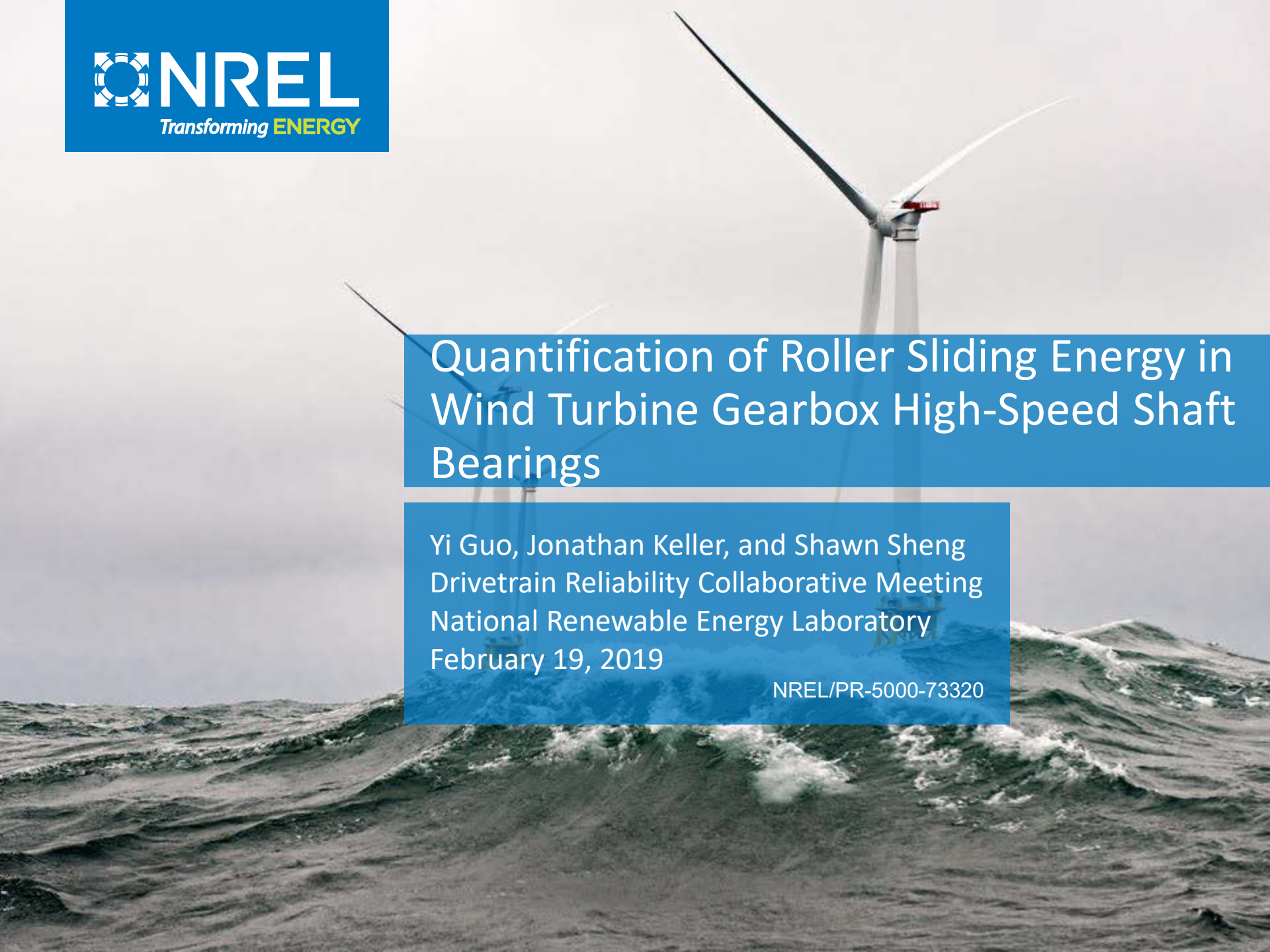


Quantification of Roller Sliding Energy in Wind Turbine Gearbox High-Speed Shaft Bearings

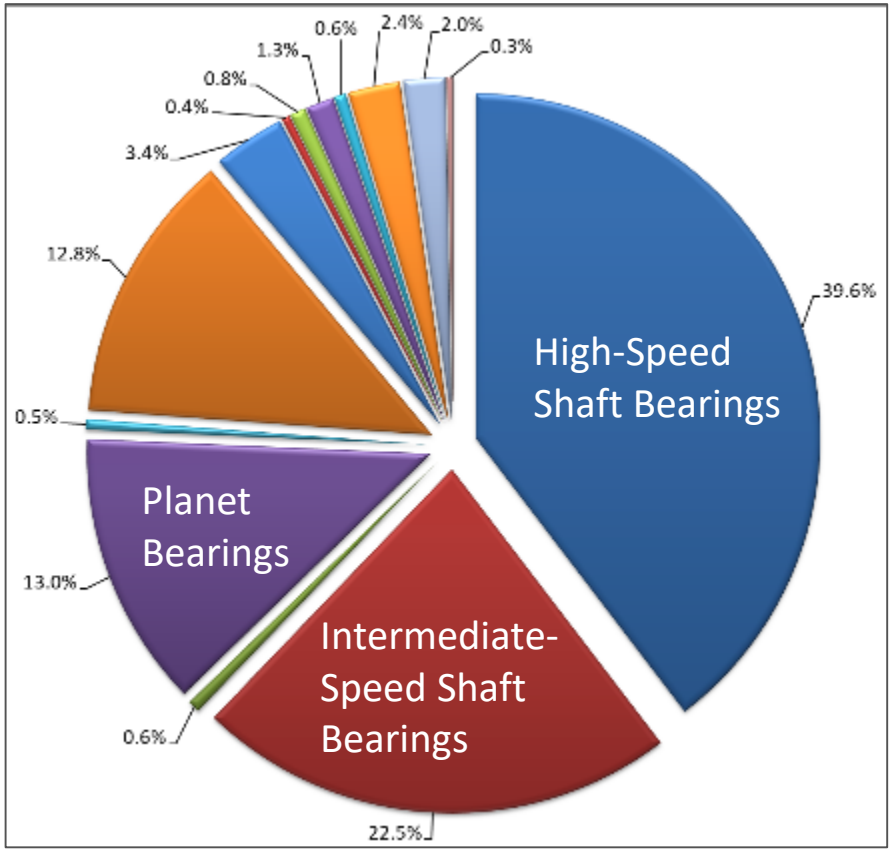
Yi Guo, Jonathan Keller, and Shawn Sheng

