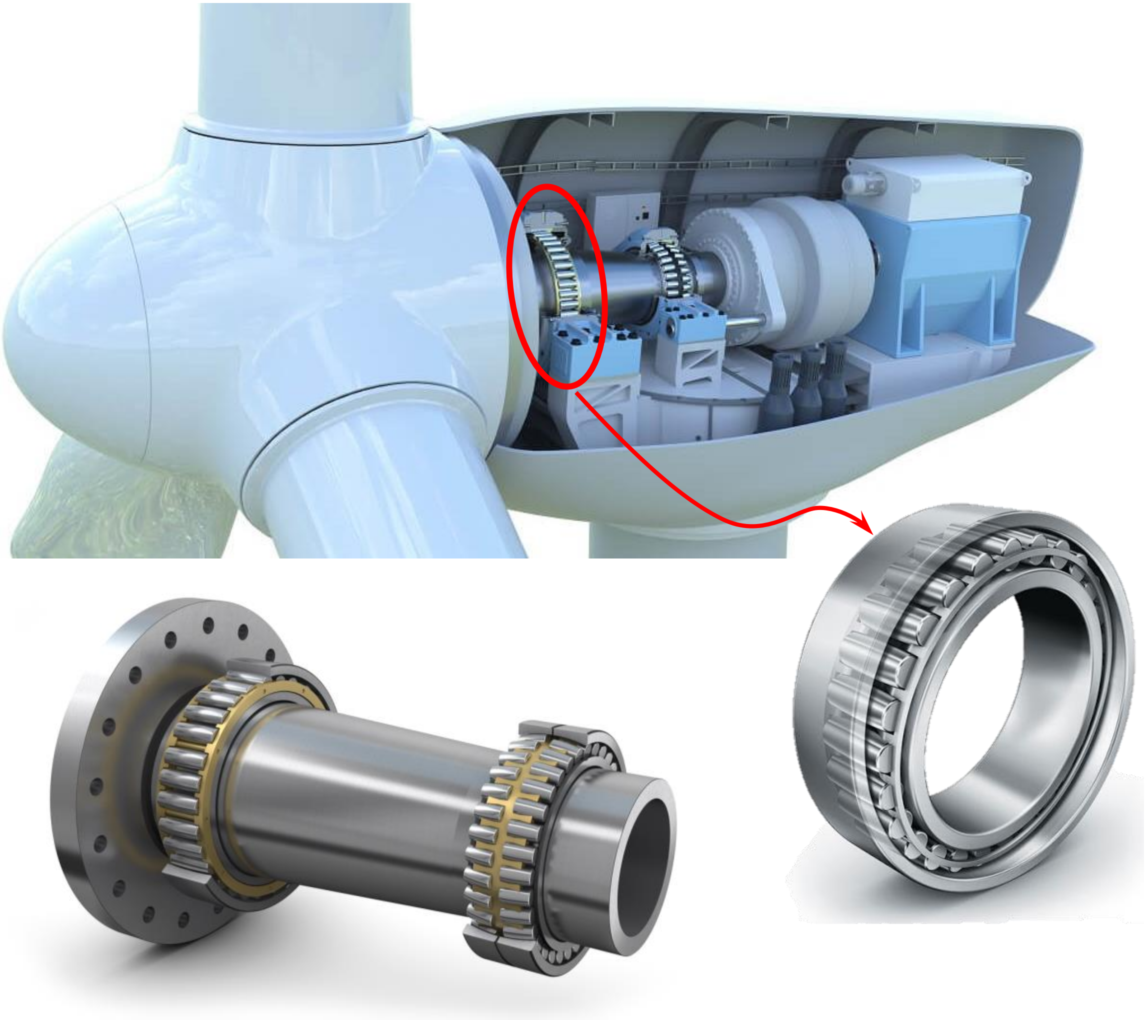
$$\left(R - \sqrt{x^2 + y^2}\right)^2 + y^2 = r^2$$

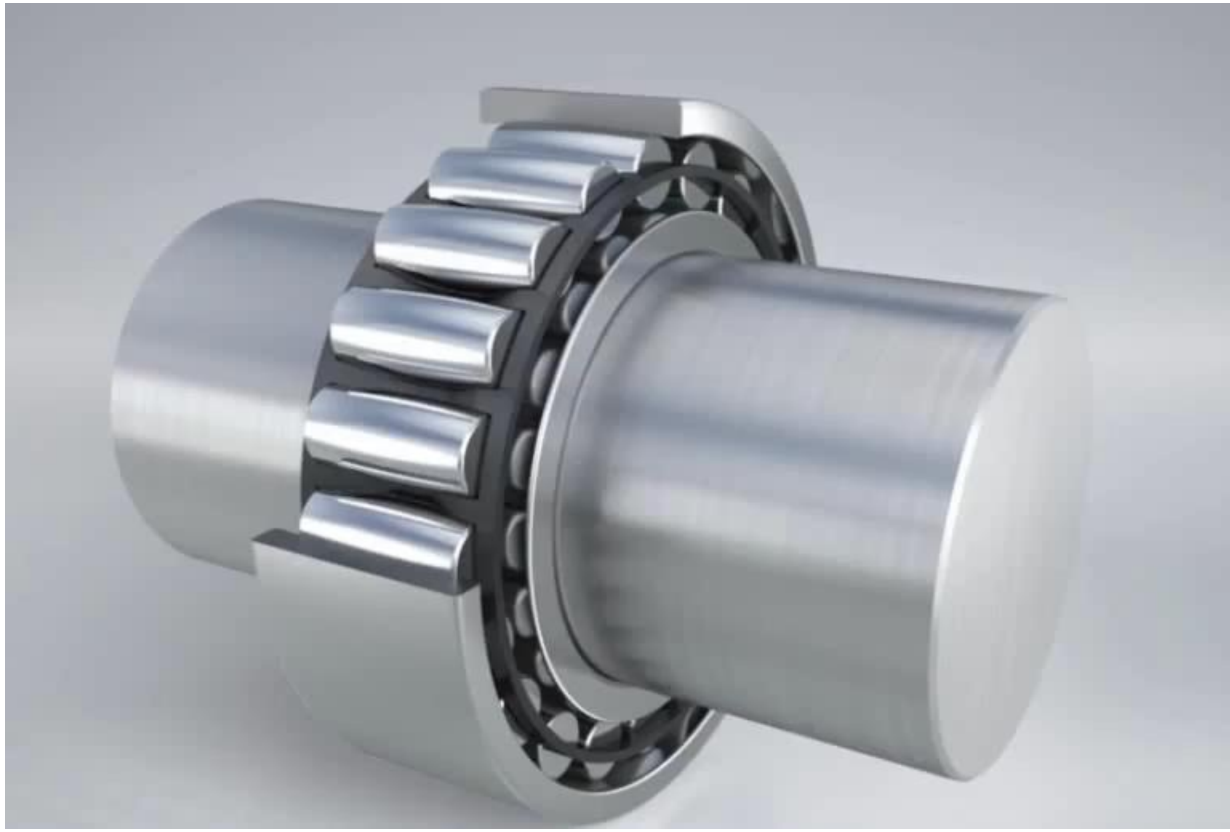
Photos courtesy of skf.com

Why Toroidal Bearings

ADVANTAGES

DISADVANTAGES



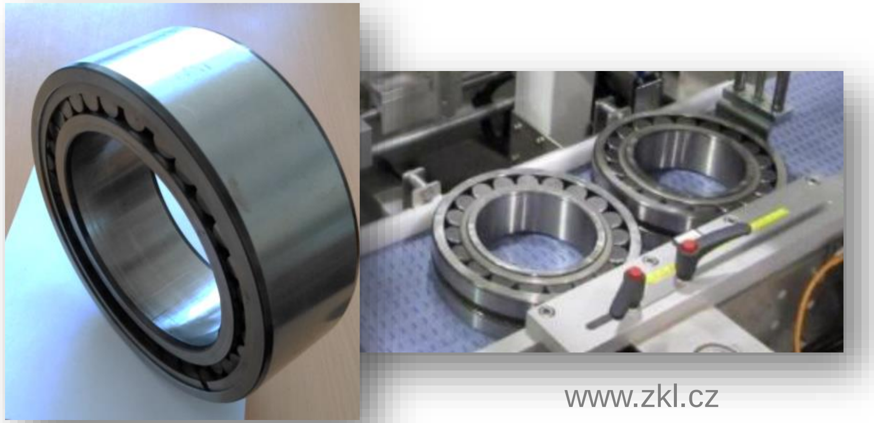


Motivation

- TRBs are **newly produced** type of bearings.
  - First was CARB by SKF, TORB (Schaeffler) and ADABT (Timken)

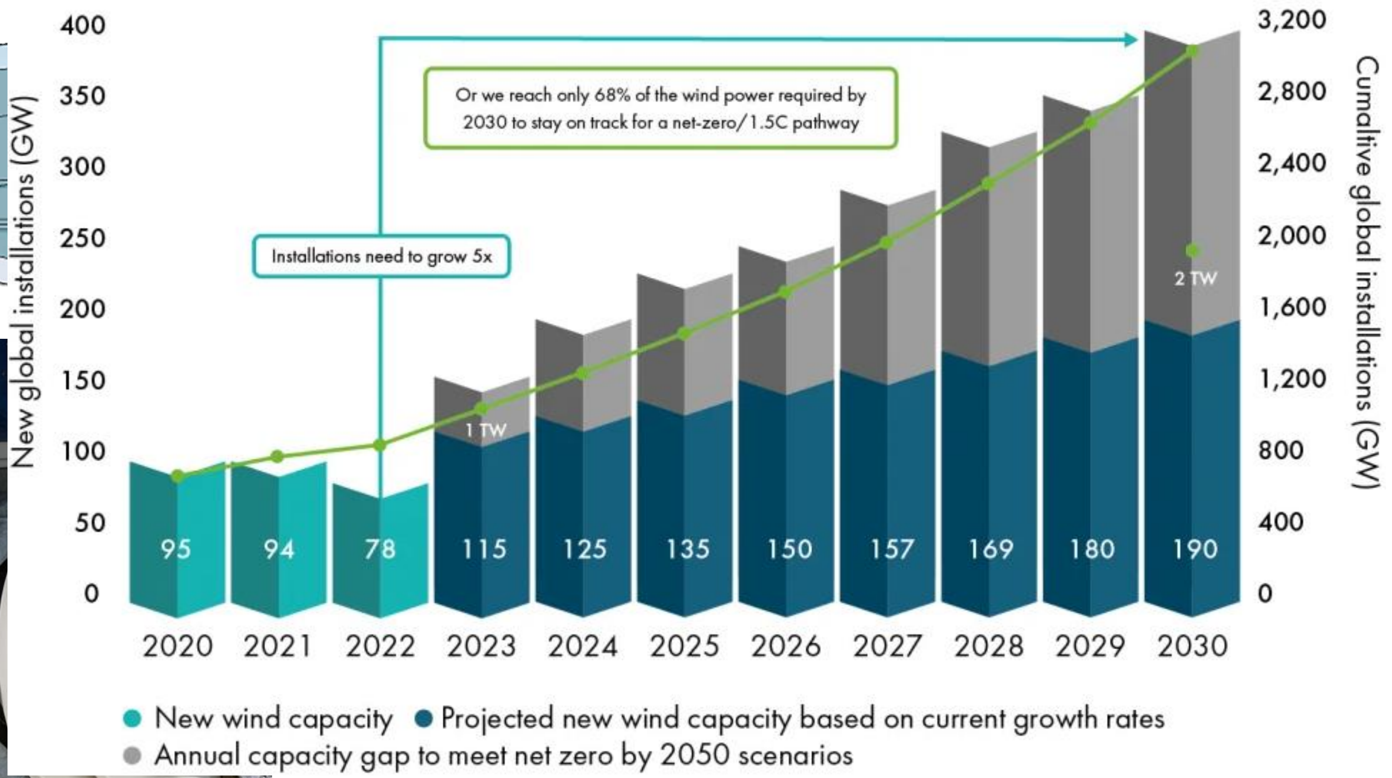
www.schaeffler.com

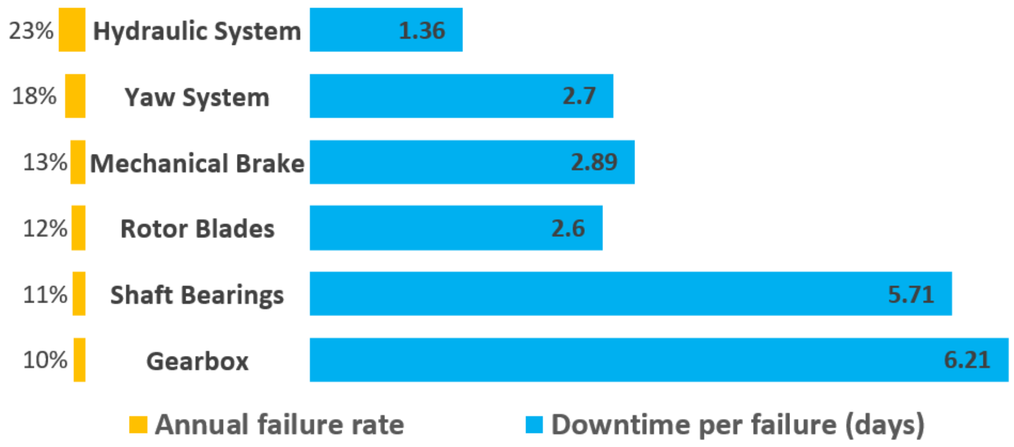
  - Recently by ZKL (CZ)



