Operating Conditions of a Main Bearing Contact in a Commercial Wind Turbine

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Outline

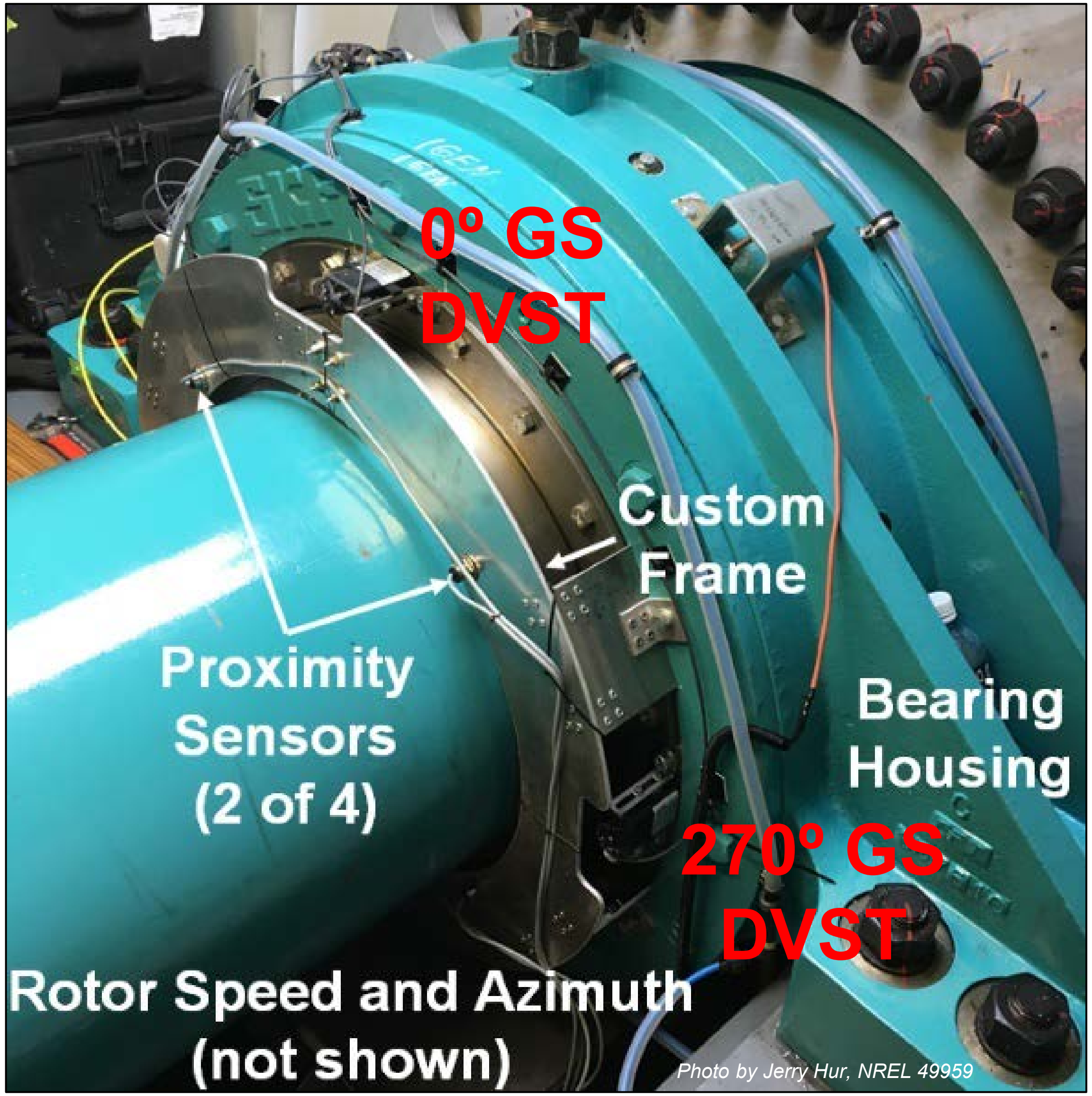
- Motivation and Background
- Instrumentations
- Testing Turbine
- Modelling Tools
- Results: Loads, Motions, and Metal-Metal Contact
- Conclusions