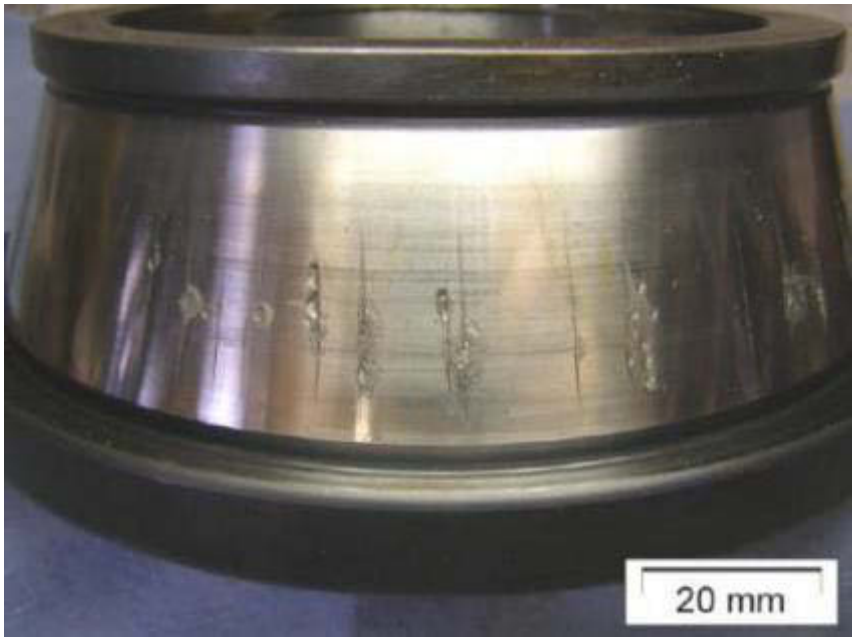
Drivetrain Reliability Collaborative Meeting

National Renewable Energy Laboratory

February 19, 2019

NREL/PR-5000-73320

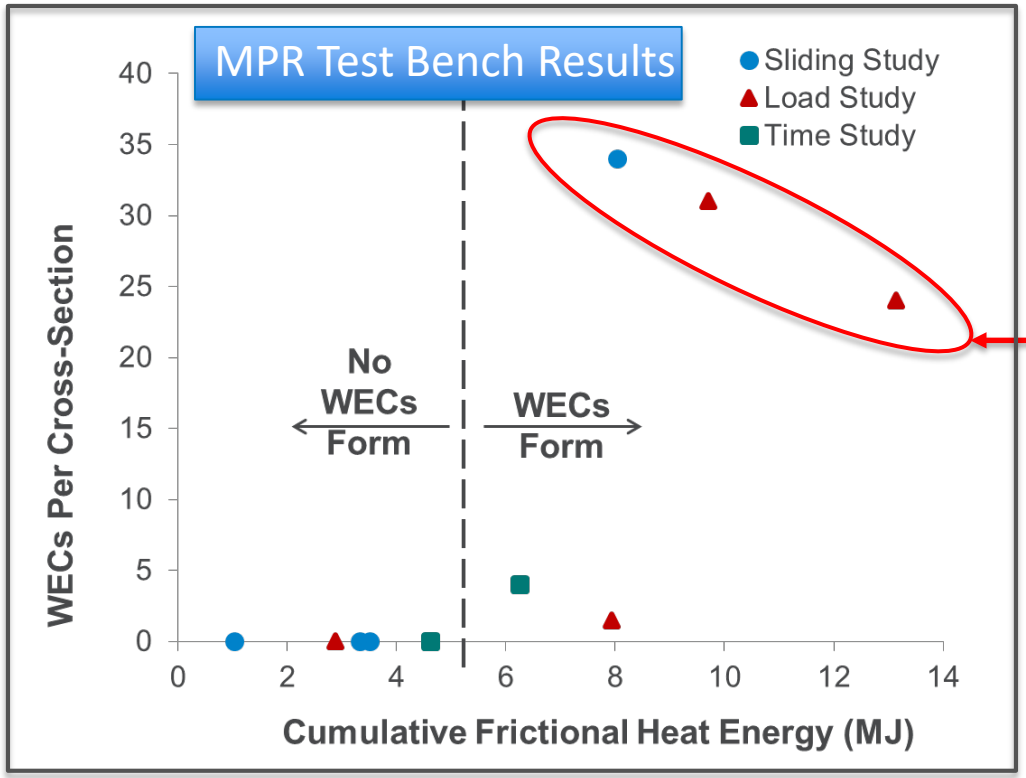




Errichello, R., S. Sheng, J. Keller, and A. Greco. 2012. *Wind Turbine Tribology Seminar- A Recap*. U.S. Department of Energy Wind and Water Power Program (image provided by Jurgen Gegner of SKF).

