Probability of Failure for Gearbox High-Speed-Stage Bearings in Wind Turbines

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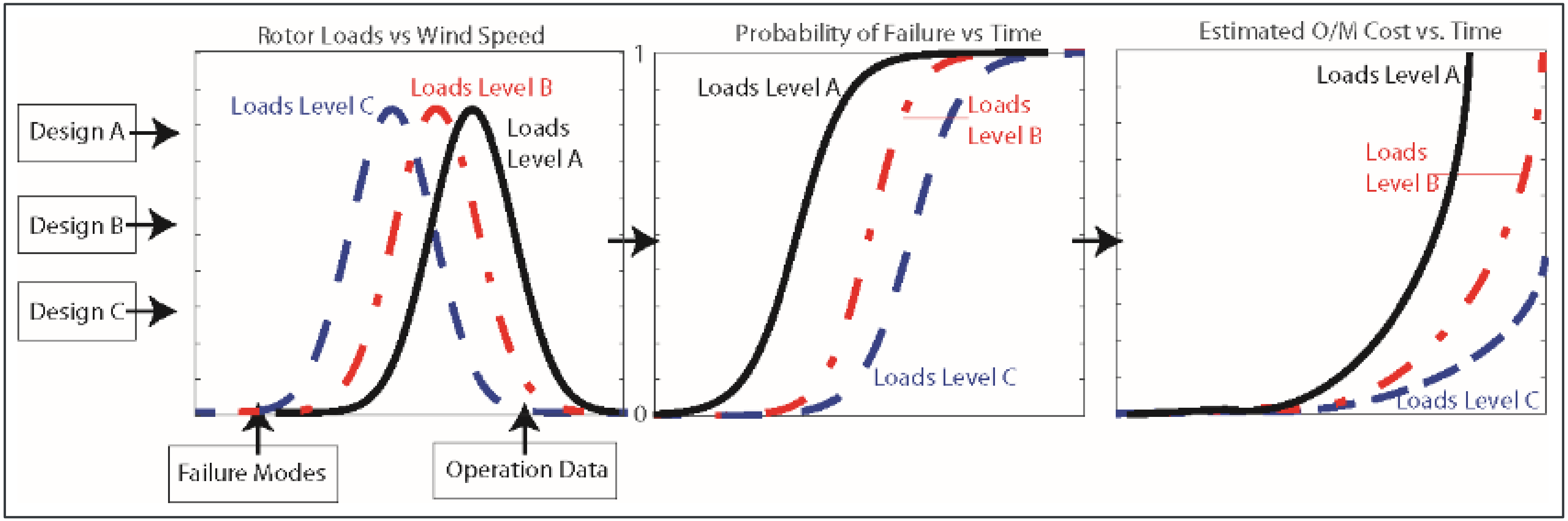
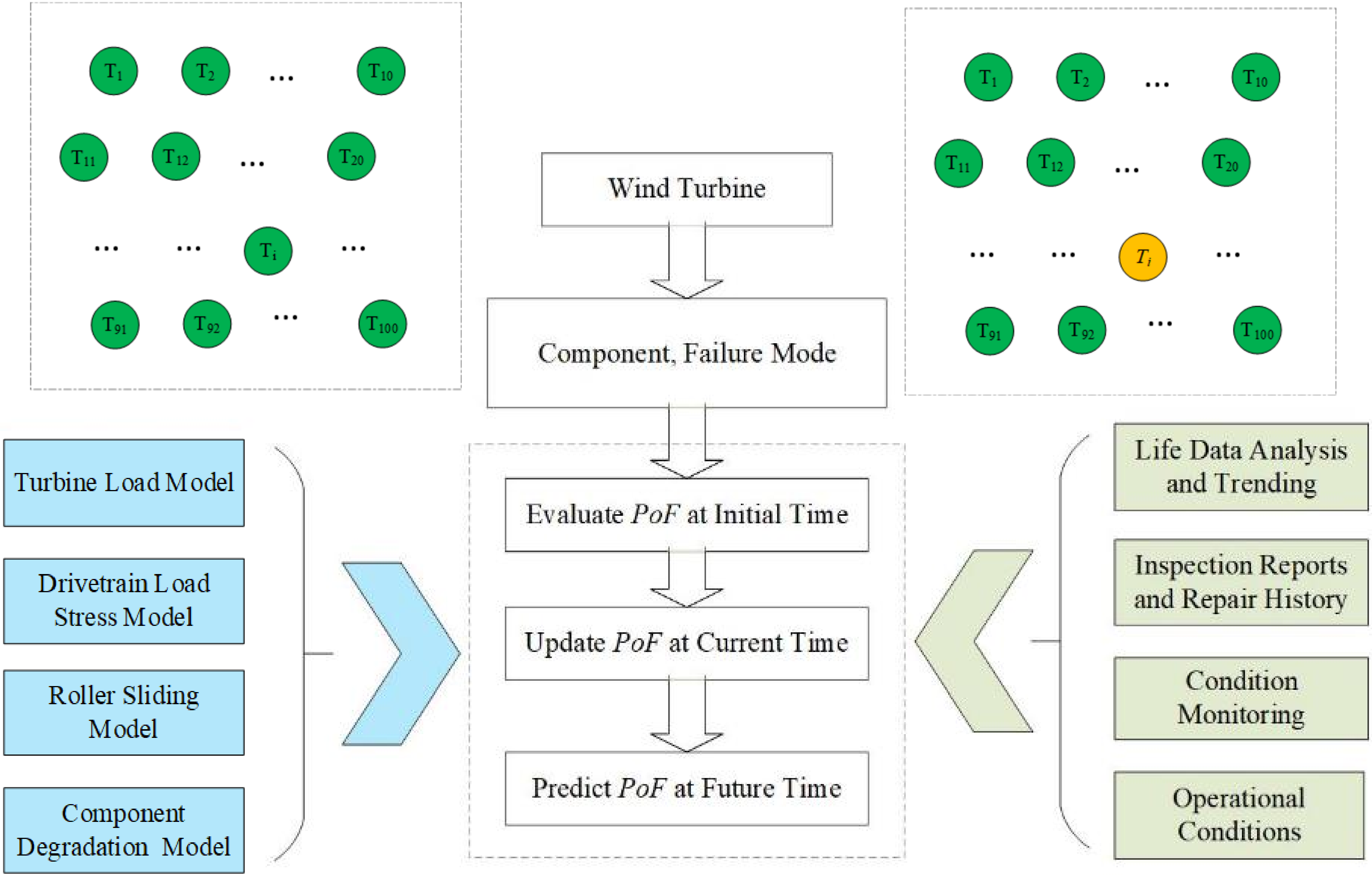
Gearbox Premature Failure Increases Costs