Motivations and Background

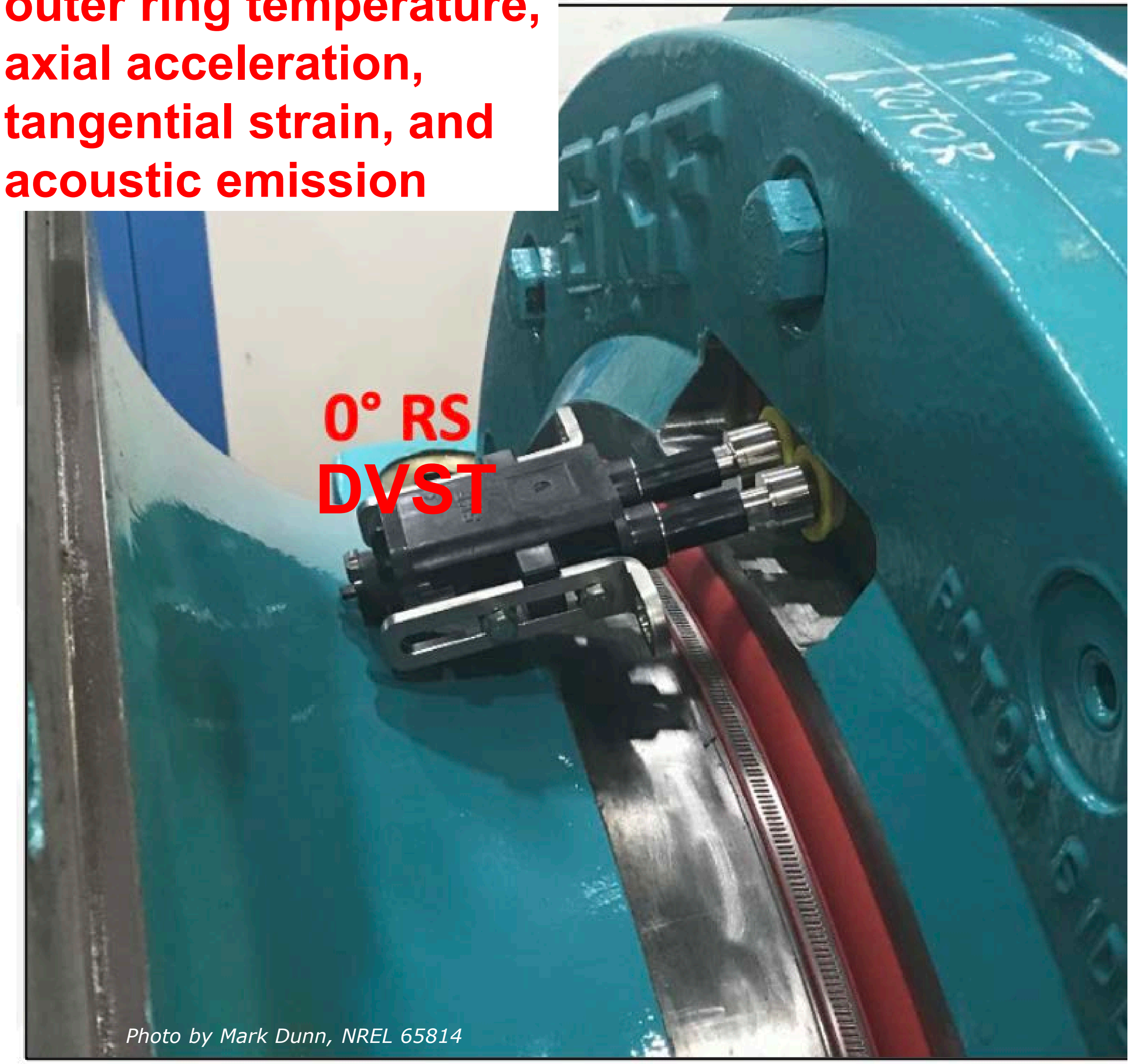
- Premature failures of main bearings observed in some populations with failure rates up to 20%–30% in 6–10 years.
- Removal and replacement of a main bearing typically requires appreciable maintenance costs and downtime.
- Key question – **Why do some main bearings fail prematurely?**
  1. *Does relative axial motion between bearing rings damage the main bearing?*
  2. *Does the bearing cage slip during operation?*
  3. *Is there metal-to-metal contact between rollers and raceways?*
- SKF provided design verification support tool (DVST) sensors, which were installed in a GE 1.5-megawatt SLE turbine at NREL.
- We examine the axial and sliding motion, loads, and lubrication of the main bearing, as correlated to turbine operating conditions.

Photo by Dennis Schroeder, NREL 21864

DVST measurements: outer ring temperature, axial acceleration, tangential strain, and acoustic emission



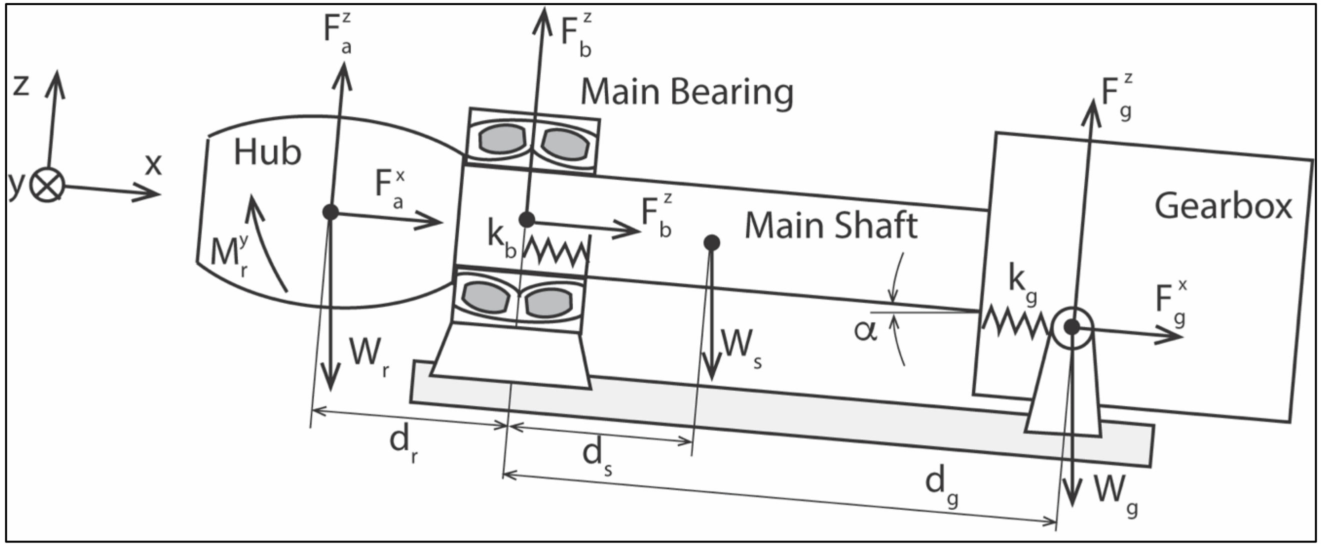
Generator-side (GS)