Gearbox Bearing Axial Cracking—Dominant Drivetrain Failure Mode

What turbine operational conditions result in critical contact conditions?



Argonne NATIONAL LABORATORY

MPR=Micro Pitting Rig
WEC=White Etching Cracks

Gould, B., and A. Greco. *The Influence of Sliding and Contact Severity on the Generation of White Etching Cracks*. doi:10.1007/s11249-015-0602-6.

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

Cumulative Frictional Energy

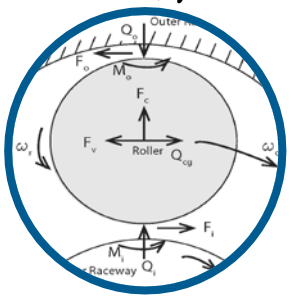
Cumulative frictional energy is considered a potential failure metric for axial cracking.

E Quantification

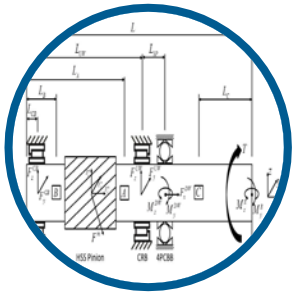
Measure ΔV

Measure N

Model $\Delta V, \mu$



Model N



Frictional Energy E

Wind Plant E

Model validated by experiments for a 1.5-MW turbine

Apply models for wind plants

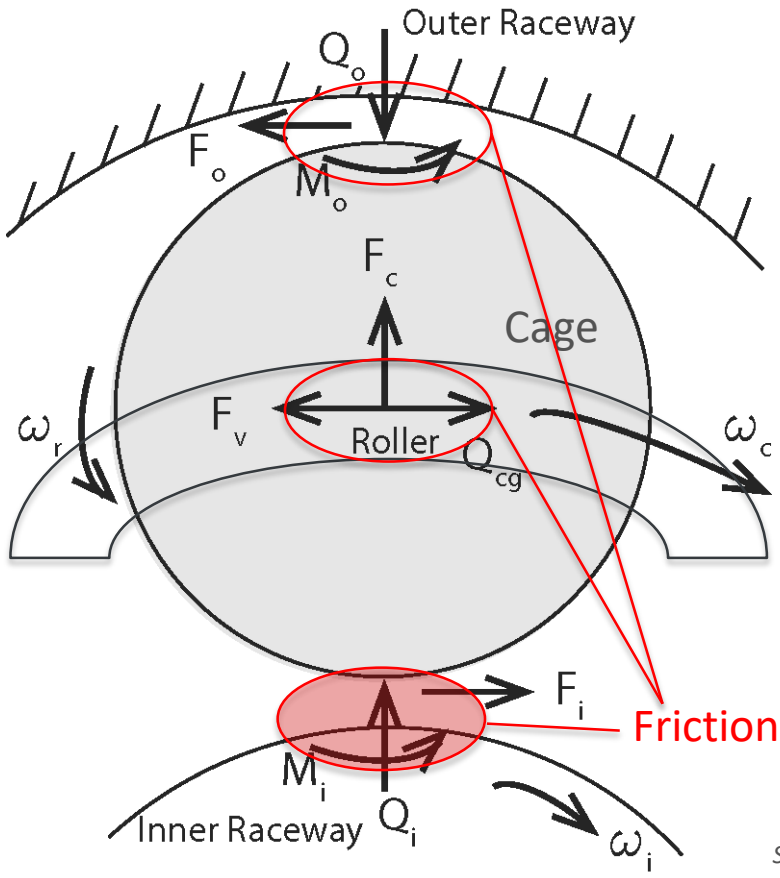
1 Background

2 Roller Sliding Measurement and Modeling

3 Bearing and Roller Loads Measurement and Modeling

4 Energy Accumulation and Reliability Assessment

5 Summary and Ongoing Research



Frictional Energy Loss

Primary Governing Equations

$$\begin{cases} F_i - F_o - F_v + Q_{cg} = 0 & \text{Tangential} \\ Q_i - Q_o + F_c = 0 & \text{Radial} \\ M_i - M_o + \frac{1}{2}\mu_{cg} D Q_{cg} = J\omega_c \frac{d\omega_r}{d\phi} & \text{Torsional} \end{cases}$$

Guo, Y., and J. Keller. Forthcoming. "Analytic Formulations of Rolling Element Bearing Sliding in Wind Turbine Gearboxes." *Mechanism and Machine Theory*.

Severity on the Generation of White Etching Cracks. doi:10.1007/s11249-015-0602-6.