- Premature failures of drivetrain components are one the top drivers for increased operation and maintenance (O&M) costs
- A reliability measure of these components and their drivetrain system, such as **probability of failures against time**, provides crucial information for wind turbine designers, controls engineers, farm operators, and so on
- Traditional life data analyses (e.g. Weibull) do not consider turbine design or load changes
  - Greatly limiting the possibilities in addressing reliability and O&M cost in initial design phases.



Methodology in Estimating O&M Cost from Wind Loads

Methodology Overview: A Power Plant Perspective



Wind Turbine

Component, Failure Mode

Evaluate *PoF* at Initial Time

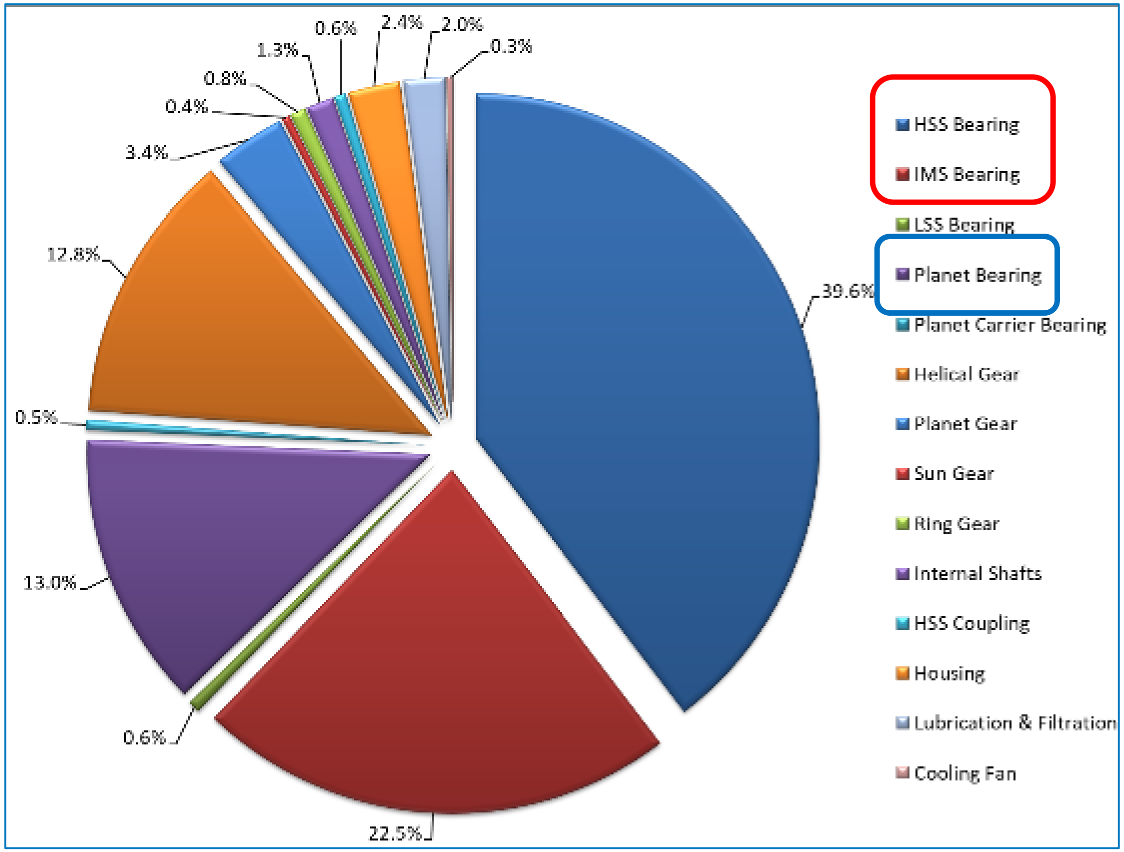
Update *PoF* at Current Time

Predict *PoF* at Future Time

- Turbine Load Model
- Drivetrain Load Stress Model
- Roller Sliding Model
- Component Degradation Model

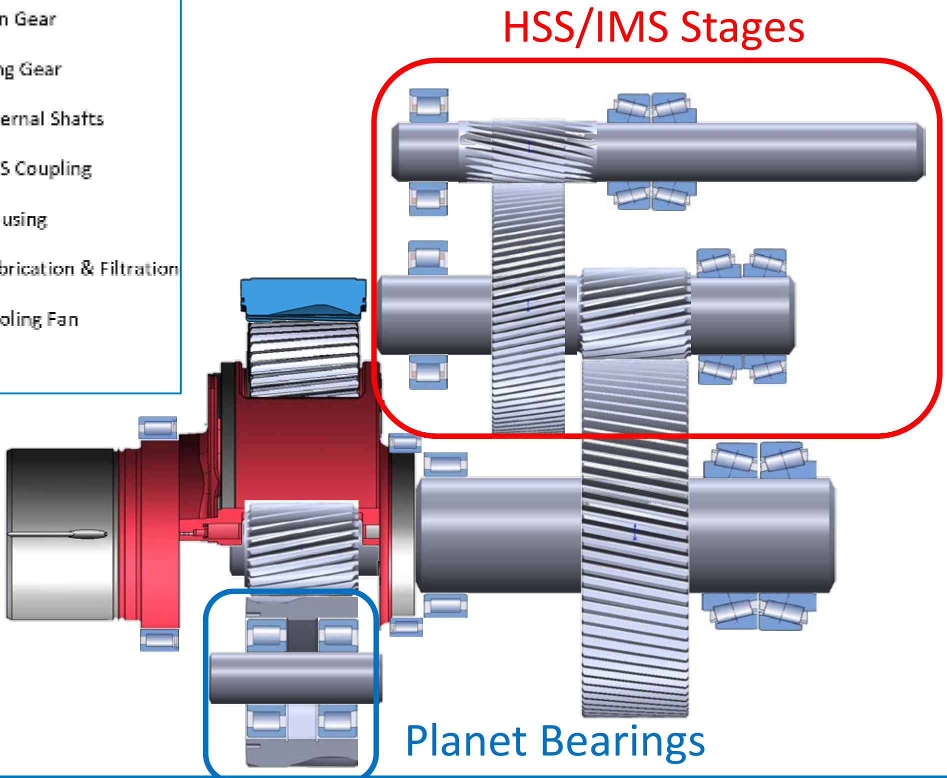
- Life Data Analysis and Trending
- Inspection Reports and Repair History
- Condition Monitoring
- Operational Conditions

Most Frequent Failures of High-Speed Bearings



Source: S. Sheng, GRC Failure Database, 2018

- **High & intermedium speed stage bearings** contribute 62% of total drivetrain failures
- **Planet bearing** failures lead to the largest O&M cost.