Rotor-side (RS)

Analytic Model for Global Loads and Motions

- Aerodynamic forces and moments as the input
- Linear estimations for component stiffnesses
- Bearing stiffness properties needed for motion estimations



Gearbox coupling force, vertical

$$F_g^z = \frac{M_r^y(t) + F_a^z(t)d_r - (W_r d_r - W_s d_s - W_g d_g)\cos\alpha}{d_g}$$

Main bearing force, vertical

$$F_b^z(t) = -F_a^z(t) - F_g^z(t) + (W_r + W_s + W_g)\cos\alpha$$

Axial roller/raceway motion

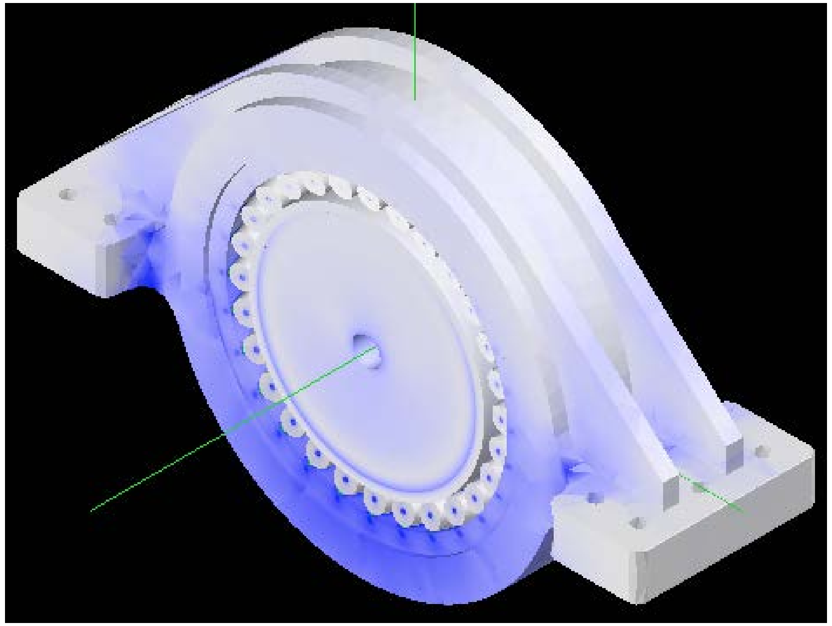
$$x(t) + x_r = \frac{F_a^x(t) + (W_r + W_s + W_g)\sin\alpha}{k_b^x + 2k_g^x}$$

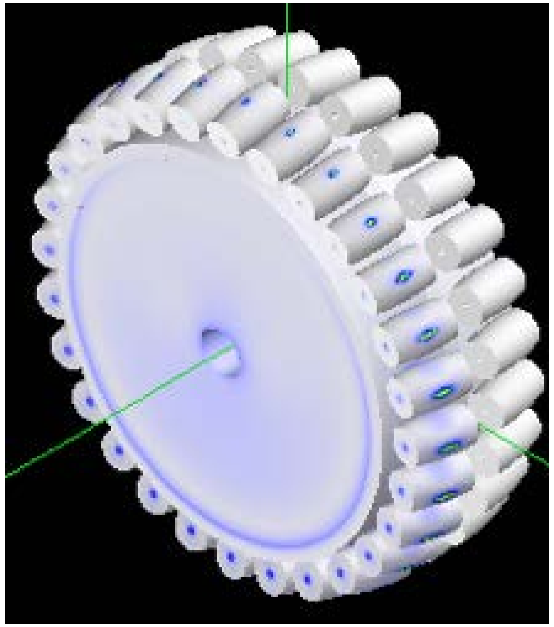
x_r – resting position under gravity

Source: Bergua Archeli, R. et al. 2021. Up-Tower Investigation of Main Bearing Cage Slip and Loads. NREL/TP-5000-81240. https://www.nrel.gov/docs/fy22osti/81240.pdf.

Computational Model for Internal Loads and Stresses

- Finite element/contact mechanics model computes load distribution, stresses, and strain
- Bearing clearances, roller, and raceway geometries included
- Bearing housing modelled as a flexible part