www.zkl.cz

Photos courtesy of skf.com

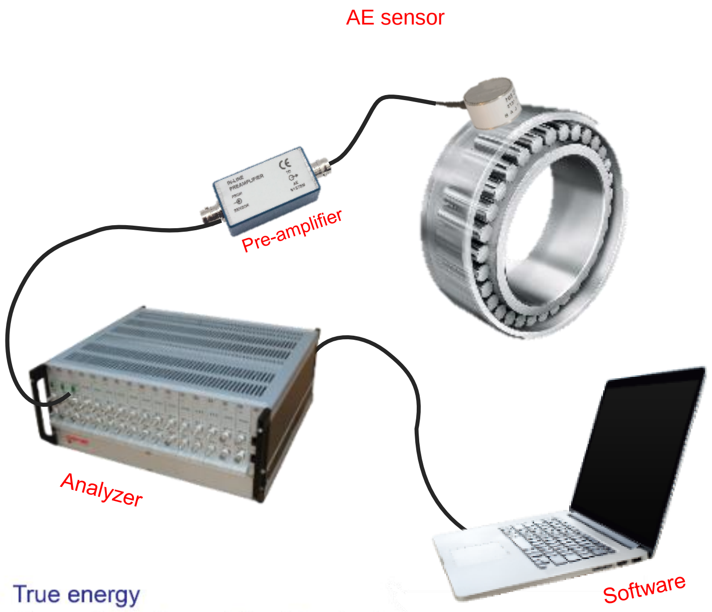




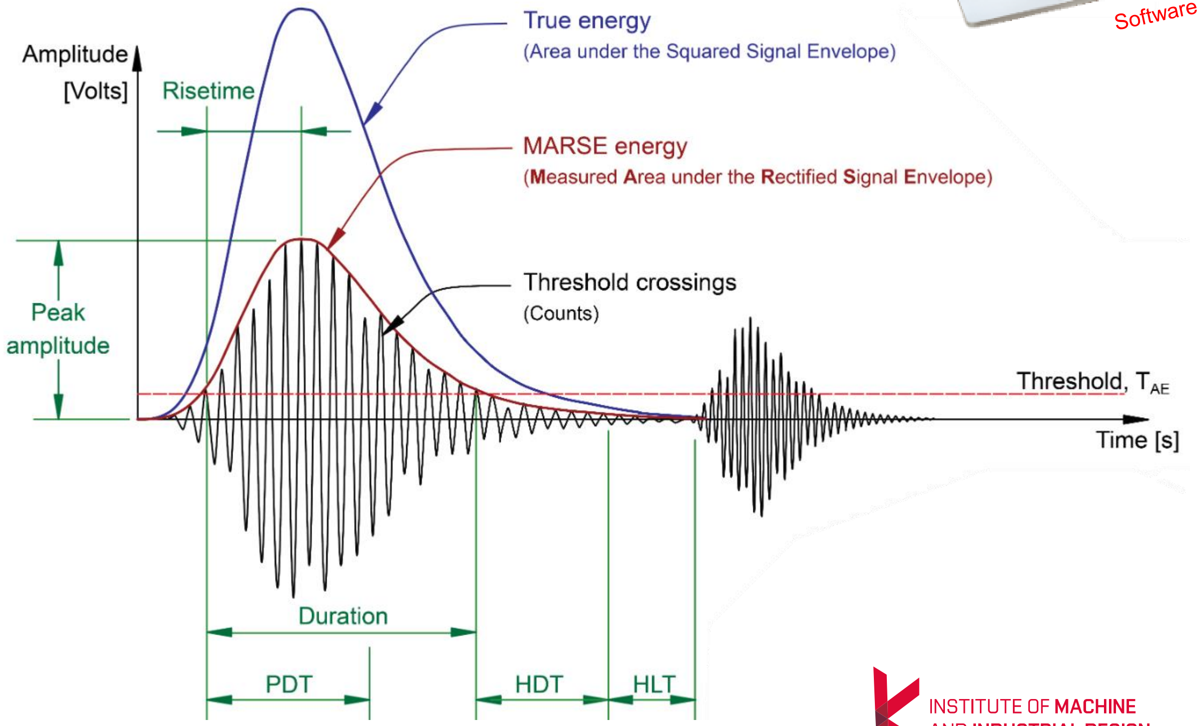
WMEP survey

Motivation

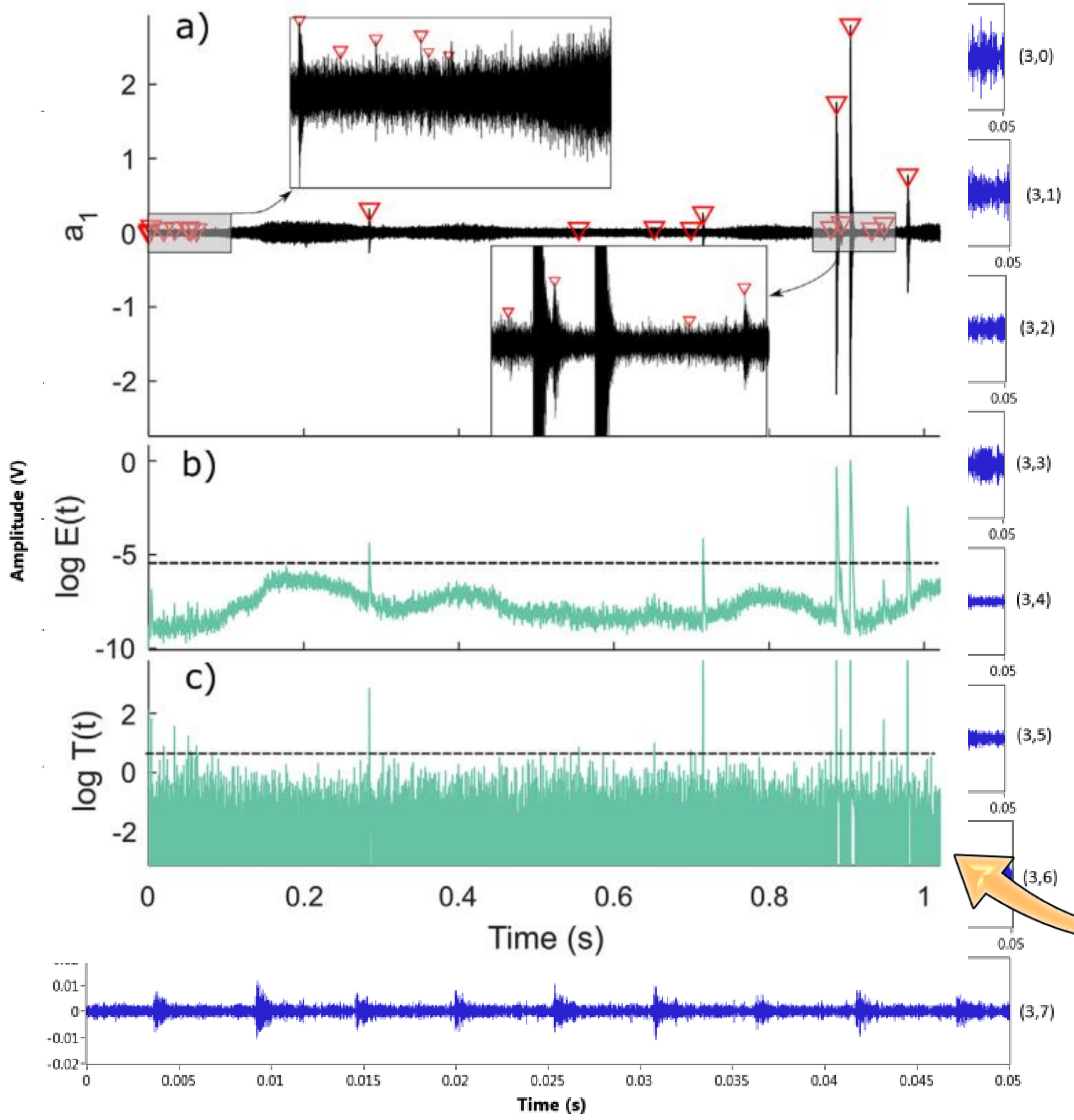
- **TRBs are expensive, and should be tested using a Non-destructive method.**
  - AE is one of the most sensitive.
  - Availability in our research group.
  - Promising results.



- A gap in the literature.
  - The use of AE Time-domain parameters is predominant, while frequency-domain parameters were not applied in studying RCF on bearings.
  - The subject of testing TRBs using NDT was not studied.



Current state of knowledge



Using AE to detect and locate defects of RCF in bearings.

1982 — Yoshioka + Fujiwara
New AE source locating system for the study of RCF. [23]

1999 — Choudhory + Tandon
AE successfully used for detecting defects in RCF [9]

2003 — Mba + Morhain
AE offers earlier fault detection than vibration. [10]

2006 — Mba + Algamd
The use of AE for identification and estimation of defect size. [22]

2008 — Rahman + Yoshioka
RCF damage detection and its propagation by AE. [12]

Studies on the AE signal, that is applied to study RCF in bearings.

2010 — Eftekharnejad + Mba
The application of spectral kurtosis on AE and Vibration. [23]

2015 — Chacon + Luis
The method combines Wavelet packet for AE, and Hilbert Transform (HT) for envelope extraction. [15]

2017 — Sharma + Bihari
...lling of AE generated in rolling element... [18]

In Roller bearing

2017 — Schnabel + Marklund
The detection of plastic deformation in rolling elements bearings by AE. [19]

2019 — Dwyer-Joyce + Fuentes
Detection of sub-surface damage in wind turbine bearings using AE. [20]

RCF in bearing

2013 — Hannes + Alfredson
Modelling of surface initiated RCF damage. [31]

2016 — Rycerz + A. Olver
Propagation of surface initiated RCF in bearing steel. [32]

Investigating the effect of RCF in TRBs using AE

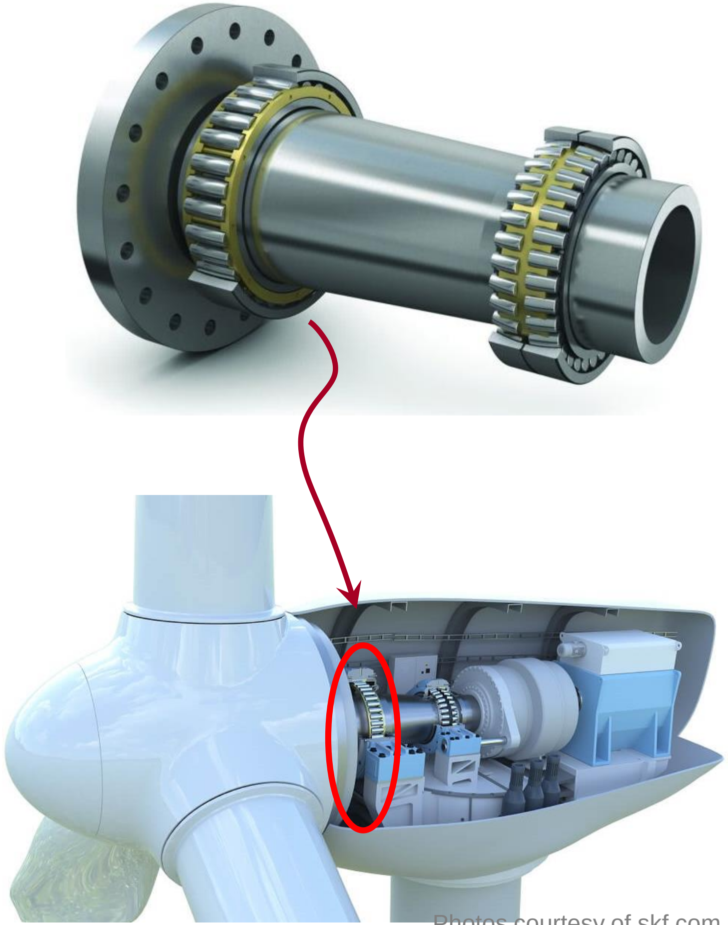
Aim of the Dissertation

Provide a **correlation** between **AE frequency-domain parameter** and the detected damage in the monitored **Toroidal Roller Bearings (TRBs).**

- **Experimental procedures**, in-situ (in Wind turbine) and in laboratory (production site).
- Using different methods to confirm the correlation.
- Visual and statistical representation of the results.