High-Speed Bearing Failure Modes

- Primary failure modes are axial cracks or spalling related to white-etching cracks
    - Appear on inner-raceway
- Root causes are highly debated, including:
    - Electrical current
    - Hydrogen embrittlement
    - Impact loading
    - Roller/raceway sliding.

With these conditions, failures were reproduced on a test bench at Argonne National Laboratory

Axial Crack

Credit: AeroTorque

Spalling

Illustration from [1]

High-Speed Bearing Reliability

- Model development
  - ➢ Dynamic load/stress
  - – Roller dynamics
  - – Bearing degradation
  - – Reliability analysis
- Case study: probability of failure for a wind plant.

U.S. Department of Energy 1.5 rotor removal/gearbox swap at the National Wind Technology Center. *Photo by Dennis Schroeder, NREL 49407*

Model Development: Drivetrain Loads & Stresses

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

Nonlinear, Time-Dependent Equations of Motion

$$\underbrace{\mathbf{M}\ddot{\mathbf{q}}+\mathbf{D}\dot{\mathbf{q}}}_{\text{Dynamic terms}}+\left[\underset{\overset{\uparrow}{\text{Gear mesh stiffness, PCL nonlinearity}}}{\mathbf{K}(\mathbf{q},t)}+\underset{\overset{\uparrow}{\text{Bearing stiffness}}}{\mathbf{B}}\right]\mathbf{q}=\underset{\overset{\uparrow}{\text{Applied torque \& surface mods.}}}{\mathbf{f}(\mathbf{q},t)}$$

- 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

Turbine Load Model

Drivetrain Load Stress Model

Roller Sliding Model

Component Degradation Model

Planet Bearing Stage Model

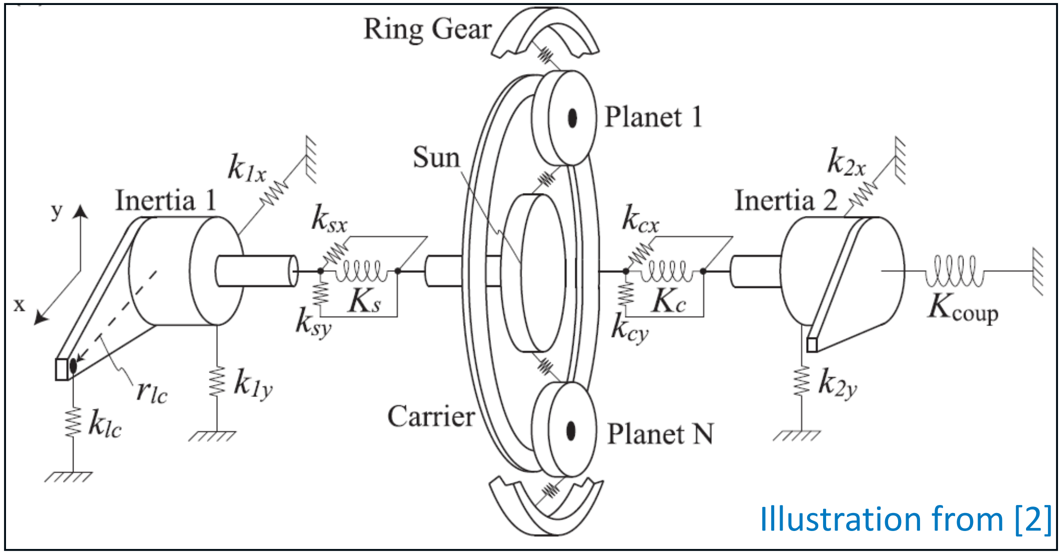
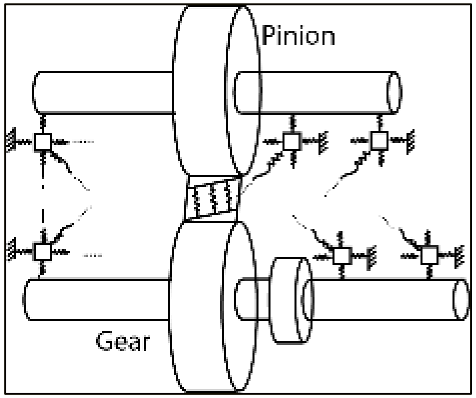