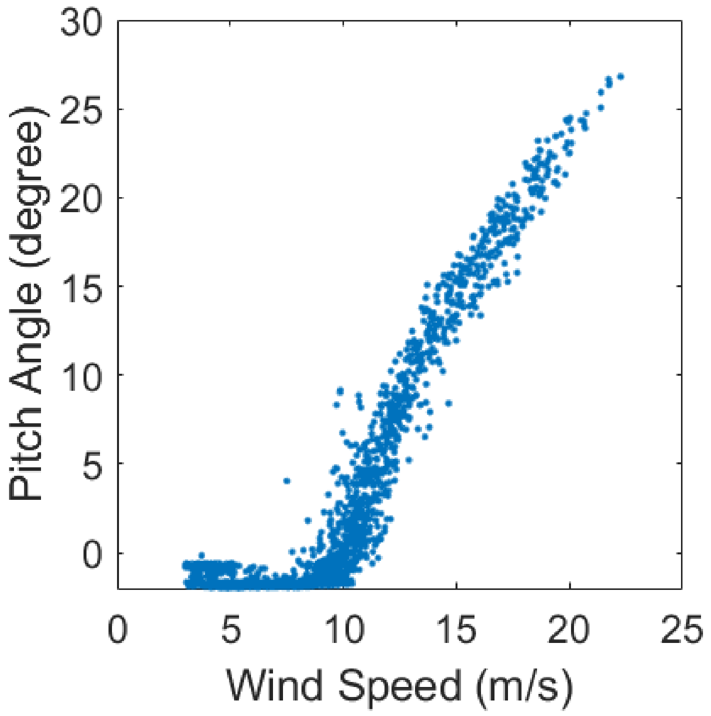


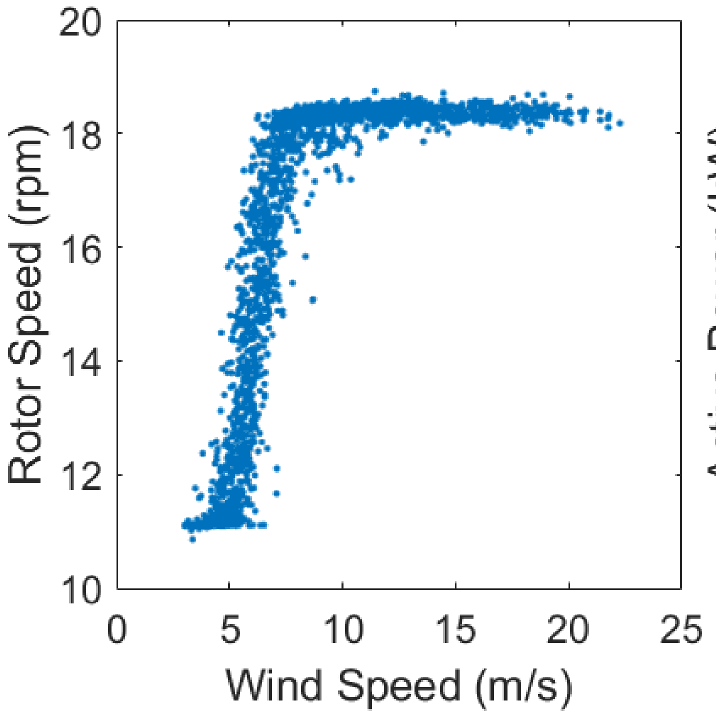


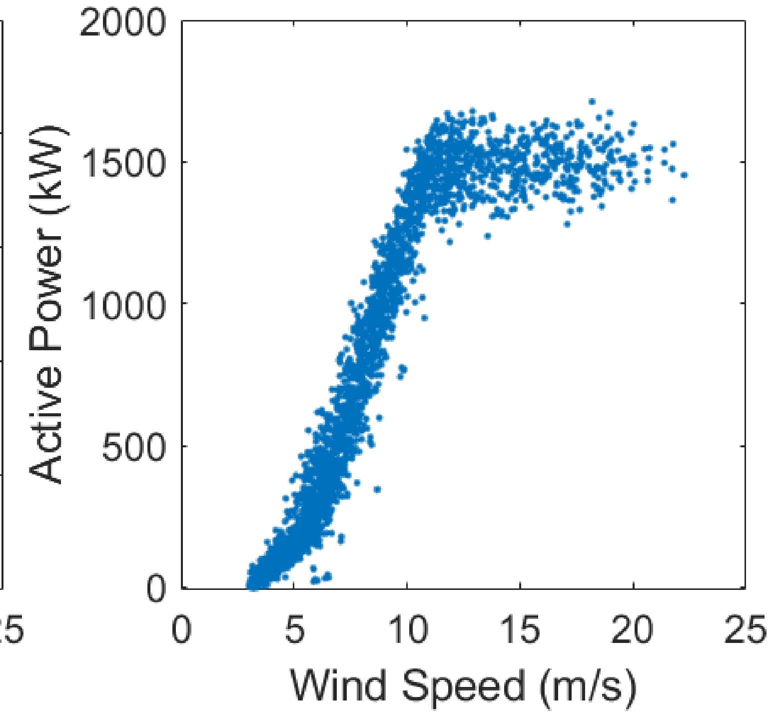
Source: Bergua Archeli, R. et al. 2021. Up-Tower Investigation of Main Bearing Cage Slip and Loads. NREL/TP-5000-81240. https://www.nrel.gov/docs/fy22osti/81240.pdf.

Turbine Operational Parameters

- Full operating envelope from the cut-in (3 meters per second (m/s)) to cut-out (25 m/s) wind speed
- Pitch angle remains near zero below 11 m/s and increases to 27° at the highest wind speeds
- Rotor speed rises from 11 revolutions per minute (rpm) at cut-in and reaches 18.4 rpm near 7 m/s wind
- Active power varies ±20% above rated wind speed.