Designing and assembly of the testing stand to fit the requirements.

Remote online monitoring of the tested subject



Photos courtesy of skf.com

Scientific Questions and Hypotheses

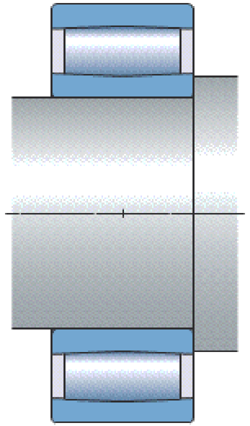
Q1. How frequency-domain parameters of AE (mainly Dominant Frequency) could be used to evaluate the level of defects on the bearings' raceways?

H1. This would require experimental study that involves in-situ measurements and laboratory experiments, where AE hits could be collected and their DFs (for example) could be extracted. Those DFs could be represented on a plot called DF map. A synchronous comparison with other solid and proven methods to establish a correlation between the DF map and the condition of the monitored bearing. Then reading the DF map statistically, by different means, would give a quantifiable measurement of the level of defects in the monitored bearings' raceways.

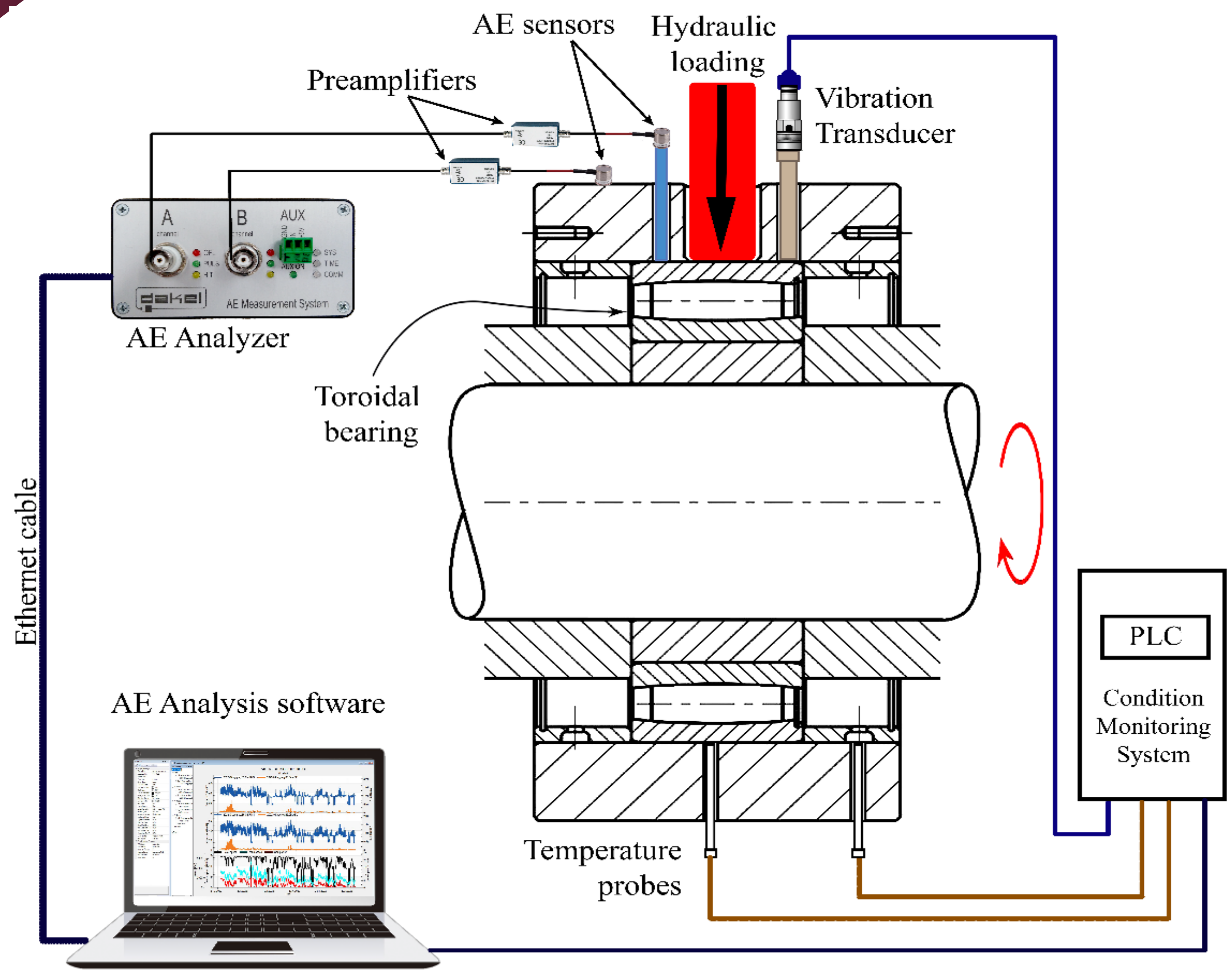
Scientific Questions and Hypotheses

Q2. How does the ability to tolerate angular and axial misalignments in toroidal bearings affect their performance and their life expectancy? And how such effect can be specified or even measured?

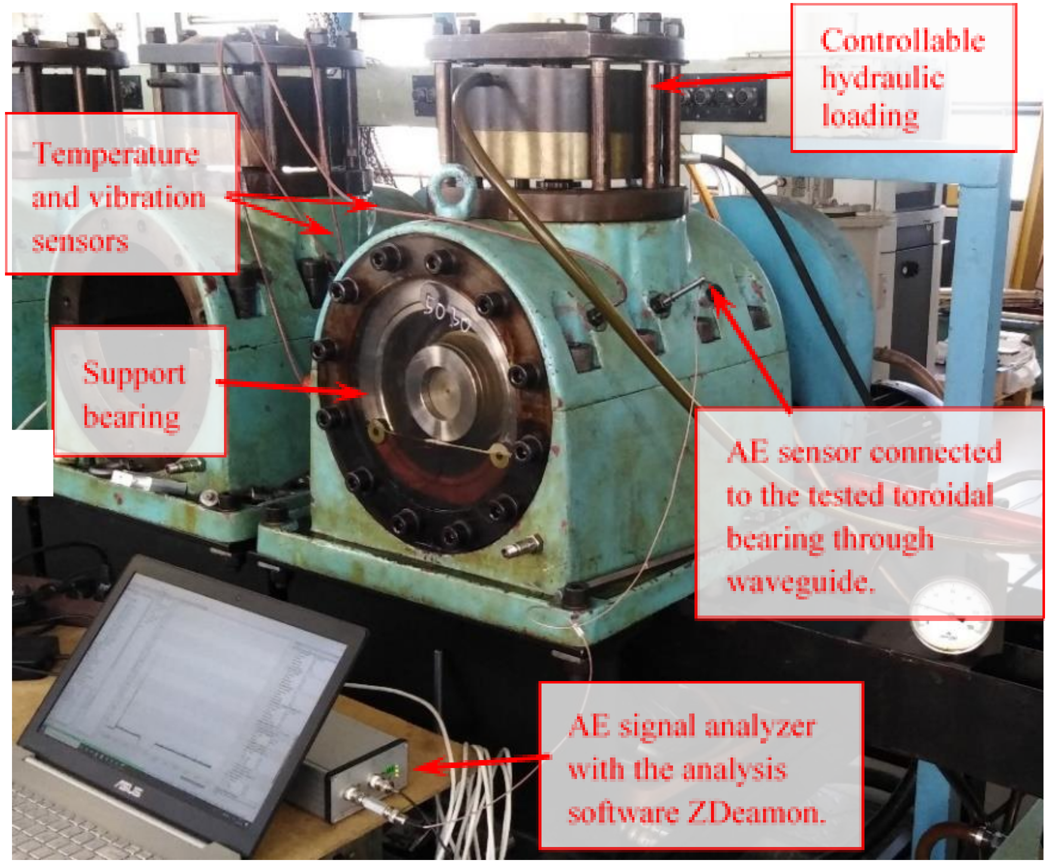
H2. Contact pressure is one of the main parameters controlling the propagation rate of surface initiated RCF cracks in bearing steel. The contact line (toroidal contour) between the rollers and the raceways in TRBs is longer than other types of bearings.
The ability to tolerate axial and angular misalignment should have a positive impact on the RCF and other characteristics of the bearing, since there is a wider (extended) contact surface between the rollers and the races.



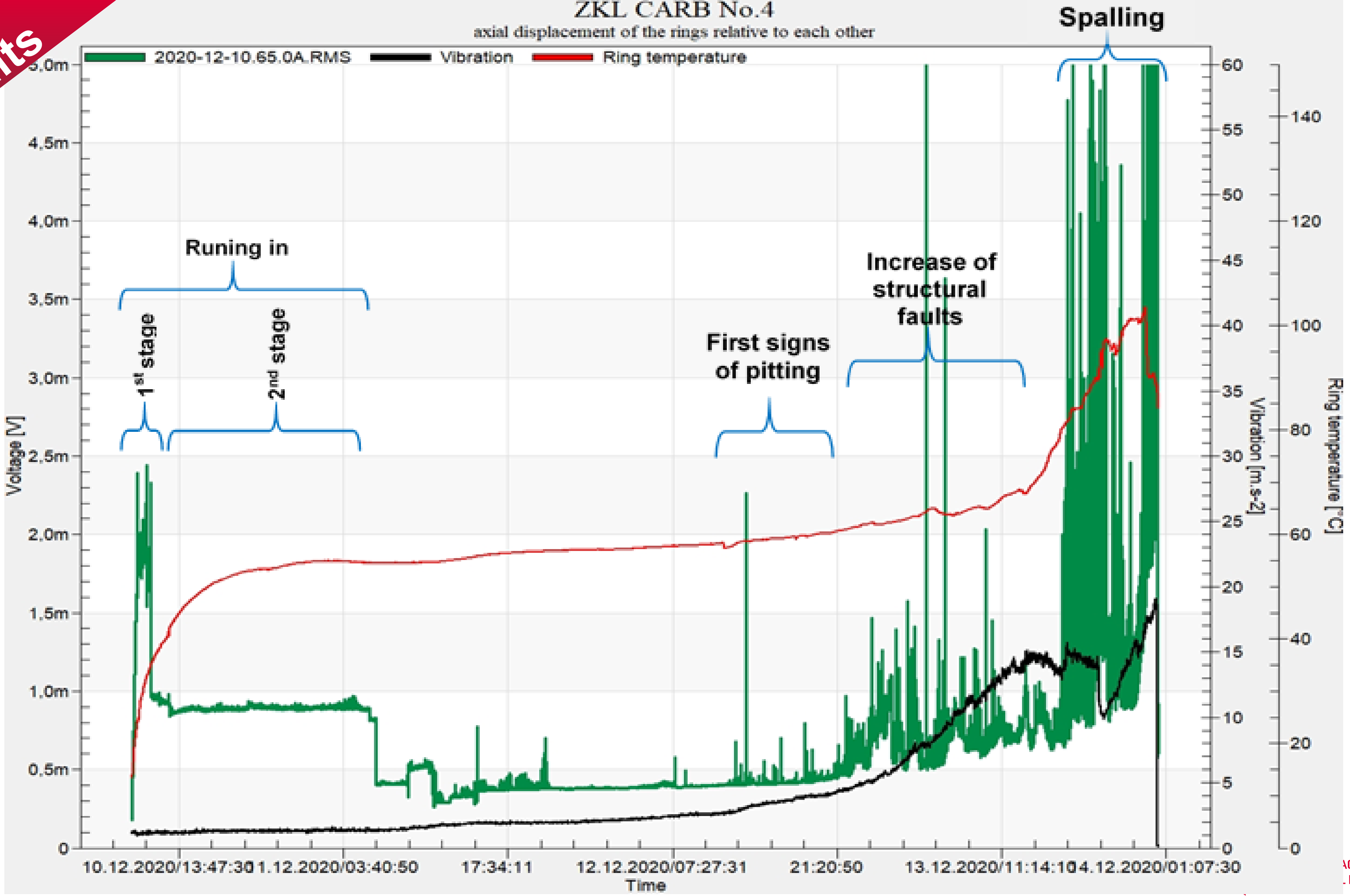
Material & Methods (laboratory)



Schematic drawing of the main part of the experiment.



Toroidal bearing testing setup in ZKL.