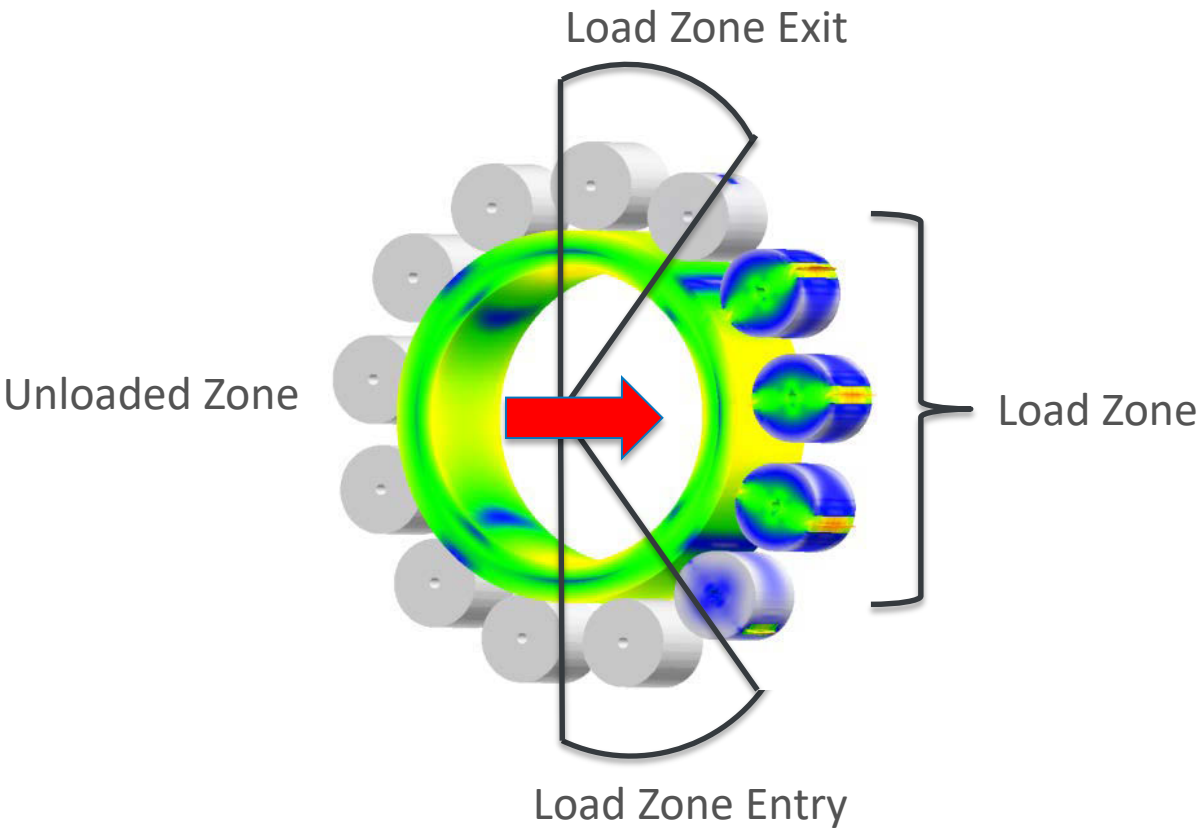
Analytical Model Predicts Roller and Cage Sliding

Roller dynamics model (analytical):

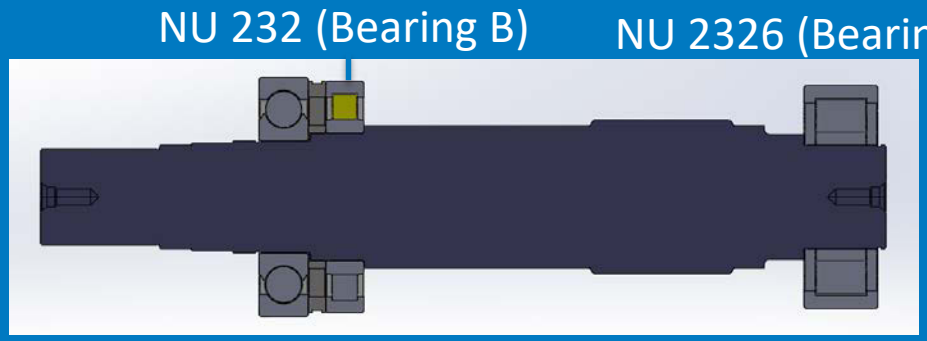
- Harris roller dynamics model

Lubricant hydrodynamics model based on:

- Bercea cage friction model
- Dowson and Higginson lubricant model



High-Speed Shaft Bearings and Load Zone



Rotor Sliding: Power Production

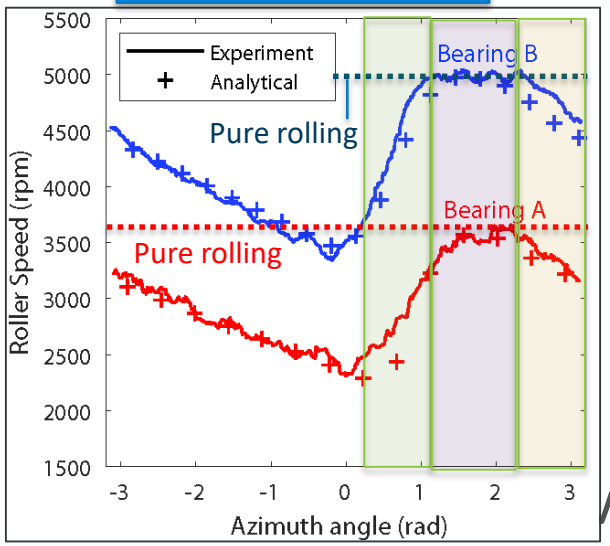
Load Zone Entry

Load Zone Center

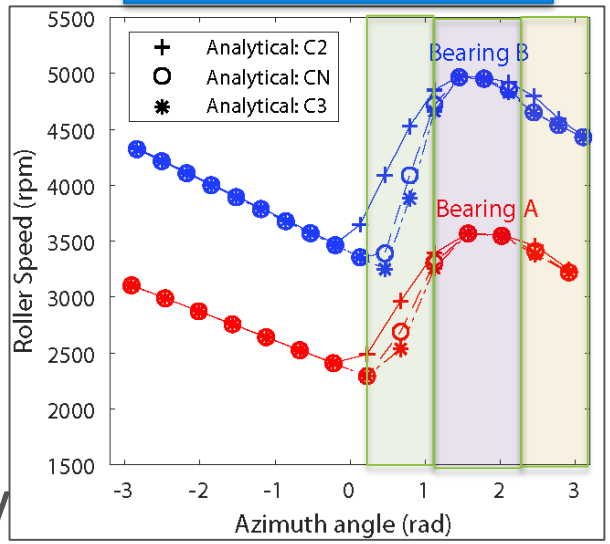
Load Zone Exit

- Rollers slide even at rated torque
- Sliding affected by lubricant temperature and clearance

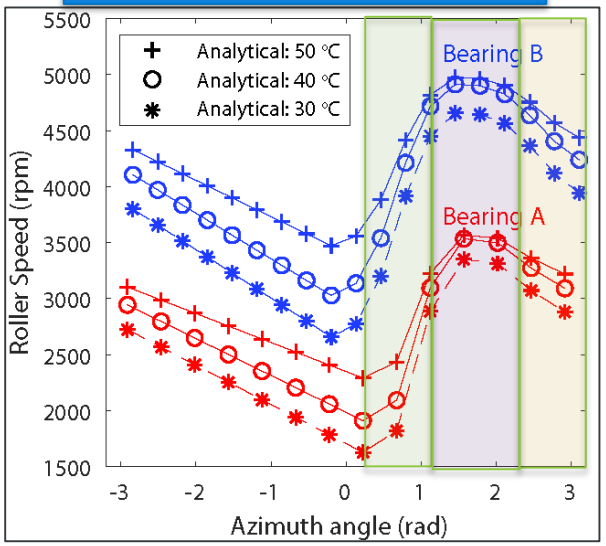
Model Validation



Effects of Clearance



Effects of Temperature



Vaes, D., Y. Guo, P. Tesini, and J. Keller. 2019. *Investigation of Roller Sliding in Wind Turbine Gearbox High-Speed Shaft Bearings*. NREL/TP-5000-73286. Golden, CO: National Renewable Energy Laboratory.