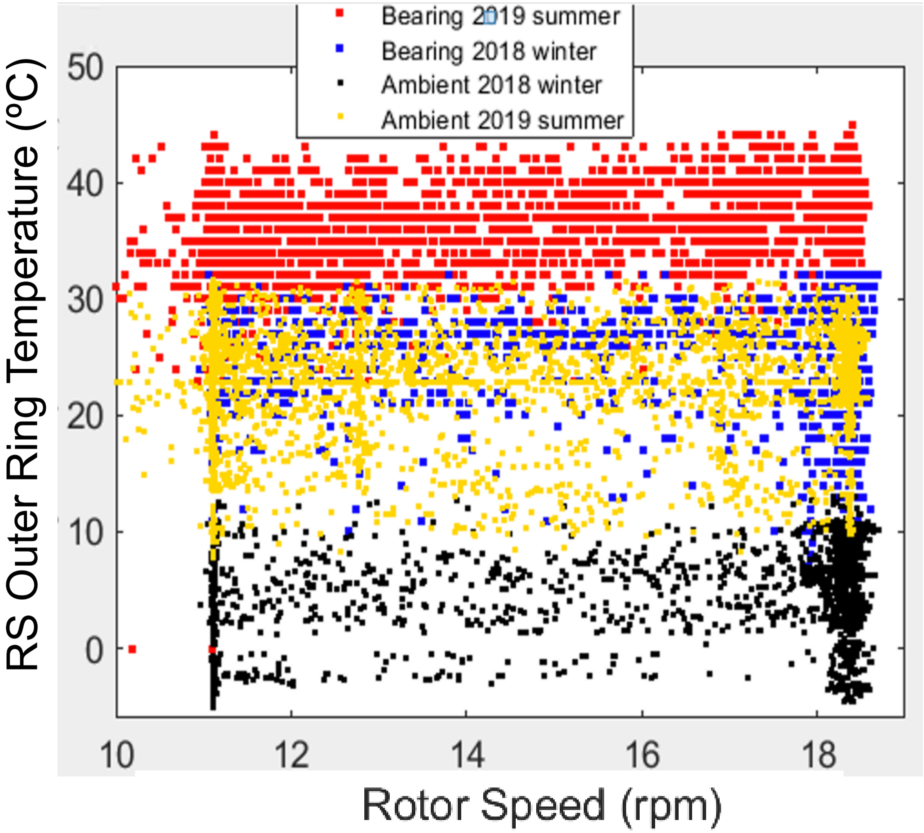






Source: Guo, Y. et al. 2022. Acoustic Emission Measurement of a Wind Turbine Main Bearing. NREL/TP-5000-83370. https://www.nrel.gov/docs/fy23osti/83370.pdf.

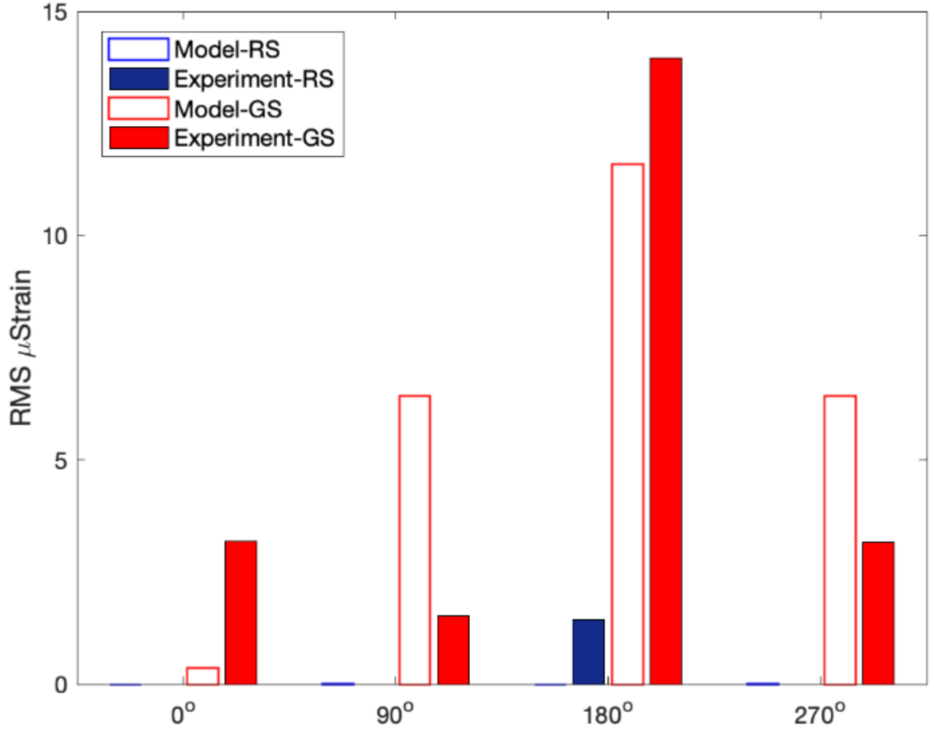
Operating Temperature of Main Bearing Outer Ring



- Operational temperatures of healthy main bearings are typically between 5°C and 47°C
- Bearing temperature approximately 20°C to 25°C higher than ambient
- In summer, bearing temperature roughly 15°C higher than winter
- Bearing temperature does not increase meaningfully with rotational speed