Illustration from [2]

High-Speed-Shaft Model



Different modules used to reduce computation time

High-Speed Bearing Reliability

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Model Development: Roller Dynamics & Sliding

- 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]

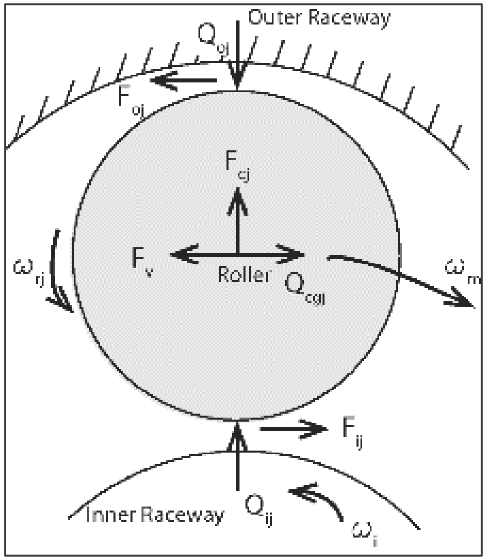
Turbine Load Model

Drivetrain Load Stress Model

Roller Sliding Model

Component Degradation Model

Forces and speeds of a roller



Force balance of a single roller

$$Q_{ij} - Q_{oj} + F_{cj} = 0 \quad (1)$$

$$F_{ij} - F_{oj} + F_v - Q_{cgj} = 0 \quad (2)$$

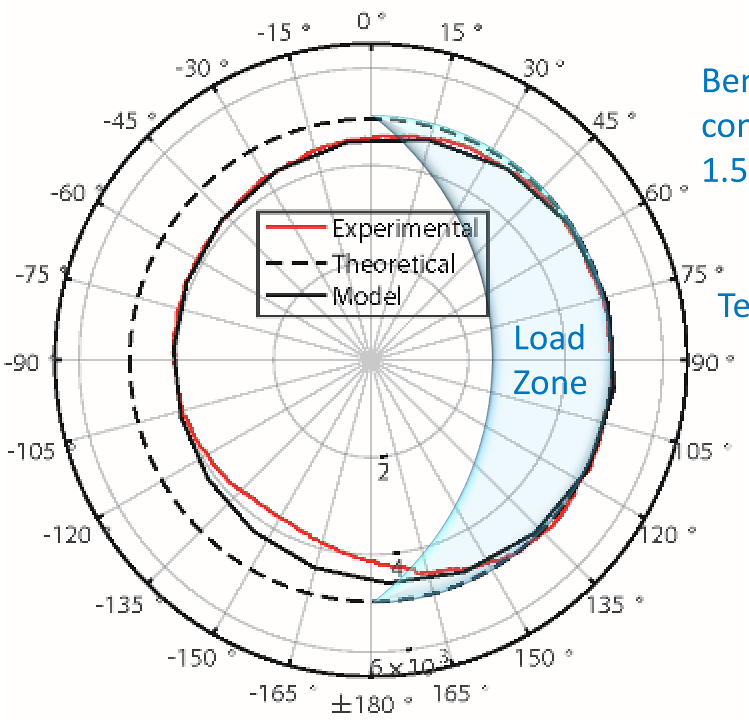
$$M_{ij} - M_{oj} + \frac{1}{2}\mu_{cg} D Q_{cgj} = F\omega_m \frac{d\omega_{rj}}{d\psi} \quad (3)$$

$$\sum_{j=1}^{z} Q_{ij}\, cos\psi_j - F_r = 0 \quad (4)$$

$$d_m \sum_{j=1}^{z} Q_{cgj} - D_{cr} F_{cl} = 0 \quad (5)$$

Model Validation: Roller Speed

- Good agreement between model & experimental results
  - Asymmetry in experimental results led by different drag forces on rollers?
- Roller speed is less than its theoretical value under pure rolling, outside load zone.

