Rolling Element Bearing Dynamics in Wind Turbines

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Wind Turbine Drivetrain Reliability Challenges

- Predominant drivetrain failure modes are:
  - Not accounted for in design standards
  - Not attributable to material deficiencies or quality control
  - Complex and independent of the component supplier

- Conduct testing and analysis to enable:
  - Improvement of inherent reliability
  - Increase of availability with less effort and drama
  - Reduction in wind plant operation and maintenance costs.
Most Frequent Failures

- High & intermediate speed stage bearings contribute 62% of total drivetrain failures.
- A planet bearing failure is more costly.

Source: S. Sheng, GRC Failure Database, 2018
Note: HSS = high-speed shaft; IMS = intermediate-speed shaft; LSS = low-speed shaft
Uptower Experiment Objectives

What turbine operations and grid conditions result in critical contact conditions for high-speed shaft and main bearings?

Gearbox Bearing Axial Cracking

Main Bearing Failure

Load impacts on component reliability addressed properly?


• **Winery PEAB 4410.4 gearbox and SKF cylindrical roller bearings**
  o 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 IMx-8 system.
Modeling of Bearing Loads & Stresses

- Lumped-parameter dynamics model
  - Transmission error
  - Bearing clearance
  - Nontorque loads
  - Gravity

- Simulate normal operation and transient events efficiently
- Failure modes, such as planet bearing fatigue, can be included
- Validation on loads will be performed during DRC 1.5 uptower testing.

Nonlinear, Time-Dependent Equations of Motion

\[ M\ddot{q} + D\dot{q} + \left[ K(q, t) + B \right]q = f(q, t) \]

- Gear mesh stiffness
- PCL nonlinearity
- Bearing stiffness

Illustration from [2]
Model Development: Roller Dynamics

- **Roller dynamics model (analytical) based on:**
  - Harris roller dynamics model [3,4]

- **Lubricant hydrodynamics model based on:**
  - Bercea cage friction model [5]
  - Dowson and Higginson lubricant model [6]

Forces and speeds of a roller

\[ Q_{ij} - Q_{o_j} + F_{c_j} = 0 \]  
(1)
\[ F_{ij} - F_{o_j} + F_v - Q_{cg_j} = 0 \]  
(2)
\[ M_{ij} - M_{o_j} + \frac{1}{2} \mu_{cg} D Q_{cg_j} = F_\omega M \frac{d\omega_{rj}}{d\psi} \]  
(3)
\[ \sum_{j=1}^{z} Q_{ij} \cos\psi_j - F_r = 0 \]  
(4)
\[ d_m \sum_{j=1}^{z} Q_{cg_j} - D_{cr} F_{cl} = 0 \]  
(5)

Force balance of a single roller
Model Validation: Roller Speed Zone

• Good agreement between model & experiments
• Outside the load zone, the roller speed is less than its theoretical value for pure rolling conditions.
Roller Speed Statistics

- Good correlation between model and experimental results
- Roller speed less than theoretical at low wind speed
  - Indicates significant roller sliding

Note: GS-in = inboard generator side; rpm = revolutions per minute; m/s = meters per second
Roller Sliding During Startup

- Significant sliding present between 110 & 220 seconds
  - Related to controller settings
- Sliding occurred because of high speed with no load
  - Roller/raceway wear could occur.

![Graph showing operating condition and cage speed with sliding highlighted at specific time intervals](image)

Note: kW = kilowatt; kNm = kilonewton-meter

Note: GS-in = generator side inboard
Roller Sliding During Emergency Stop

- No significant sliding occurred
  - Limited roller sliding present only when braking started
- Strong impact loading initiated by the braking
- Maximum torque exceeded 169% of rated.

![Operating Condition](image1)

![Cage Speed](image2)

**Note:** kW = kilowatt; kNm = kilonewton-meter

**Note:** GS-in = generator side inboard
Roller Sliding During Normal Stop

- Sliding occurs when generator disconnected at 75 seconds
- High sliding risks under high-speed & low to zero load.

Operating Condition

- Active Power (kW)
- Main Shaft Torque (kNm)
- HSS Speed (rpm)

Cage Speed

- Measured
- Pure Rolling
- Model

Sliding

Note: kW = kilowatt; kNm = kilonewton-meter

Note: GS-in = generator side inboard
Conclusions

• Unique experimental results on bearing roller and cage speed presented
• Analytic model for calculating bearing speed described
  o Model validated through uptower experiments
• Bearing speed affected by drivetrain load and speed
• Bearing sliding widely present during regular turbine operations
• Significant sliding occurs during transient events
  o Can lead to bearing failures or shortened life
  o Risks of sliding-induced failures to be quantified in the future.
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References