Result Correlation: Model and Experiments

Bearing Ring Tangential Strain at Rated Wind Speed



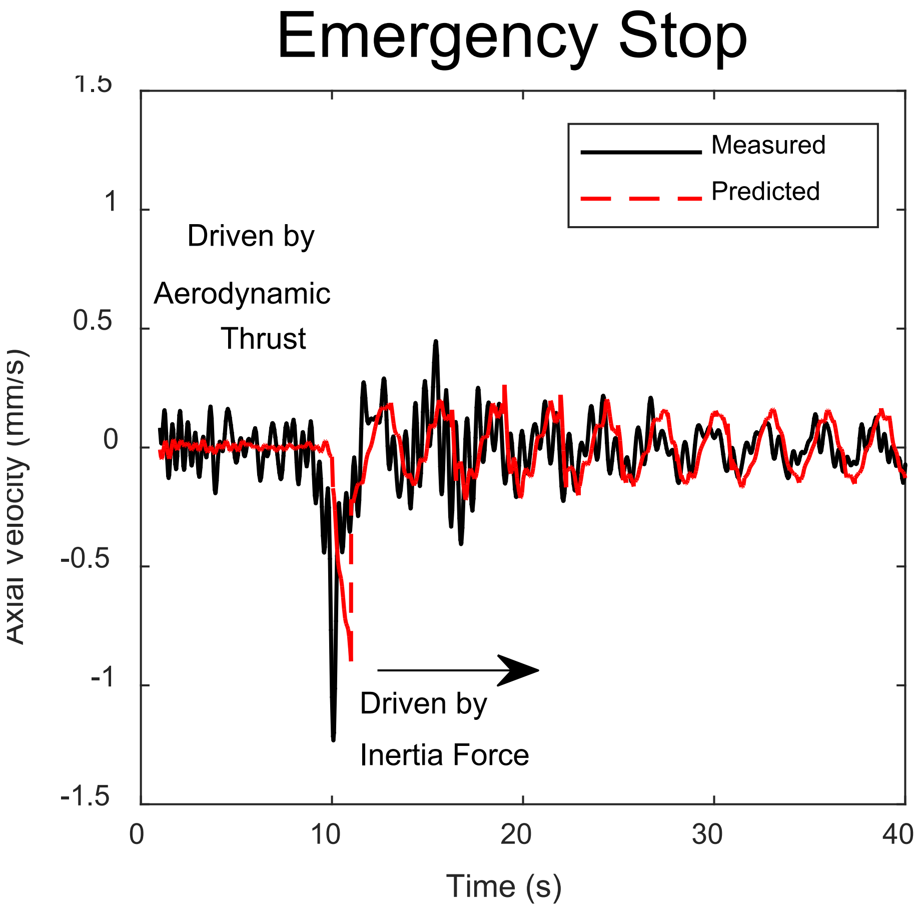
- Agreement between experimental and modeling results reasonably good
  - Nature of the contact (rather than bonded) strain gauge – data drifting might occur
  - Lack of bedplate and other model details
- Highest strain occurs at 180° when load highest
- Rotor-side bearing row almost unloaded

Source: Bergua Archeli, R. et al. 2021. Up-Tower Investigation of Main Bearing Cage Slip and Loads. NREL/TP-5000-81240. https://www.nrel.gov/docs/fy22osti/81240.pdf.

Does relative axial motion damage main bearing?

Relative Axial Velocity Between Bearing Rings

- Axial motion within axial clearance in spherical roller bearings – up to several millimeters
- When axial velocity < 10% of speed of rolling (352 mm/s), no appreciable effects on lubrication film (threshold based on SKF experiments)
- Measured maximum axial velocity < 1.5 mm/s during emergency stop – lubrication film deterioration not anticipated
- Generally good agreement between model and experimental results



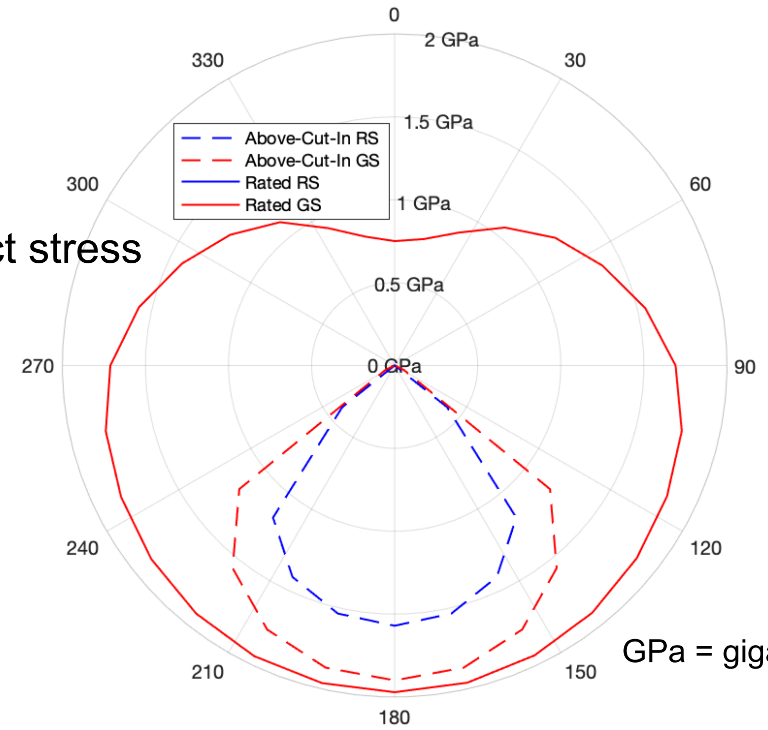
Source: Guo, Y. et al. 2021. "Investigation of Main Bearing Operating Conditions in a Three-Point Mount Wind Turbine Drivetrain." Forschung im Ingenieurwesen. doi: [10.1007/s10010-021-00477-8](https://doi.org/10.1007/s10010-021-00477-8)

Does bearing cage slip during operation?