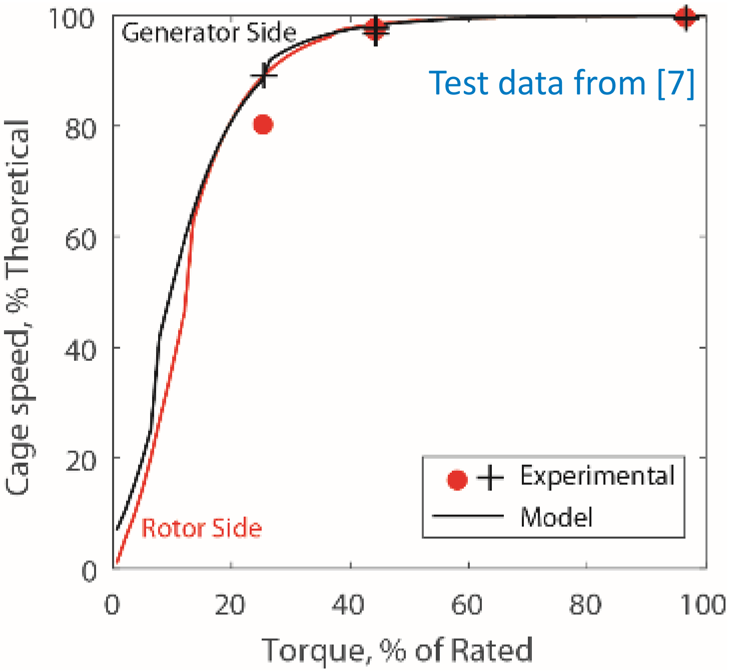


Bench top testing was conducted for DOE’s 1.5 MW turbine

Test data from [7]

Simulated at rated power

Model Validation: Cage Speed



- Bench top testing was conducted for DOE’s 1.5 MW turbine
- In general good agreement between model and experimental results
- Model overpredicts cage speed for lower torque
- Model needs to be further evaluated during transients.

High-Speed Bearing Reliability

- Model development
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Model: Accumulative Energy Loss, E

- Accumulative energy loss proposed as a measure of failure [1]
- Focused on frictional energy because of roller sliding
- E during both normal, E_{np} & transient events, E_{tt} considered

Turbine Load Model

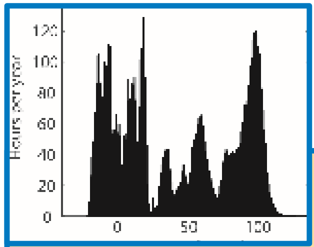
Drivetrain Load Stress Model

Roller Sliding Model

Component Degradation Model

$$E = E_{np} + E_{tt}$$

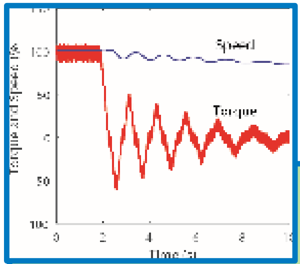
Operation



$$E_{np} = f(\mu, N, F, \Delta v)$$

- μ: friction coefficient
- N: number of cycles (roller)
- F: load
- Δv: sliding velocity between roller/raceway

Transient



$$E_{tt} = f(\mu, t, F, \Delta v)$$

- μ: friction coefficient
- t: time
- F: load
- Δv: sliding velocity between roller/raceway

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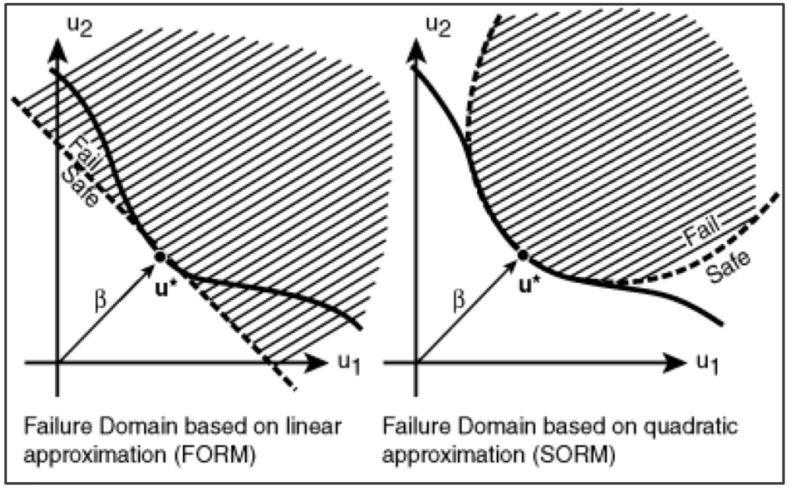
Probability of Failure, P_f

- Failure occurs when energy loss reaches its threshold (e^*)

$$G = e^* - (E_{np} + E_{tt})$$

- First (FORM) & second-order (SORM) reliability methods

$$P_f = P\{G(U) < 0\}$$



Failure Domain based on linear approximation (FORM)

Failure Domain based on quadratic approximation (SORM)

Illustration from [9]

- P_f considers uncertainties, U:
  - Wind turbulence
  - Frictional coefficients
  - Bearing stiffnesses
  - Temperature influence on lubricant.
- P_f estimates the amount of probability that lies in the portion of the space with a negative $G(U)$.