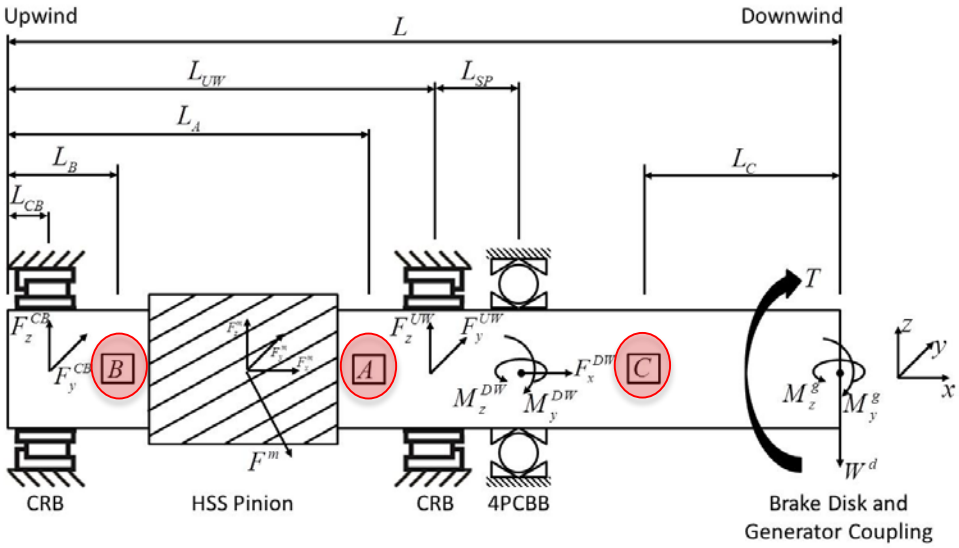
1 Background

2 Roller Sliding Measurement and Modeling

3 Bearing and Roller Loads Measurement and Modeling

4 Energy Accumulation and Reliability Assessment

5 Summary and Ongoing Research



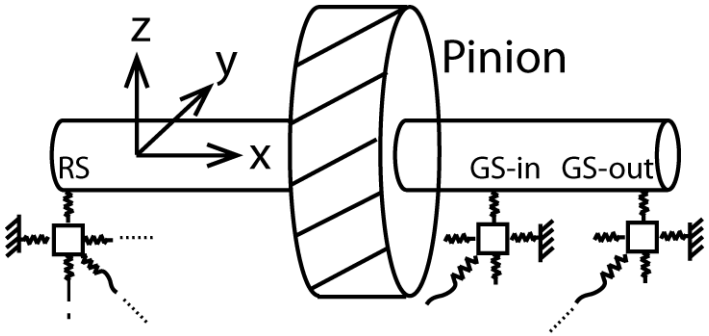
Bearing loads approximated as

$$
\begin{cases}
F_y^{CB} = \dfrac{1}{(L_a - L_{cb})}\left[-M_z^B - \dfrac{T}{R_b}\sin(\gamma)(L_a - L_p)\right] \\
F_z^{CB} = \dfrac{1}{(L_a - L_{cb})}\left[-M_y^B - \dfrac{T}{R_b}\cos(\gamma)(L_a - L_p)\right] \\
F_y^{UW} = -F_y^{CB} - \dfrac{T}{R_b}\sin(\gamma) \\
F_z^{UW} = -F_z^{CB} - \dfrac{T}{R_b}\cos(\gamma) + W_b
\end{cases}
$$

Guo, Y., and J. Keller. *Investigation of High-Speed Shaft Bearing Loads in Wind Turbine Gearboxes Through Dynamometer Testing*. doi:10.1002/we.2150.
Gould, B., and A. Greco. *The Influence of Sliding and Contact Severity on the Generation of White Etching Cracks*. doi:10.1007/s11249-015-0602-6.

Semi-Experimental Approach—Strain Gaging Bearing Ring Not Needed

- 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.



Governing Equation

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

- $\mathbf{M}$ Mass
- $\mathbf{C}$ Damping
- $\mathbf{K}$ Stiffness
- $\mathbf{q}$ Displacement
- $\mathbf{f}$ Applied loads

Gould, B., and A. Greco. *The Influence of Sliding and Contact Severity on the Generation of White Etching Cracks*. doi:10.1007/s11249-015-0602-6.

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.

1 Background

2 Roller Sliding Measurement and Modeling

3 Bearing and Roller Loads Measurement and Modeling

4 Energy Accumulation and Reliability Assessment

5 Summary and Ongoing Research

Frictional Energy: Power Production

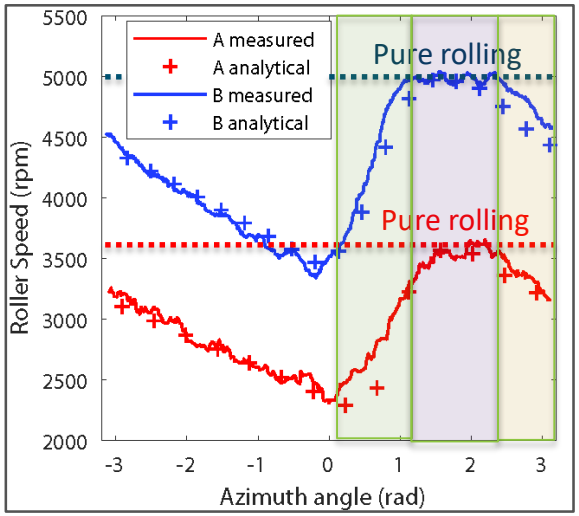
Load Zone Entry

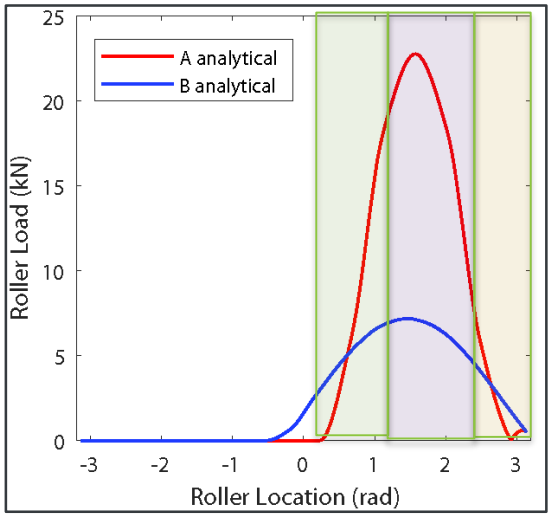
Load Zone Center

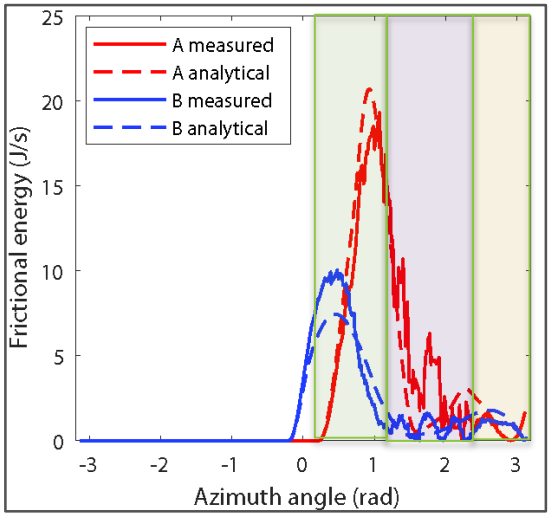
Load Zone Exit

- Accumulates most sliding energy at the load zone entry
- Rollers slide most outside the load zone
  - No frictional energy generated