Measurement Results – Tangential Strain

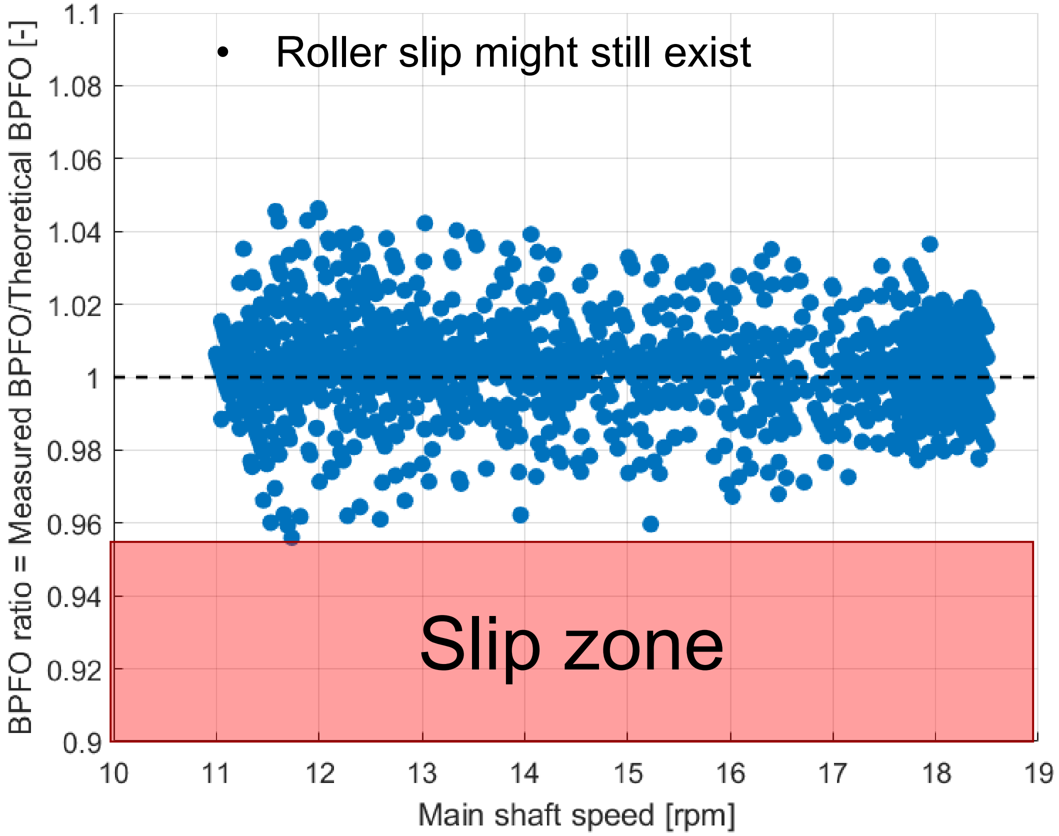
- Tangential strain measurement used to examine cage slip
- Measured vibration signature at roller pass frequency compared against theoretical value under pure rolling:
  <0.95 might indicate cage slip