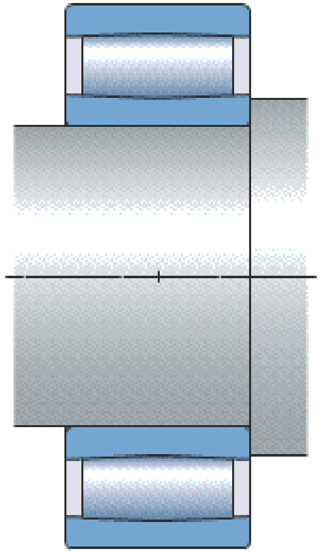

ZKL CARB No.4
axial displacement of the rings relative to each other
2020-12-10.65.0A.RMS
Vibration
Ring temperature
Spalling
Runing in
1st stage
2nd stage
First signs of pitting
Increase of structural faults
Voltage [V]
5,0m
4,5m
4,0m
3,5m
3,0m
2,5m
2,0m
1,5m
1,0m
0,5m
0
Vibration [m.s-2]
60
55
50
45
40
35
30
25
20
15
10
5
0
Ring temperature [°C]
140
120
100
80
60
40
20
0
10.12.2020/13:47:30
11.12.2020/03:40:50
17:34:11
12.12.2020/07:27:31
21:20:50
13.12.2020/11:14:10
14.12.2020/01:07:30
Time

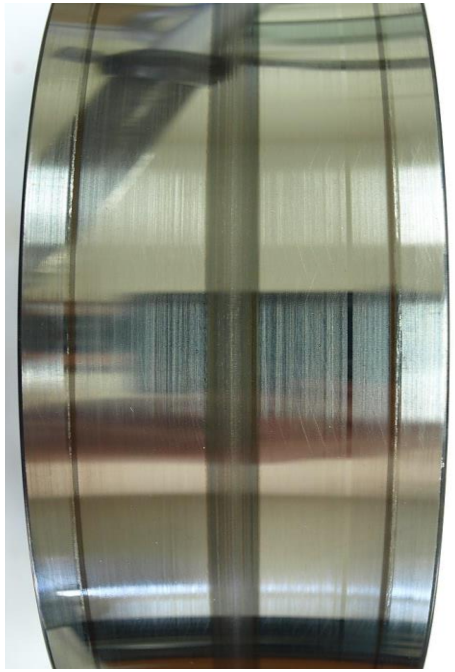
Results from the Lab. experiments

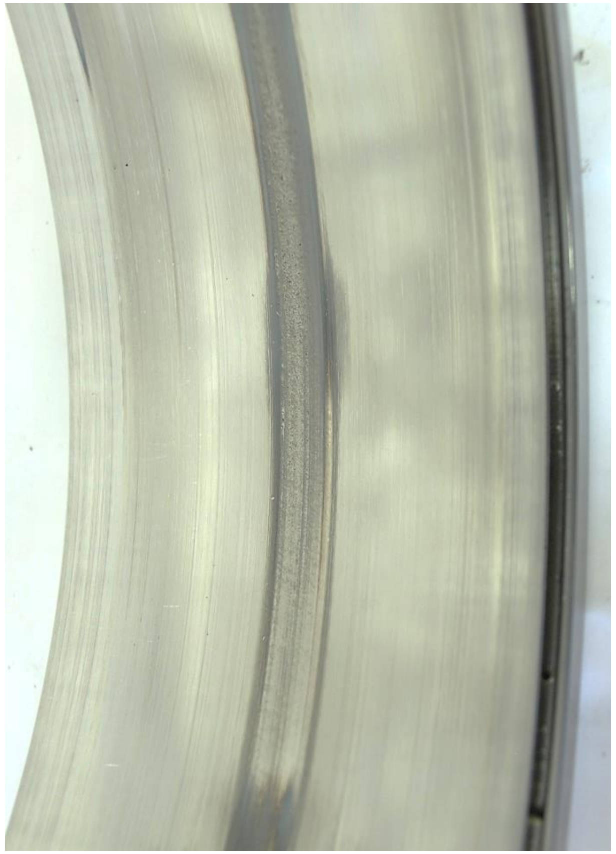
AE is more sensitive than vibration, and it can detect the defects in the bearing in early stage.

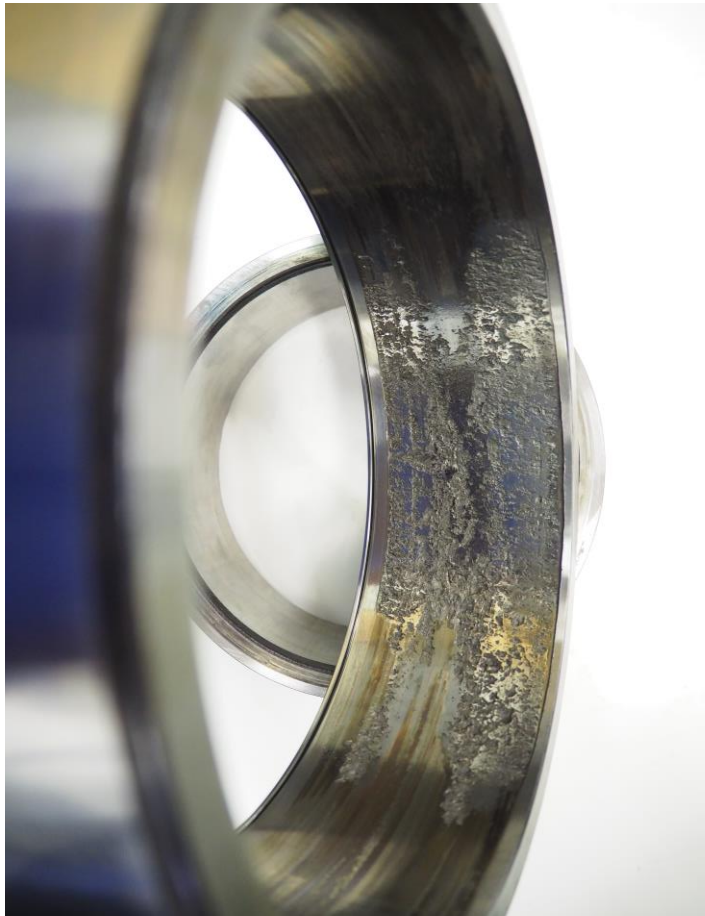
AE parameters were more sensitive to r.p.m than to loading.

Temperatures was less sensitive and less reliable for detection of RCF effects on the bearing.



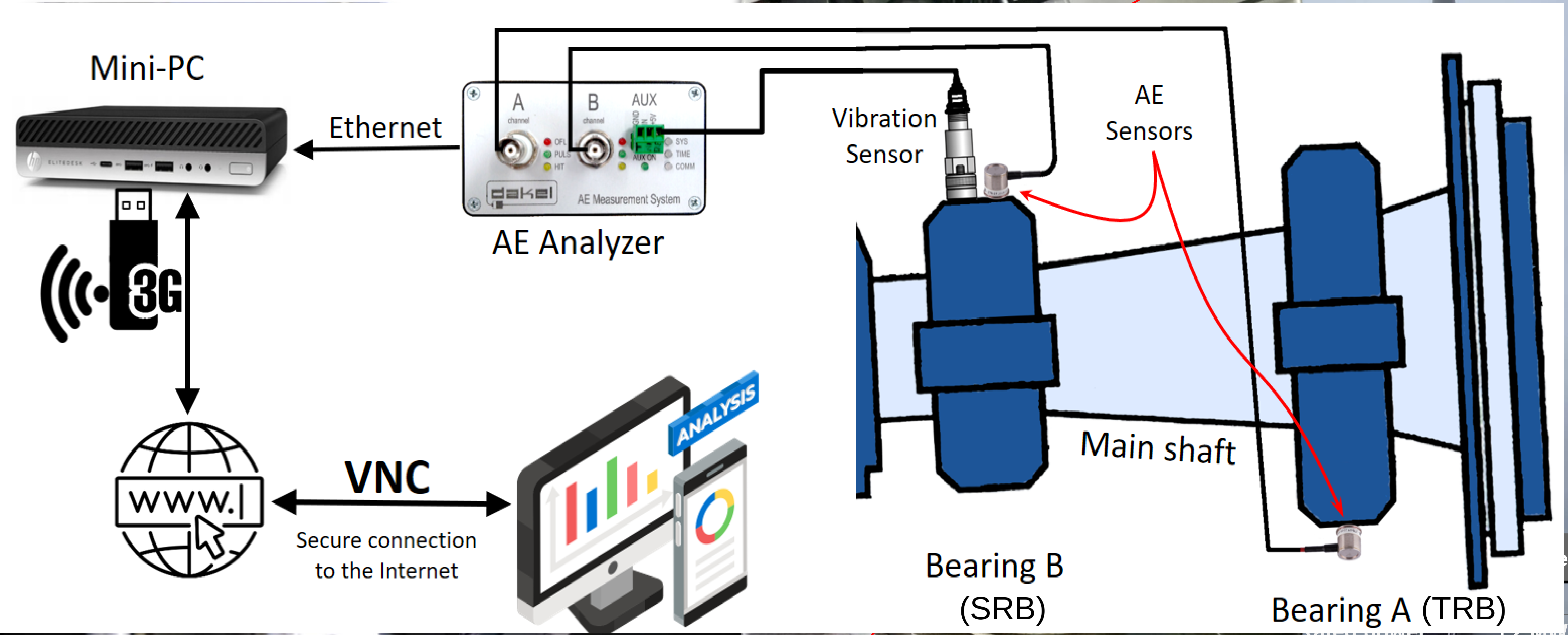






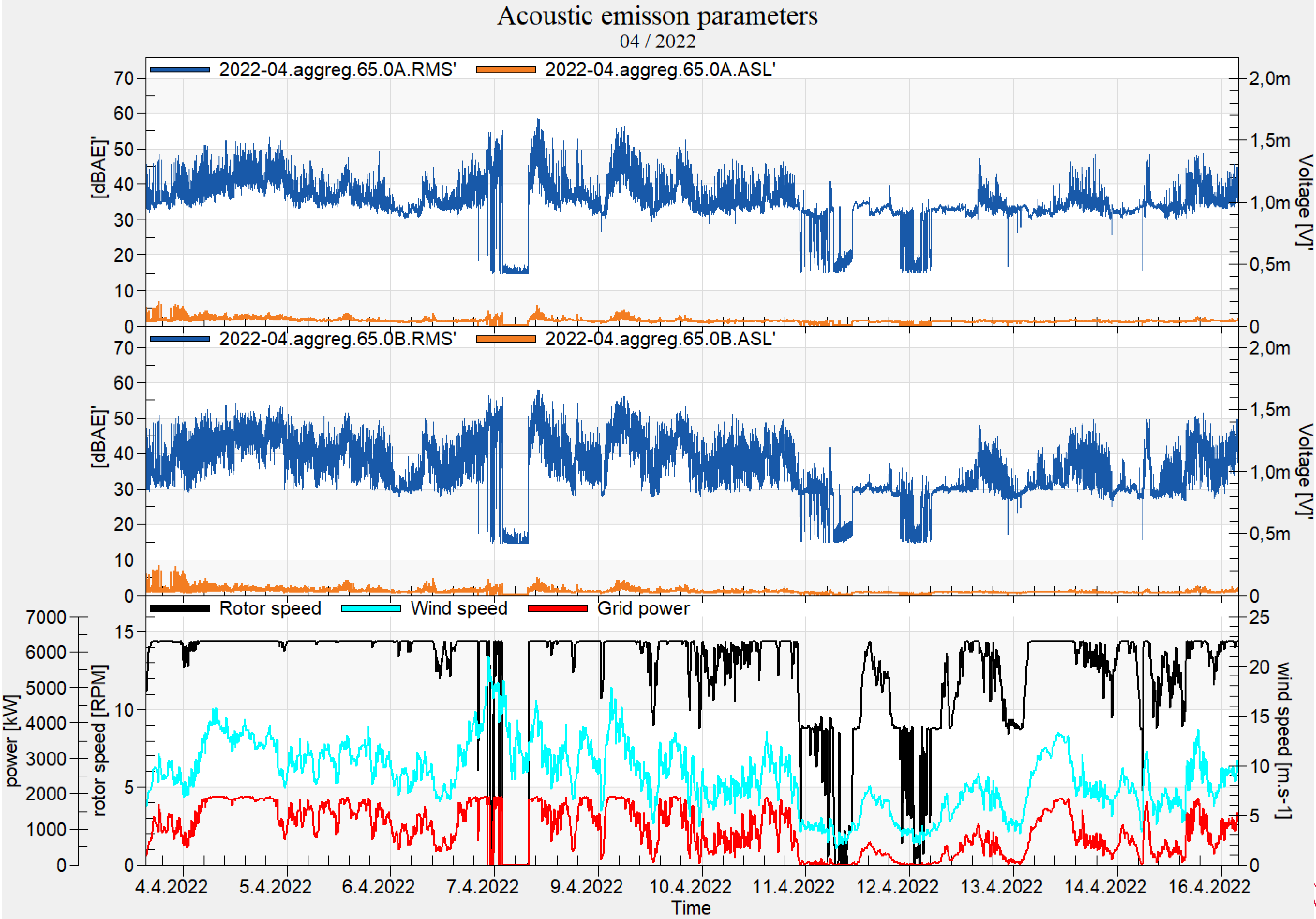
Material & Methods (In-Situ)

