Roller Sliding in Wind Turbine Gearbox High-Speed-Shaft Bearings

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Photo by Jonathan Keller, NREL 49037
Overview

• Background
• Measurement setup
• Numerical model building and verification
• Transient load conditions
• Conclusions
Background
Background: Premature Failures with White Etching Cracks

- During recent years several countermeasures have been taken
- Since introduction of black-oxidising, no serial failure case reported by gearbox original equipment manufacturer
- Some failures still reported today by after market and end users:
  - Proper statistics are missing.
Premature Bearing Failures: Understanding the Drivers

White Etching Cracks (WECs) Occurrence in Bearings

Rolling Contact Fatigue

‘Cyclic’ Stresses and Loading

Structural Stresses (Sub-Surface)

Short Heavy Loads

Frictional Stresses and Wear (Surface, Near-Surface)

Higher ‘Stresses’

Lower ‘Material Strength’

Hydrogen (Surface and Sub-Surface)

Role of lubricant and tribochemistry

Low Film and Slip

Standstill Corrosion

Electrical Current

WEC in bearing test exposed to additional tensile stresses.

WEC in bearing test exposed to short heavy loads.

WEC in bearing test running under mixed friction and slip.

WEC in bearing test exposed to water standstill corrosion.

WEC in bearing exposed to electrical currents.

Photos from SKF
The exact combination of drivers that explains the failures in wind gear units is not yet understood:
- Limits of current solutions are not fully understood
- A better understanding of critical operating conditions in wind gearboxes still required

Simulations and measurements complete each other.

### Simulation
- Requires a detailed set of boundary conditions
- Requires tuning of model parameters
- Disturbances are negligible
- Possibility of in-depth analysis of roller kinematics.

### Measurement
- Provides data in complex operating conditions
- Only requires to process the measured signals
- Limited number of output parameters
- Measurement disturbances and input uncertainties.

**Pros**

**Cons**
Measurement Setup

Photo by Jonathan Keller, NREL 49037
Gearbox Instrumentation

Winergy PEAB 4410.4 Gearbox and SKF Cylindrical Roller Bearings

- Instrumentation focused on high-speed shaft, bearings, and lubricant:
  - Shaft speed
  - Cage speed
  - Roller speed
  - Shaft torque and bending
  - Stray current
  - Bearing temperatures
  - Air temperature and humidity
  - Lubricant temperatures and moisture content
  - LogiLube and Poseidon lubricant monitoring and routine oil samples
  - SKF iMX8 system.

Turbine and Meteorological (Met) Tower Instrumentation

GE 1.5 SLE turbine:
- Blade flap and edge bending
- Blade pitch angles
- Rotor azimuth and speed
- Main shaft torque and bending
- Active and reactive power
- Nacelle yaw
- Tower bending and torsion
- Wind vane offset

M5 met tower:
- Air temperatures and humidity
- Wind speed and direction

And more…GPS time stamped.
Roller and Cage-Speed Measurement

Cage-speed measurement:
- Pin passage detected by proximity sensor
- One speed measurement per cage revolution.

Roller-speed measurement:
- Magnetized roller
- Changing magnetic field detected by coil next to the bearing
- Position of magnetized roller determined by cage pin.

Photos by Jonathan Keller, NREL 40979 and 40981
Numerical Model Building and Verification
Measurement Limitations and Processing

- Mean cage speed during each revolution is available
- Instantaneous roller speed is available but highly disturbed
- Operating bearing clearance is unknown (bearing inner ring temperature often not available)

Postprocessing of the measurement is necessary:

1. Select time intervals where the cage speed is constant
2. Use several cage revolutions to filter the disturbance of the roller speed
3. Select best measured intervals.
Measurement Screening

1. Systematic detection of all cage-speed plateaus:

<table>
<thead>
<tr>
<th>Speed [rpm]</th>
<th>Time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>450</td>
<td>50</td>
</tr>
<tr>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>550</td>
<td>150</td>
</tr>
<tr>
<td>600</td>
<td>200</td>
</tr>
<tr>
<td>650</td>
<td>250</td>
</tr>
</tbody>
</table>

2. Least-squares fit of a piece-wise approximation of the roller speed:

<table>
<thead>
<tr>
<th>Azimuth [deg]</th>
<th>Speed [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6000</td>
</tr>
<tr>
<td>50</td>
<td>5000</td>
</tr>
<tr>
<td>100</td>
<td>4000</td>
</tr>
<tr>
<td>150</td>
<td>3000</td>
</tr>
<tr>
<td>200</td>
<td>2000</td>
</tr>
<tr>
<td>250</td>
<td>1000</td>
</tr>
</tbody>
</table>

3. Systematic selection based on error:

Final selection, based on most interesting and diverse operating conditions to increase the validity of the semiempirical model.
Effect of Temperature on Roller Speed: “Down Slope”

- At lower operating temperature, the rollers decelerate significantly more in unloaded zone.
- Higher temperature $\rightarrow$ lower viscosity $\rightarrow$ less drag losses on rollers in unloaded zone $\rightarrow$ slower deceleration.