Outer ring contact stress



GPa = gigapascal

- No evidence of cage slip!
- Roller slip might still exist

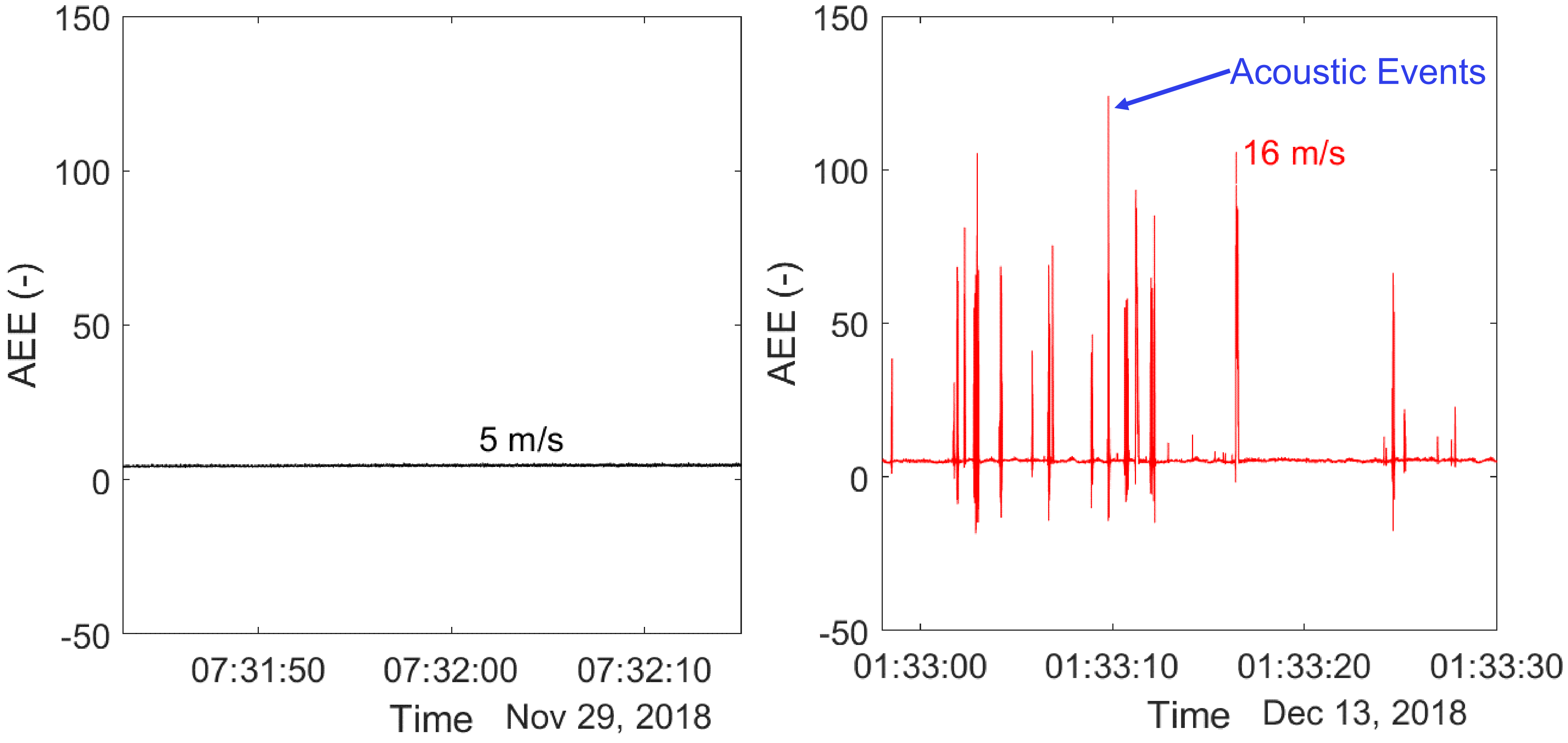


BPFO = ball-pass frequency for the outer ring

Source: Bergua Archeli, R. et al. 2021. Up-Tower Investigation of Main Bearing Cage Slip and Loads. NREL/TP-5000-81240. https://www.nrel.gov/docs/fy22osti/81240.pdf.

Is there metal-to-metal contact between bearing surfaces?

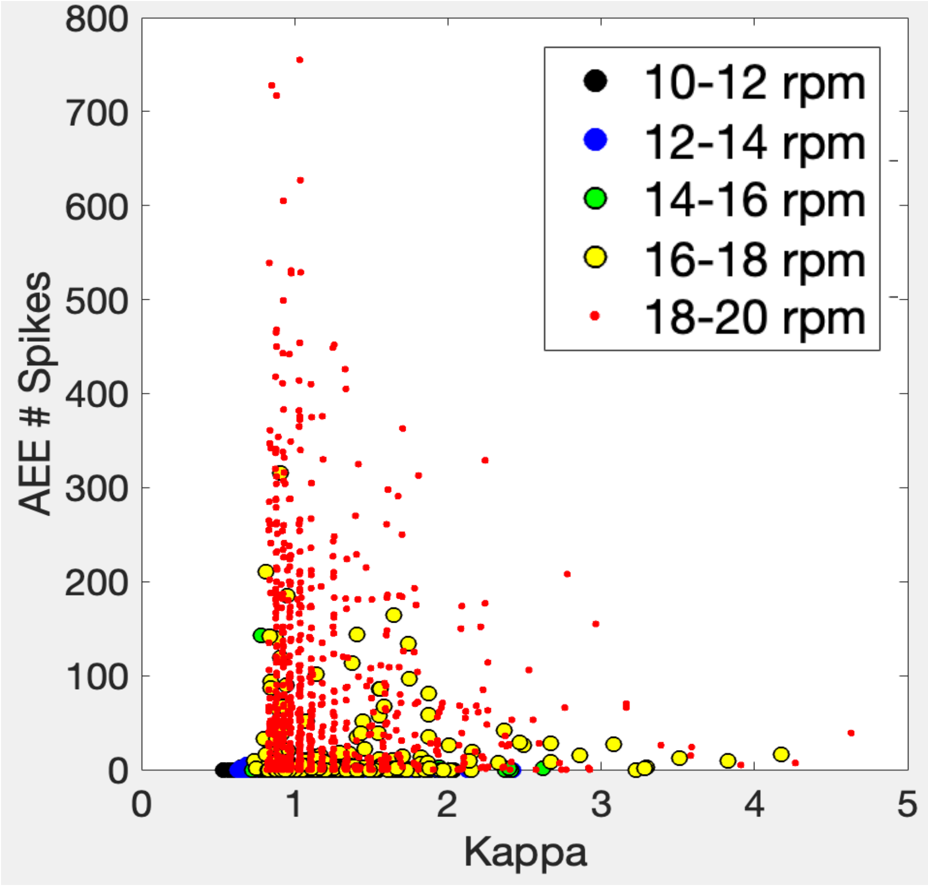
Measurement Results – AEE Wave Forms (Rectified and Enveloped)



Source: Guo, Y. et al. 2022. Acoustic Emission Measurement of a Wind Turbine Main Bearing. NREL/TP-5000-83370. https://www.nrel.gov/docs/fy23osti/83370.pdf.

Acoustic Emission vs. Kappa (Viscosity Ratio)

- Kappa can indicate lubricant conditions, with a typical desired range from 1 to 4
- When Kappa is less than 1, risk of roller/raceway asperity contact present
- Main bearing is often under mixed lubrication during normal operation
- Elevated AEE spikes combined with low Kappa may indicate roller/raceway asperity contact
  – Kappa ≈ 1 and main shaft speed ≥ 18 rpm



Conclusions

- Typical operational conditions of a spherical roller main bearing of a three-point-mount wind turbine drivetrain described
  - Strain gages used to examine load zone and cage slip
  - Relative axial velocity between bearing rings derived from proximity measurements
  - Acoustic emission monitors metal-to-metal contact

- Analytic and finite element/contact mechanics models established, and results match experimental data reasonably well
  - Analytic model estimates bearing loads, and relative axial motion and velocity
  - Finite element/contact mechanics model computes internal loads, stress, and strain

Conclusions

Key question – **Why do some main bearings fail prematurely?**

- *Does axial roller/raceway motion damage main bearing?*
  - *Relative axial velocity between bearing rings much lower than speed of rolling – lubrication film deterioration not anticipated*

- *Does the bearing cage slip during operation?*
  - *No appreciable cage slip discovered for the generator-side row*
  - *No cage slip anticipated for the rotor-side row because of shared cage*
  - *Roller slip might still exist*

- *Is there metal-to-metal contact between the rollers and raceways?*
  - *Spikes and elevated values of the acoustic emissions present during operations*
  - *Lubricant film might not be sufficient to prevent asperity contacts in some conditions*

Photo by Dennis Schroeder, NREL 49418

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