$$\Delta V \qquad \mu \qquad N \qquad = \qquad E/t$$



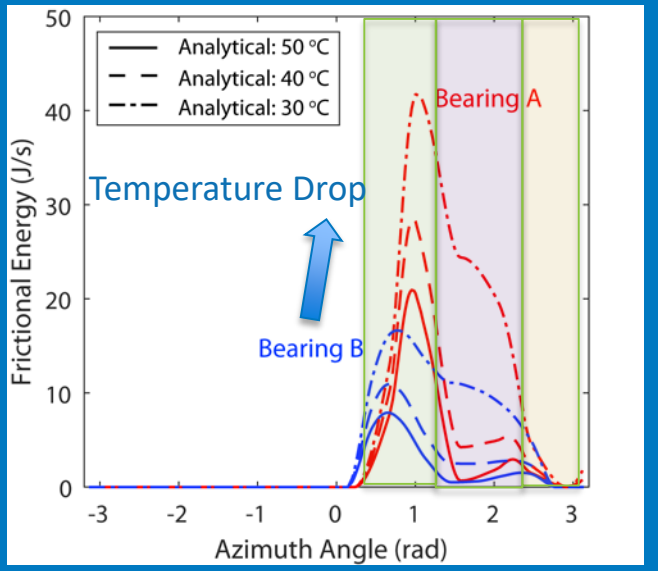




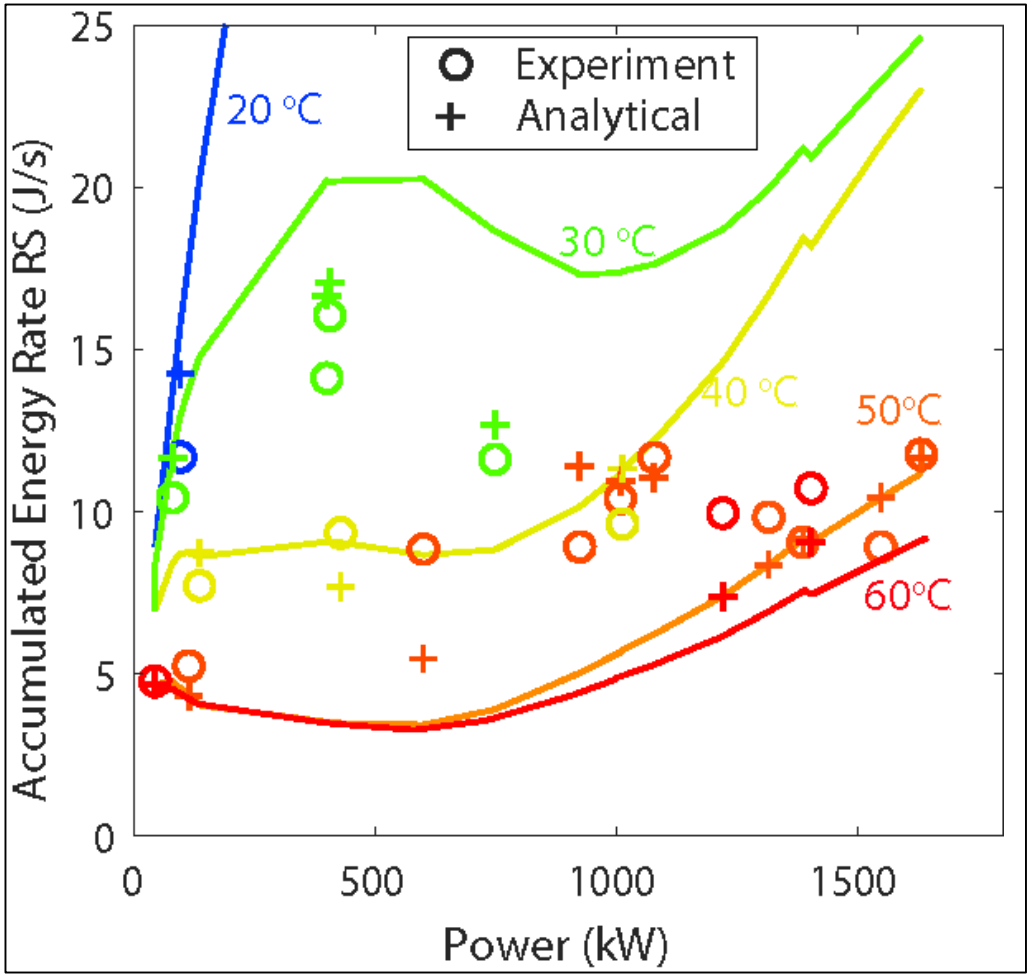
Keller, J., and Y. Guo. 2019. *Analysis of High-Speed-Shaft Bearing Roller Sliding and Frictional Energy in a Wind Turbine Gearbox*. NREL/TP-5000-72415. Golden, CO: National Renewable Energy Laboratory.