AE Analyzer



Constant electrical source from the grid

Rated power	2 MW
Rated wind speed	13.0 m/s
Rotor Diameter	90.0 m



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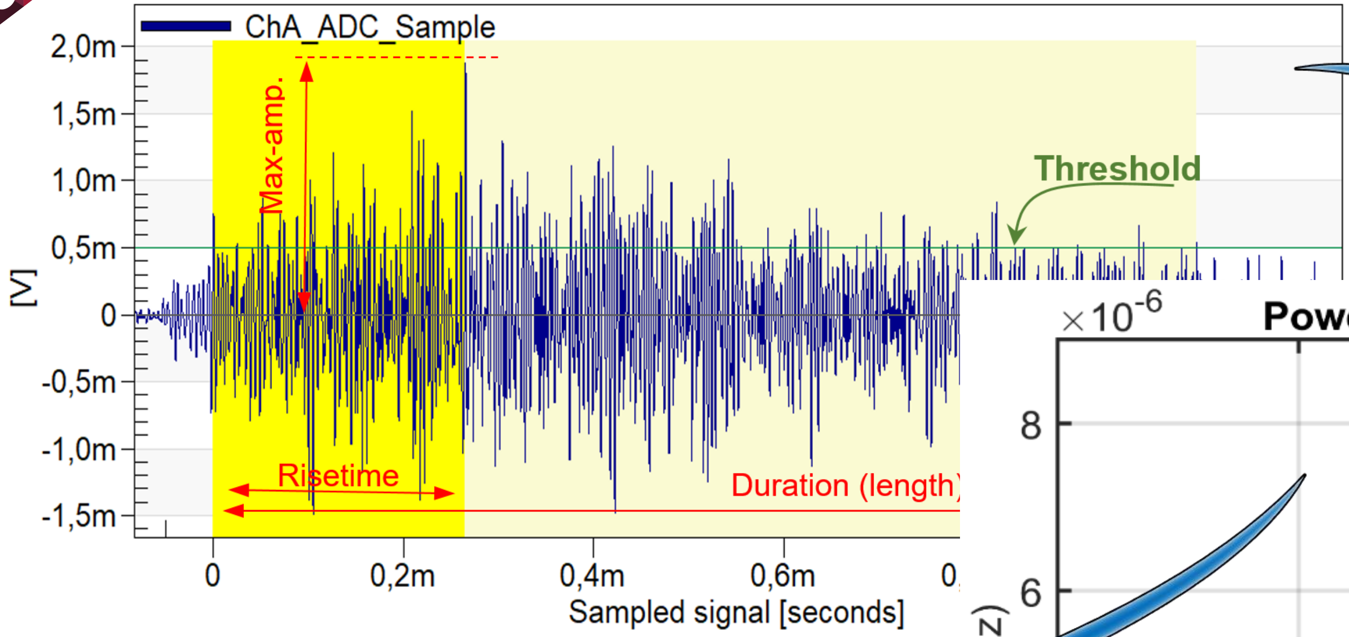
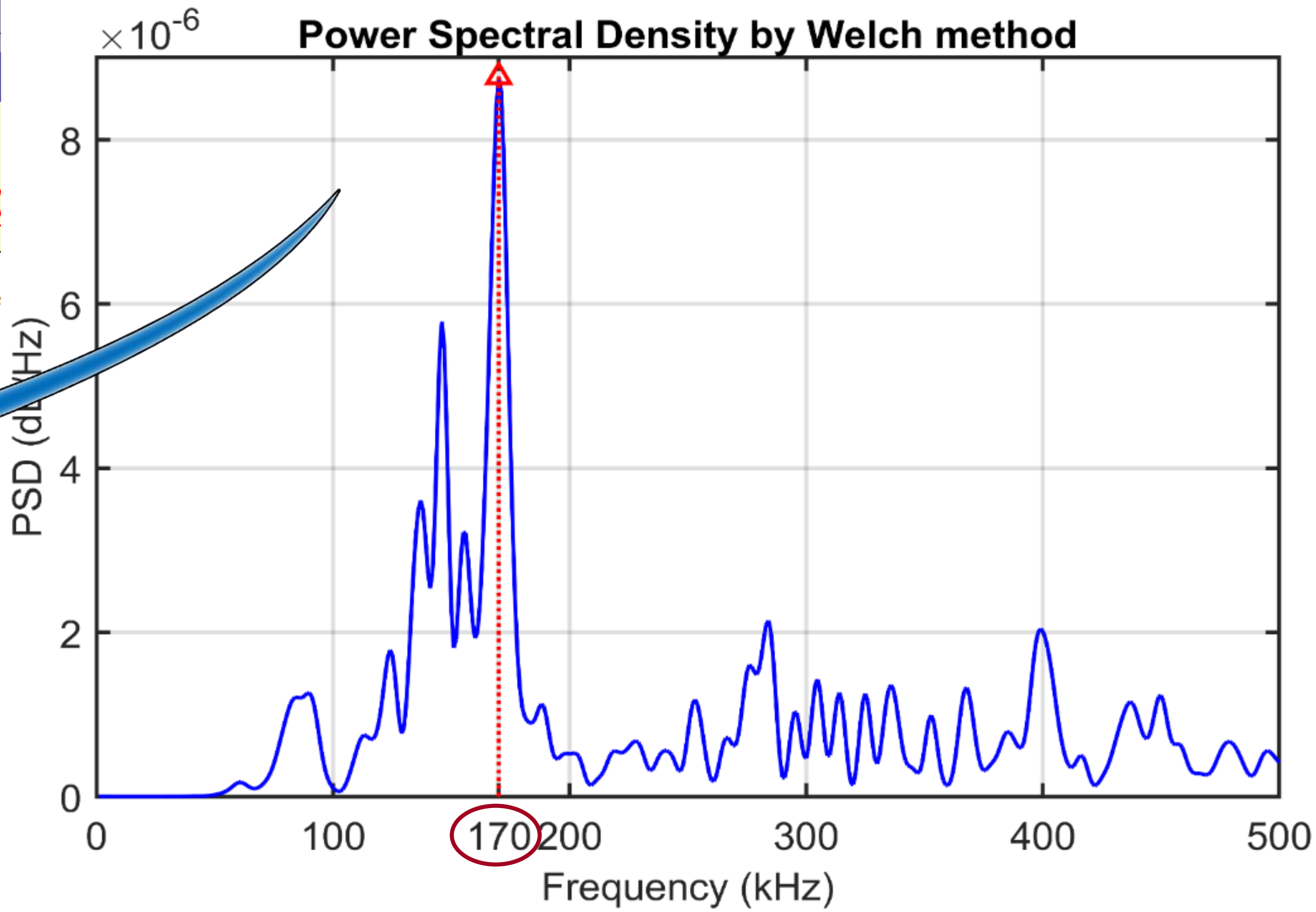
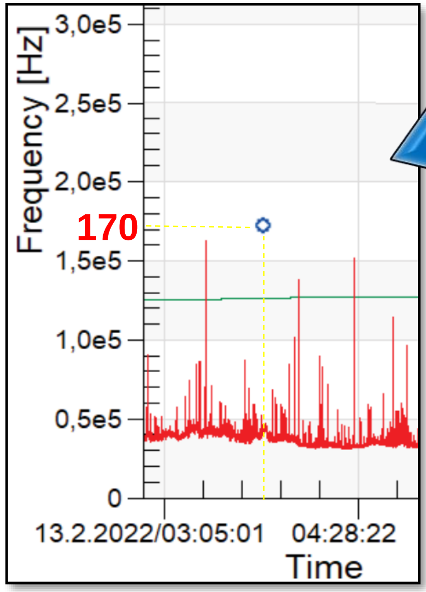
Results


ChA_ADC_Sample
2,0m
1,5m
1,0m
0,5m
0
-0,5m
-1,0m
-1,5m
[V]
Max-amp.
Threshold
Risetime
Duration (length)
0
0,2m
0,4m
0,6m
Sampled signal [seconds]

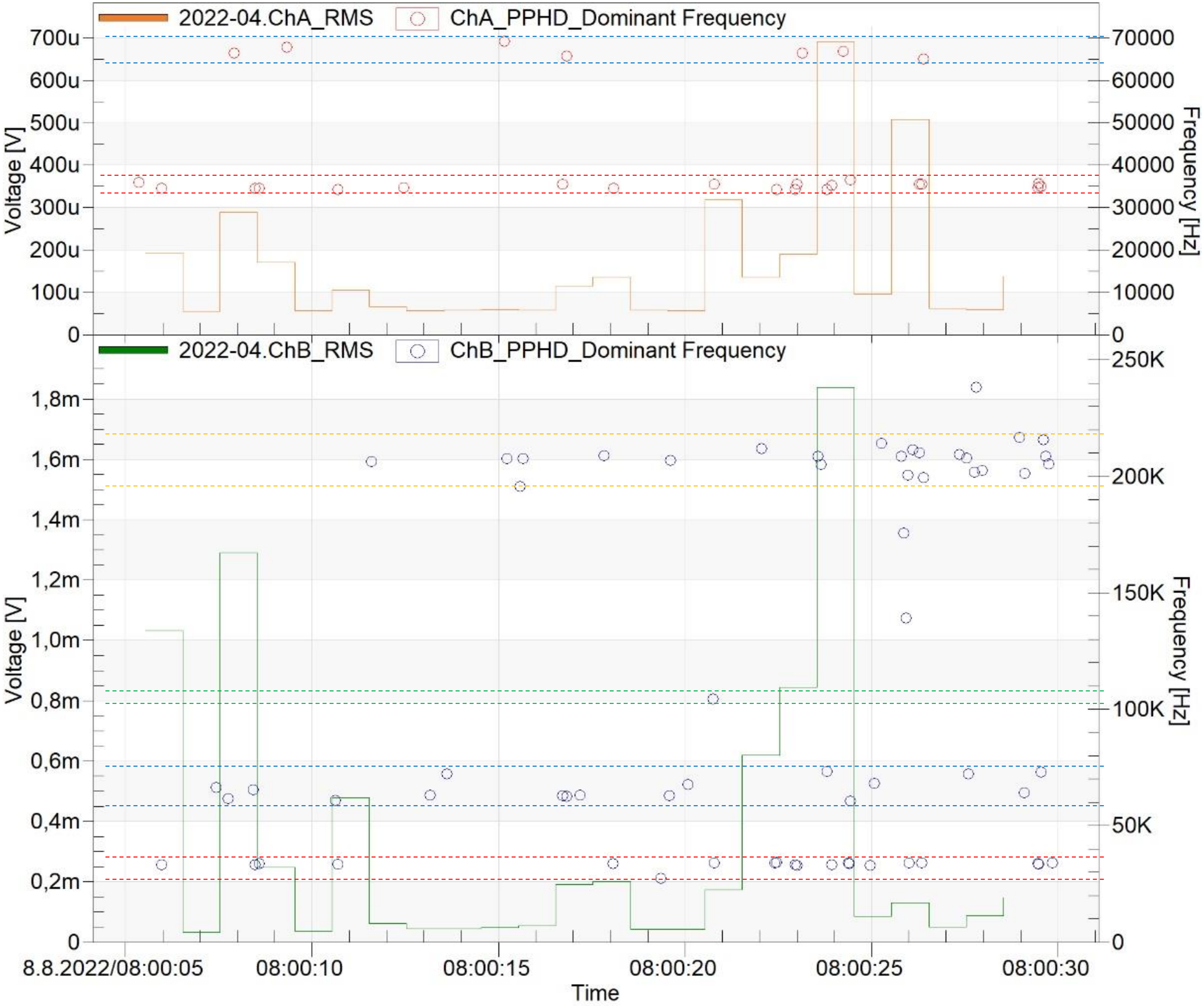

×10^-6
Power Spectral Density by Welch method
8
6
4
2
0
PSD (dB/Hz)
0
100
170
200
300
400
500
Frequency (kHz)


3,0e5
2,5e5
2,0e5
170
1,5e5
1,0e5
0,5e5
0
Frequency [Hz]
13.2.2022/03:05:01
04:28:22
Time