![Graphs showing the effect of temperature on roller speed.](image)
Effect of Temperature and Oil Viscosity – Overview

- A significantly larger temperature difference is measured on bearing B than on bearing A:
  - Bearing B has much smaller radial clearance and a larger loaded zone than bearing A
- Slower deceleration of the rollers in unloaded zone at increasing temperature (lower oil viscosity)
- Drag losses increase with the size of the roller (larger projected surface of the rollers).
SKF Numerical Modelling

The model is designed by two SKF proprietary software.

- Transient multibody dynamic solver
- Detail contact calculation, elastohydrodynamic layer lubrication
- Cage-roller interaction
- Drag losses not automatically modeled.

Linear rotational damping torque is applied to both the cage and the rollers.

Illustrations from SKF
Analytical Model Predicts Roller and Cage Sliding

Roller Free Body Diagram

Primary Governing Equations

\[
\begin{align*}
F_{ij} - F_o + F_v - Q_{cg} &= 0 & \text{Tangential} \\
Q_i - Q_o + F_c &= 0 & \text{Radial} \\
M_i - M_o + \frac{1}{2} \mu_{cg} D Q_{cg} &= J \omega_c \frac{d\omega_r}{d\phi} & \text{Torsional}
\end{align*}
\]


Roller dynamics model (analytical):
- Harris roller dynamics model

Lubricant hydrodynamics model based on:
- Bercea cage friction model
- Dowson and Higginson lubricant model
Parametric Studies To Verify Model Parameters

Example in BEAST: Influence of Rotational Damping

Example in Analytical Model: Influence of Temperature

Nms = newtonmeter-second | rad = radian
Verification of Simulation Results

Input

Torque = 7,930 Nm,
TOR ~ 41°C,  Toil = 45°C
δ_B = 5μm, δ_A = 95μm

Torque = 7,930 Nm,
TOR ~ 63°C,  Toil = 63°C
δ_B = 30μm, δ_A = 145μm

Torque = 9,520 Nm,
TOR ~ 57°C,  Toil = 41°C
δ_B = 20μm, δ_A = 145μm

Nm = newtonmeters | TOR = Outer ring temperature | Toil = Oil supply temperature | δ = Clearance
Measurements at Transient Conditions

Drivetrain Conditions during Emergency Stop

- Power [kW]
- Torque LSS [kNm]
- HSS speed [rpm]

kW = kilowatt | LSS = Low-speed shaft | HSS = High-speed shaft | kNm = kilonewtonmeter
Transient Conditions – Emergency Stop

- Torque oscillations at drivetrain 1st eigenfrequency
- Oscillations result in cage and roller dynamics
- Rotor side more sensitive to torque oscillations than generator side
- Roller speed measurements unreliable at low speed conditions.
- At brake engagement roller speed reduces to about 80% slip and accelerates back in about 1.5 seconds.
Transient Conditions – LVRT (50% Drop for 300 milliseconds)

- Torque oscillations at drivetrain 1st eigenfrequency after Low-Voltage Ride Through (LVRT)
- Load oscillations resulting in cage and roller dynamics
- Roller speed reduces to about 50% slip and accelerates back in about 0.5 seconds.
Operating at low load results in much higher slip levels.
Ongoing Steps

- Repeat the procedure for the cage speed at low load. The proximity sensor is not affected by the same disturbance as the induction coil.
- Simulation of transient conditions (i.e., when measurement cannot be efficiently filtered from noise).
- Use simulation results to evaluate critical conditions for the bearings (e.g., by power slip density or cumulative frictional energy).

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**Power Slip Density**

Roller Speed

- B computed BEAST
- A computed BEAST
- A measured
- B measured

Power Slip Density

Frictional Energy

W/mm² = watts per millimeters squared | J/s = joules per second
Conclusions

• Measurement of roller and cage speed gives useful insight in the bearing kinematics at different operating conditions:
  – Low load/curtailment
  – Emergency stop
  – LVRT
• High roller slip and accelerations have been measured at these events
• BEAST model has been built and shown to be able to accurately predict roller and cage behaviour at different loads and temperature
• Next steps:
  – Apply and validate the models at special events
  – Evaluate the roller slip losses at special events.
Thank you for your attention!


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