High-Speed Bearing Reliability

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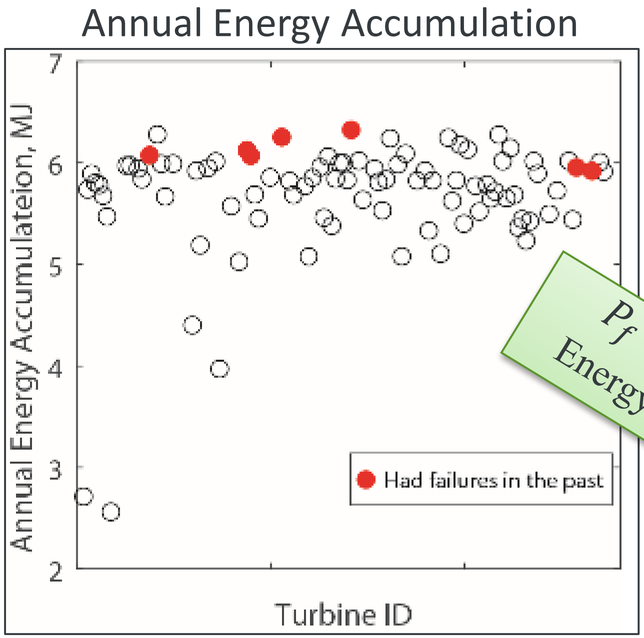
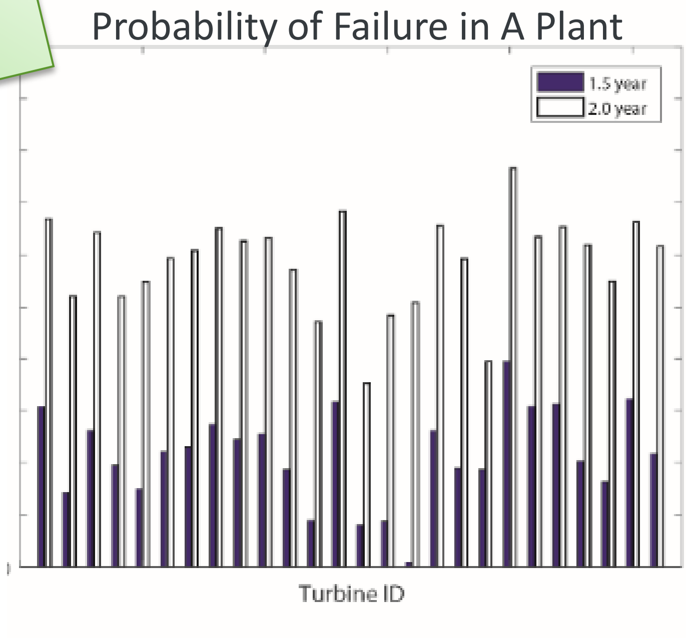
Probability of HSS Bearing Failure for a Wind Plant



Annual Energy Accumulation

- P_f quantifies failure risk for each turbine
- P_f is a function of age, wind loads, turbine design, & operations

P_f Calculated from Energy Accumulation



Probability of Failure in A Plant

- Some correlation between high energy with HSS failures present

- Turbine failures occurred two years earlier than the evaluation period that was available for analysis.
  - Failure records yet to be updated
  - Large amount of SCADA data needed

Summary and Future Work

- A physics-based approach proposed to quantify failure risks of high-speed bearings for a wind power plant
  - Output is the probability of failure for each HSS bearing to exceed a specified damage limit
  - Failure risks between turbines can be differentiated
    - Unavailable through traditional life data analysis (e.g. Weibull)
  - Applicable to different wind turbines
    - Parameter-based models
  - Core models validated by experiments

- Results provide a more accurate metric for design, control, & operation strategy than a deterministic time to failure

- In the future, research will focus on:
  - Exploring other candidate damage function(s)
  - Validating failure state function(s) through life data analysis.

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