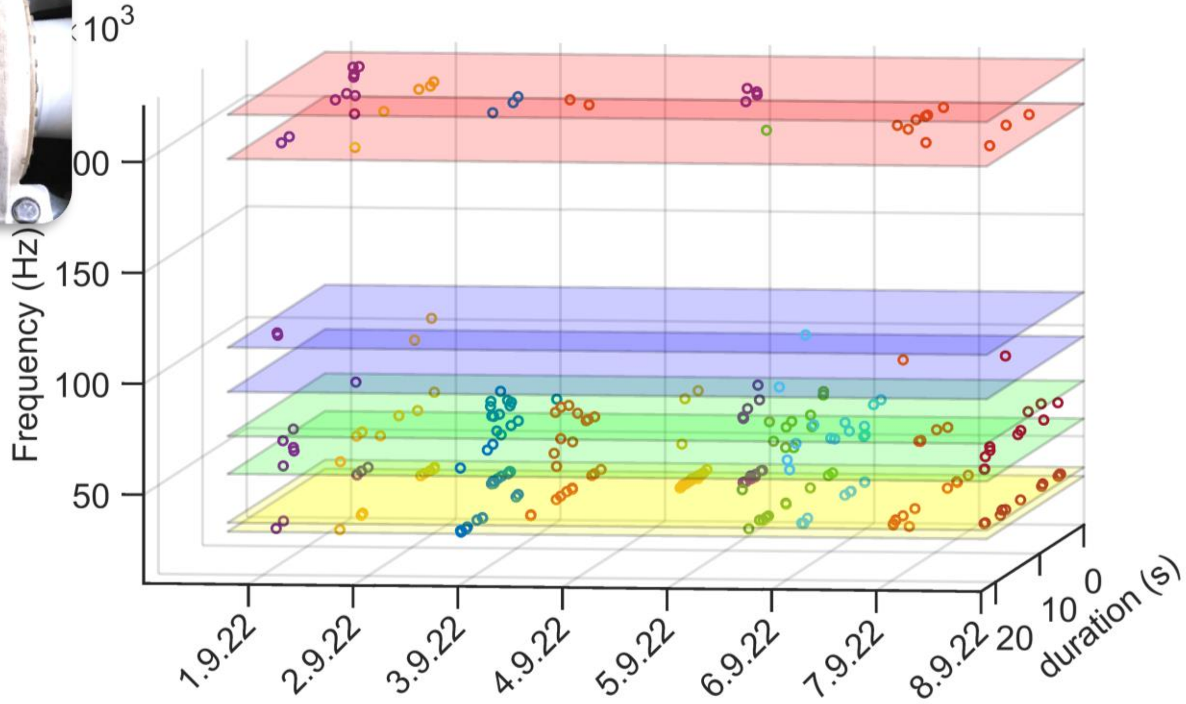
Results

Bearing A
TRB

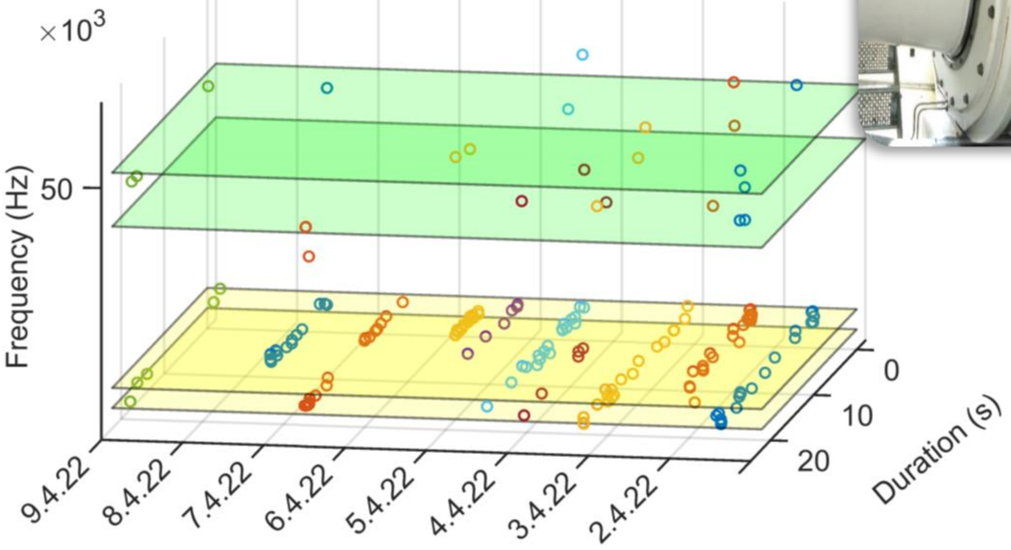
Bearing B
SRB



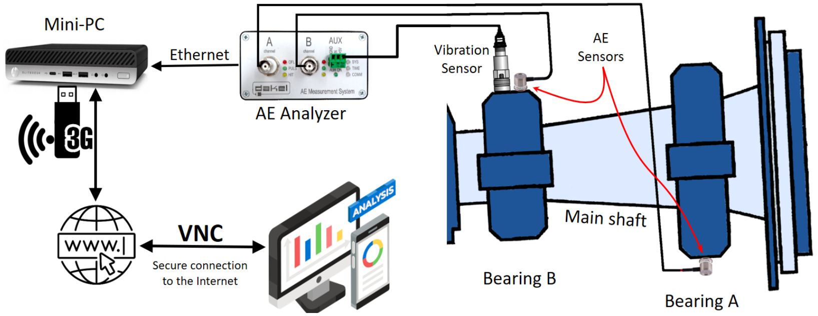
Results from the WT measurements



Bearing B
(Spherical)



Bearing A
(Toroidal)

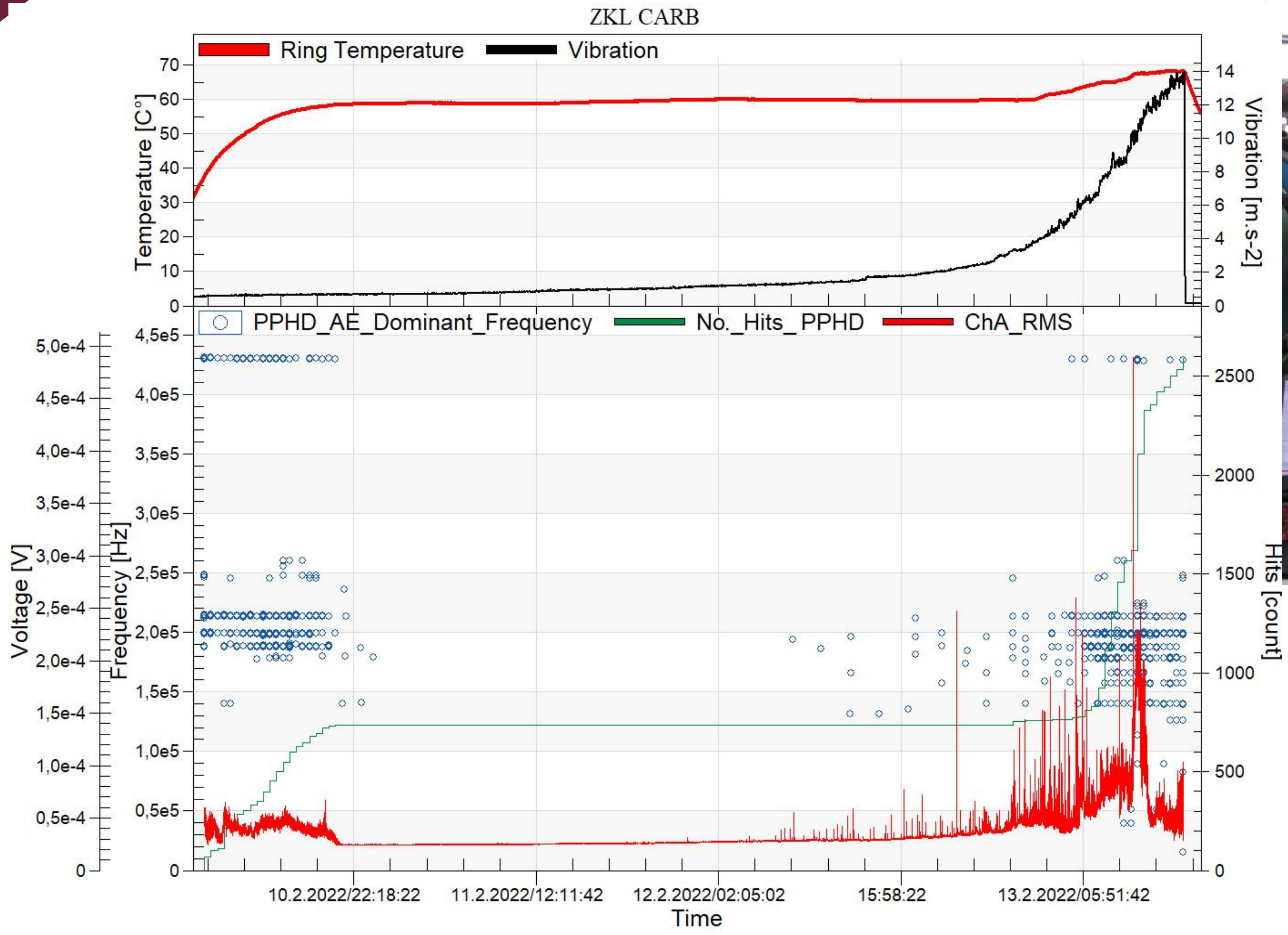


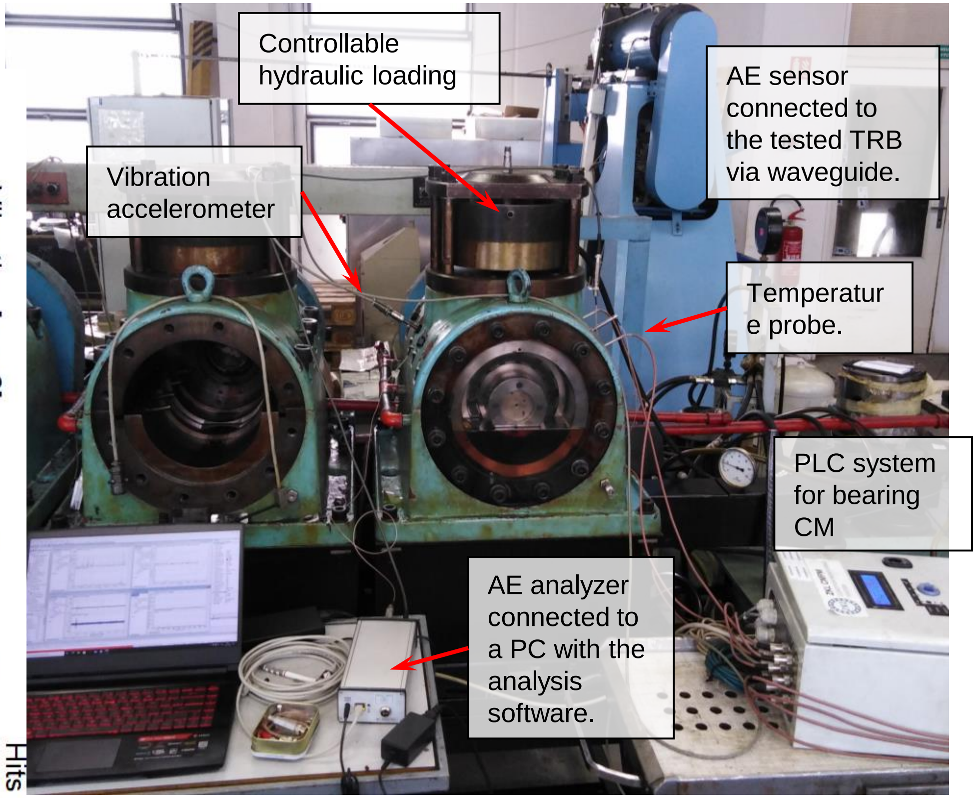
Results from the WT measurements

- The DFs of AE hits are grouped in well-defined bands. Those groups represent different types and sizes of defects.
- AE time-domain parameters, such as RMS, did not completely correspond to the events. Alone cannot be depended upon for the determination of the condition of a bearing.

