Quantification of Roller Sliding Energy in Wind Turbine Gearbox High-Speed Shaft Bearings

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4 Energy Accumulation and Reliability Assessment
5 Summary and Ongoing Research
Gearbox Bearing Axial Cracking—Dominant Drivetrain Failure Mode

What turbine operational conditions result in critical contact conditions?

Cumulative frictional energy is considered a potential failure metric for axial cracking.

\[ E = \mu N \Delta V t \]

Cumulative Frictional Energy
E Quantification

Measure $\Delta V$

Model $\Delta V, \mu$

Measure $N$

Model $N$

Frictional Energy $E$

Wind Plant $E$

Model validated by experiments for a 1.5-MW turbine

Apply models for wind plants

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5 Summary and Ongoing Research
Roller dynamics model (analytical):
- Harris roller dynamics model

Lubricant hydrodynamics model based on:
- Bercea cage friction model
- Dowson and Higginson lubricant model

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

Analytical Model Predicts Roller and Cage Sliding


High-Speed Shaft Bearings and Load Zone

NU 2326 (Bearing A)  
NU 232 (Bearing B)
• Rollers slide even at rated torque
• Sliding affected by lubricant temperature and clearance

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High-speed shaft bearing loads derived from the measured shaft-bending moments and torque through force and moment balance.

Bearing loads distributed among rollers using the Harris approach.

Semi-Experimental Approach—Strain Gaging

Bearing Ring Not Needed


Simple Analytical Model Calculates Bearing Loads

- Three degrees of freedom lumped-parameter model calculates bearing loads
- Bearing loads distributed among rollers using the Harris approach.


Governing Equation

\[ M \ddot{q} + C \dot{q} + K(q, t)q = f(q, t) \]

- \( M \): Mass
- \( C \): Damping
- \( K \): Stiffness
- \( q \): Displacement
- \( f \): Applied loads
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• Accumulates most sliding energy at the load zone entry
• Rollers slide most outside the load zone
  – No frictional energy generated

\[
\Delta V \quad \mu \quad N \quad = \quad \frac{E}{t}
\]

Frictional Energy Varies with Power and Temperature

Cold operations at low power generate more frictional energy than warm operations at high power.

Frictional Energy: Startup Event

- Normal startup
- Energy accumulates during the runup once grid is connected

\[
\Delta V \quad \mu \quad N \quad t = E
\]

Frictional Energy: Emergency Stop Event

- Emergency stop—induced from tower base
- Limited energy accumulation
  - But many torque oscillations and reversals $\rightarrow$ contact stress up to 2 GPa

$$\Delta V \quad \mu \quad N \quad t = E$$

Energy Accumulation Comparison

• Compare total sliding energy between turbine operations
• Transients vs. 10-minute projections of normal power
  – Normal power contributes more energy
  – RS (A) has more energy than generator-side inboard (GS-in or B)

• Nearly 200 wind turbines with multiple gearbox suppliers
• Investigate high-speed and intermediate-speed stage bearings
• Correlate energy accumulation with failure records

What are other contributors to WECs? Higher-resolution SCADA?

Summary and Ongoing Research

- Up-tower testing campaign investigated major contributors to WECs
  - Roller sliding and frictional energy accumulation
- Newly developed analytical tools calculate roller loads and sliding
  - Can simulate a variety of turbines and plants
  - Validated by experiments
- Frictional energy accumulated the most during power production
  - Transient events contribute less energy
- Lubricant temperature greatly affects energy generation
  - Lubricant heater/cooler function improvement?
- Relate frictional energy with plant failure records (ongoing)
- Reliability assessment during early design phase (ongoing)
- Prediction of remaining useful life (ongoing)
Recent References

- T. A. Harris, *An analytical method to predict skidding in high speed roller bearing*, ASLE Transaction, 1966
Thank You!
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