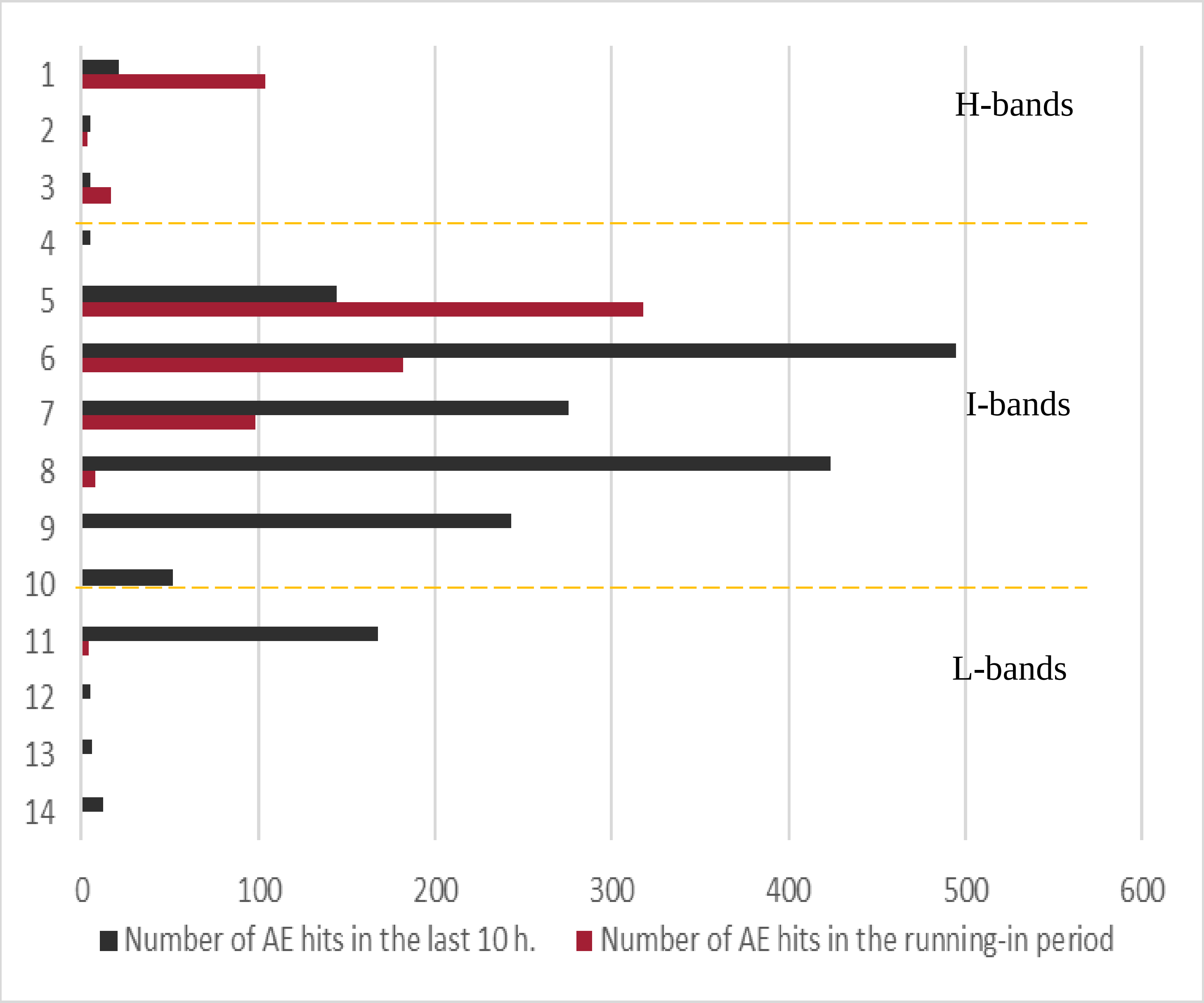
- The comparison between DF maps for both bearings, taken simultaneously, provided the basis for assessing the condition of the bearings.

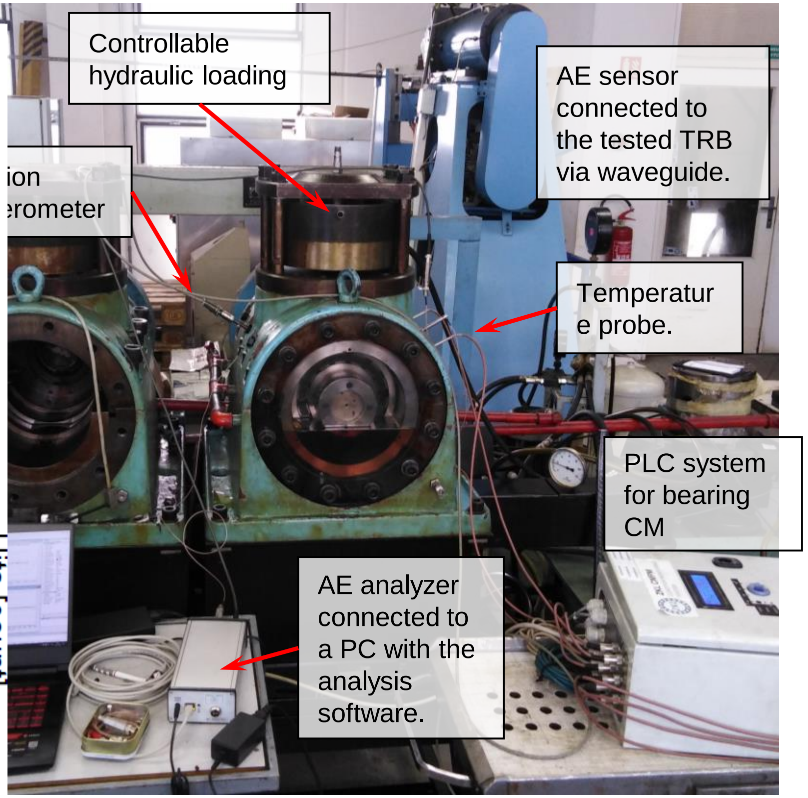
Results from the TRBs experiments





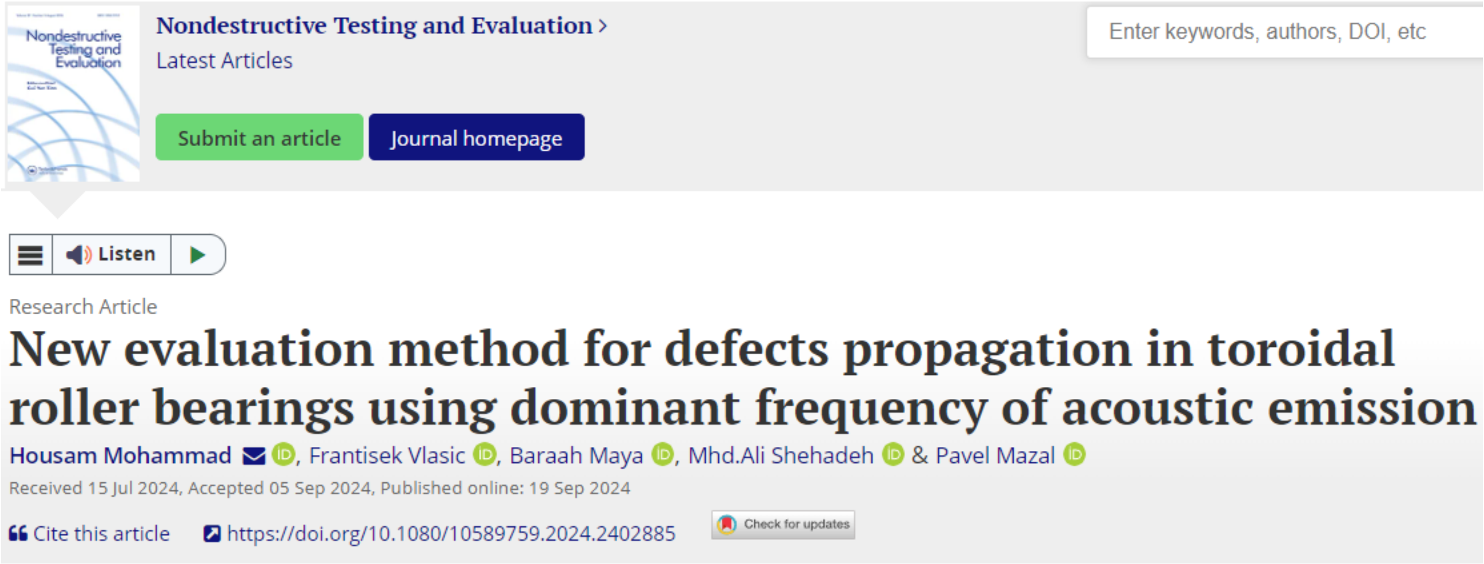
Results from the TRBs experiments





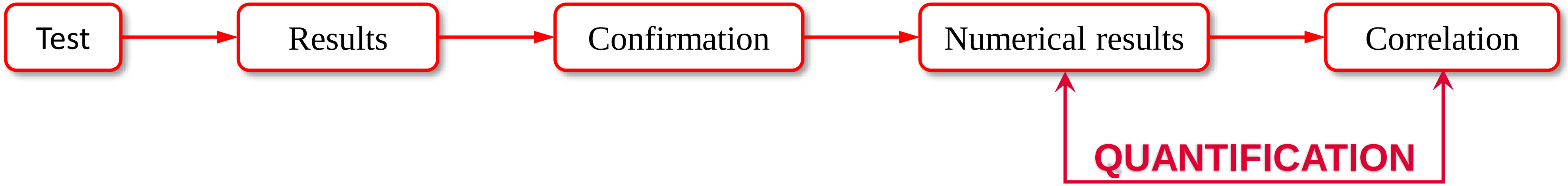
Results from the TRBs experiments

- DFs of AE hits were naturally distributed to different discrete frequency ranges
- During running-in, No. of AE hits with DFs in the H-band is significantly larger than the number of DFs during the defects formation period (concentrated in the highest band ~ 430 kHz).
- Intermediate frequency bands, the number of DFs was larger than the other two bands. It is a combination of AE hits from both the running-in and the defect formation periods.
- No. of AE hits with DFs in the L-bands was low. Entirely from the defect formation in the last 12 hours



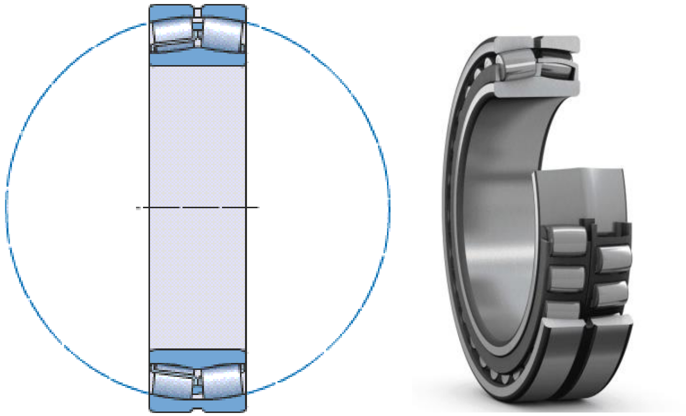
Conclusion

- The main output of this work is a method by which we can **Quantify** the Condition Monitoring of bearings using AE frequency-domain parameter (DF).

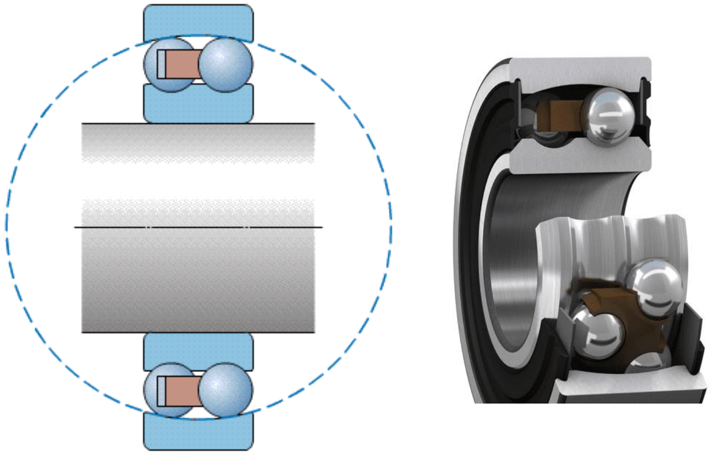


- The **resulting number** of Dominant Frequencies of AE hits can be used by codes in a programming languages or in a Machine Learning model.
- A statistical representation of the results was provided.
- We established a reliable remote monitoring system for valuable assets.

Future Steps - Extending the Results



Spherical roller bearings



Self-aligning ball bearings

Tapered Roller Bearings
for Wind Turbines

Participation in design of new AE sensor

Development of a Preventive CM model for WT bearings using AE

Photos courtesy of skf.com

Publication Activities

- Active Monitoring of RCF in Toroidal Bearings using Acoustic Emission. Lecture Notes in Mechanical Engineering. **IF: 0.7**
- Using acoustic emission for condition monitoring of the main shaft bearings in 4-point suspension wind turbine drivetrains. Nondestructive Testing and Evaluation. **IF: 3**
- New Evaluation Method for Defects Propagation Using Dominant Frequency of Acoustic Emission Hits in Toroidal Bearings. Nondestructive Testing and Evaluation. **IF: 3**
- New Method for Condition Monitoring of Slow-Speed Bearings Using Peak Frequency of Acoustic Emission Hits. British Institute for NDT (in process). **IF: 1**

➢ One **Peer-review** activity for the journal Nondestructive Testing and Evaluation.

Conferences & Cooperation

The 2nd European NDT & CM Days in Prague

5th International Conference on CM and Diagnostics, Finland

Regular participant in ČNDT activities and Defektoskopie

The R&D department in ZKL a.s.

Technology Agency of the Czech Republic (TAČR).

The Czech private AE producer of AE systems - DAKEL

Multiple funding research programs by VUT CZ

Thank you for your attention

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Answers to the oponent’s questions:

Q1. I assume that Mr. Mahammad carried out the essential parts of the research work himself. For me, however, his part and also the parts that existed before his work are not entirely clear.

Answer:

I confirm that the whole essential parts of the research were carried out completely by myself.

However, I have been supported by the experience of my supervisor doc. Pavel Mazal, and my colleague dr. Frantisek Vlasic, who are experts in the field of AE.

I have been supported by the head of the R&D section in ZKL, Eng. Nemecek, and other workers there.

Answers to the oponent’s questions:

Q2. What is the difference between broad band sensors and resonate sensors, and which are the advantages and disadvantages of this different sensor types?.

A2.

<u>Broadband Sensors:</u>

Frequency Range: Detect a wide range of frequencies.

Advantages: Can capture a broad spectrum of acoustic emissions, making them versatile for detecting various types of faults.

Disadvantages: Less sensitive to specific frequency ranges, which may result in lower detection precision for certain faults.

<u>Resonant Sensors:</u>

Frequency Range: Tuned to a specific frequency, amplifying signals around that range.

Advantages: Highly sensitive to emissions within their frequency range, making them excellent for detecting specific types of events.

Disadvantages: Limited frequency range, which makes them less suitable for detecting faults outside their resonance band.

Therefore, **Broadband sensors** offer versatility and a wide detection range but may lack sensitivity in certain frequencies. **Resonant sensors** provide higher sensitivity in a narrow range but are limited in detecting events outside that range.

Answers to the oponent’s questions:

Q3. What are the measures used to **filter out noise** in acoustic emission measurements?

A3.

1. **Thresholding:** Set a minimum amplitude level to ignore low-level noise and capture only significant AE signals.
2. **Bandpass Filtering:** Use filters to allow only signals within a specific frequency range, eliminating high- and low-frequency noise.
3. **Waveform Analysis:** Analyze the shape of the AE signal to distinguish between noise and true AE events.
4. **Duration Counting:** Ignore brief, non-repetitive signals typically associated with noise by focusing on consistent AE events.

- **Signal Averaging:** Average multiple signals to reduce random noise and emphasize genuine AE events.
- **Sensor Placement Optimization:** Position sensors away from external noise sources and vibrations to reduce noise interference.

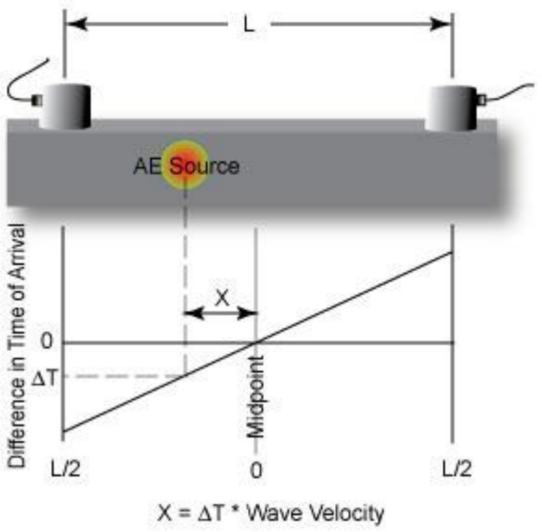
These techniques help ensure the accuracy and reliability of AE measurements by minimizing noise interference

Answers to the oponent’s questions:

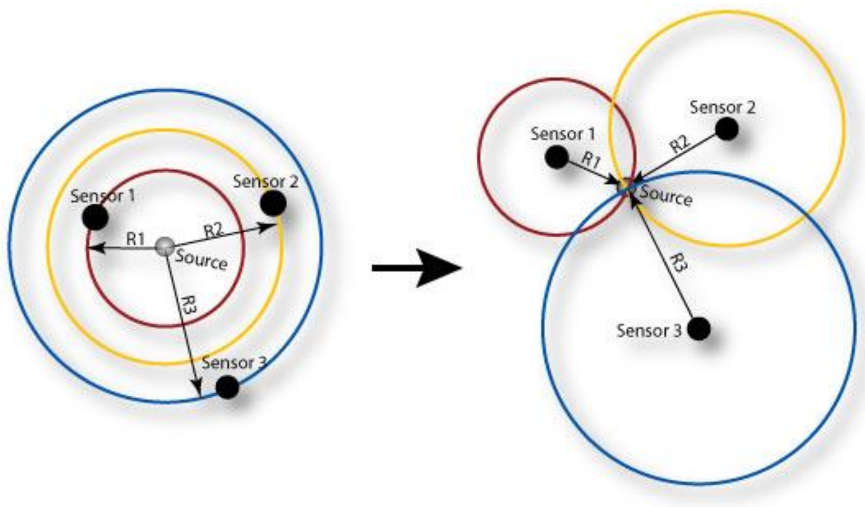
Q4. Explain briefly what is source location in AE measurement and how it is done?

A4.

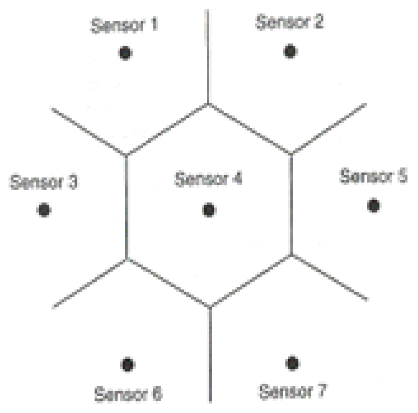
- **Sensor Array Placement:** Multiple AE sensors are strategically placed around the material or structure.
- **Time of Arrival (TOA):** The difference in the arrival times of the AE signal at each sensor is measured.
- **Triangulation:** Using the TOA differences, the location of the AE source is calculated through triangulation, similar to how GPS works.



Linear Location Technique



Point Location



Zonal Location

Answers to the oponent’s questions:

- **Q5. Physical origin of AE**
- **A5.**
  - **Crack Formation and Growth:** As cracks initiate or propagate, they release elastic waves.
  - **Plastic Deformation:** Dislocations and movements of atoms in stressed materials generate AE.
  - **Friction and Wear:** Contact between surfaces, such as in bearings, emits AE signals.
  - Corrosion, Fatigue, Chemical, and mechanical processes also release energy as AE signals.
  - **Phase Transformations:** Changes in the material’s structure (e.g., solid to liquid) can generate AE.

The definition of AE by ISO 12716:2001:

Class of phenomena whereby **transient elastic** waves are generated by the rapid release of energy from localized sources within a material.

It is included in ISO/ TC 135 / SC 9 , which is the category of the Non-Destructive Testing (NDT) methods.

Answers to the oponent’s questions:

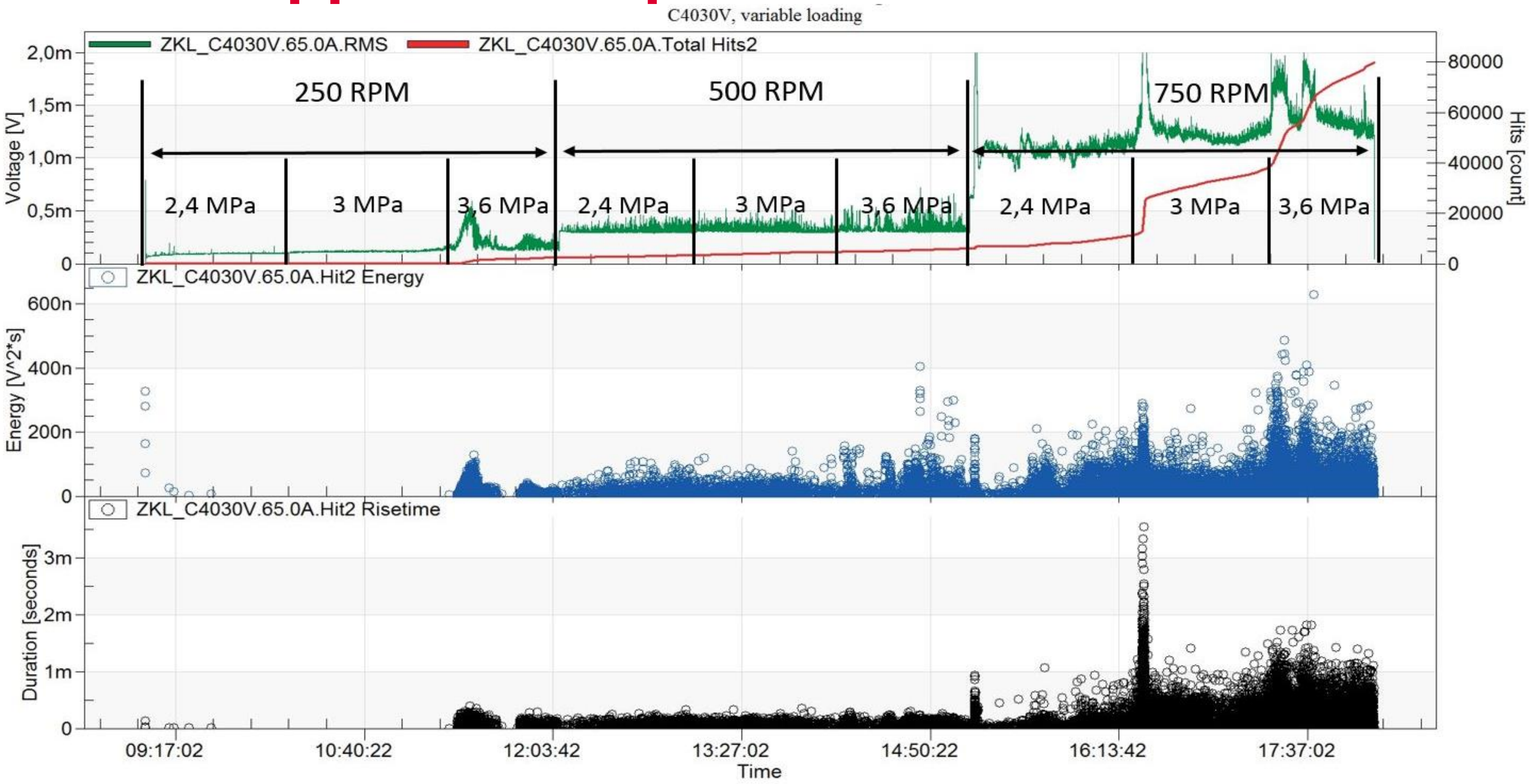
Q1. Have you considered introducing feature selection procedures for the selection of the most relevant subset of features of AE signals?

A1.

Well, feature selection is an important aspect, and although we did not apply formal feature selection techniques in the context of ML for this work, we carefully selected the most relevant AE parameters manually. These parameters were chosen based on their known relevance to the detection and analysis of rolling contact fatigue in bearings. However, we do recognize the value of automated feature selection techniques, particularly in machine learning models, to improve accuracy and reduce redundancy. In future work, we plan to explore these methods to identify the most significant features from a broader set of AE signals, enhancing the robustness and efficiency of our analysis.

Answers to the opponent‘s questions:

The relationship between AE parameters (voltage, energy, and duration) with the rotation speed, and loading of the toroidal bearing.



	Stage 1			Stage 2			Stage 3		
Speed (r.p.m)	250			500			750		
Loads (MPa)	2.4	3	3.6	2.4	3	3.6	2.4	3	3.6
Duration (hour)	1	1	1	0.5	1	1	0.5	1	1

Answers to the oponent’s questions:

Q2. What is your insight on the introduction of established ML methods in the study? How would the introduction of established ML methods affect the diagnostic ability to detect defects on the rolling surfaces of bearings?

A2.

Introducing established ML methods, such as KNN, Random Forests, or Neural Networks, into our study would surely enhance the diagnostic ability of AE testing for detecting defects on rolling surfaces. While we manually selected AE parameters in this work based on their known relevance, ML could automate feature selection and identify patterns that may not be obvious through manual methods. In future research, we aim to integrate machine learning techniques, which could provide a more comprehensive and data-driven approach to diagnosing bearing defects. This would ultimately increase the efficiency and precision of our diagnostic process.

Machine learning models, such as **convolutional neural networks (CNNs)**, could help to recognize complex patterns in AE that are strongly correlated with specific defect types. As a result, the introduction of ML could significantly enhance **early fault detection**, **diagnostic accuracy**, and the ability to differentiate between various types of defects (e.g., spalling, pitting).