Frictional Energy Varies with Power and Temperature

Effects of Temperature on E



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

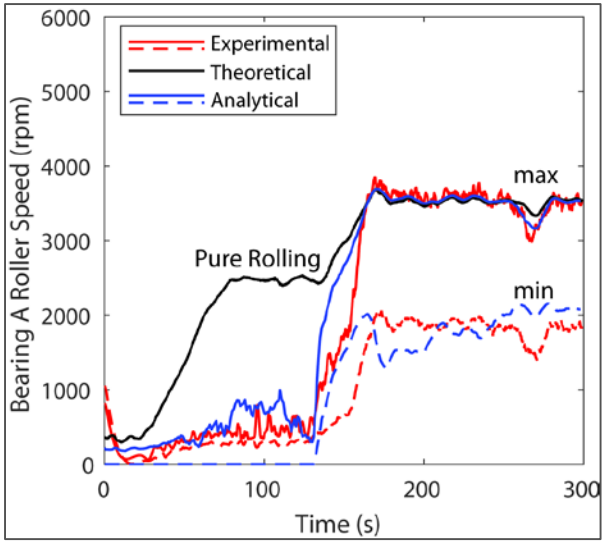


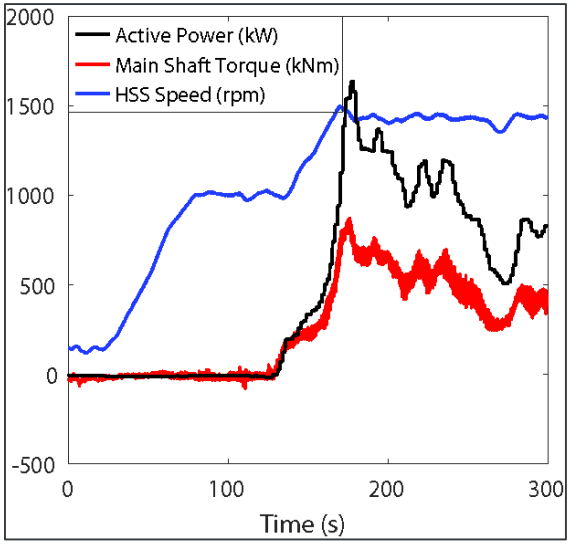
Keller, J., and Y. Guo. 2019. *Analysis of High-Speed-Shaft Bearing Roller Sliding and Frictional Energy in a Wind Turbine Gearbox*. NREL/TP-5000-72415. Golden, CO: National Renewable Energy Laboratory.

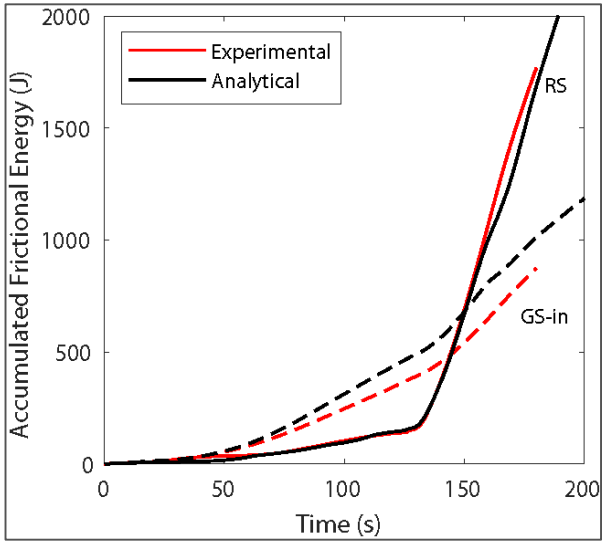
Frictional Energy: Startup Event

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

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





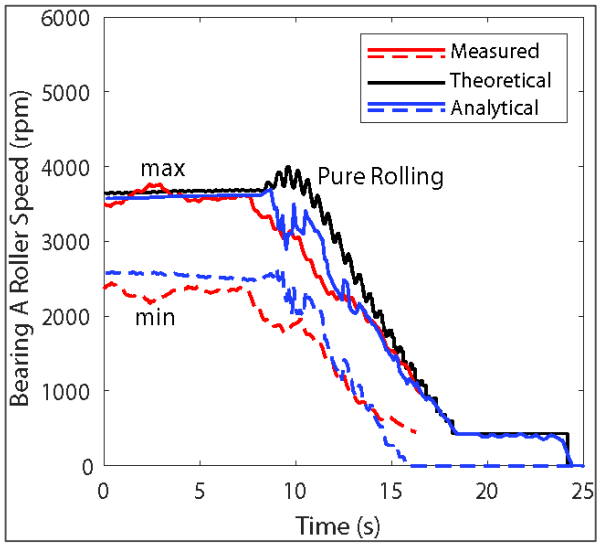


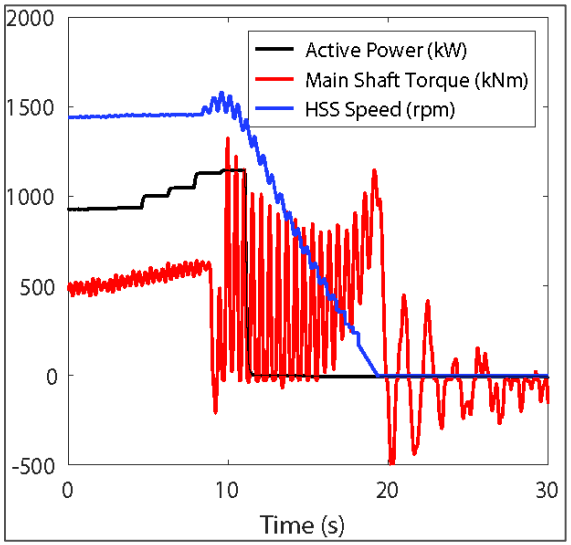
Keller, J., and Y. Guo. 2019. *Analysis of High-Speed-Shaft Bearing Roller Sliding and Frictional Energy in a Wind Turbine Gearbox*. NREL/TP-5000-72415. Golden, CO: National Renewable Energy Laboratory.

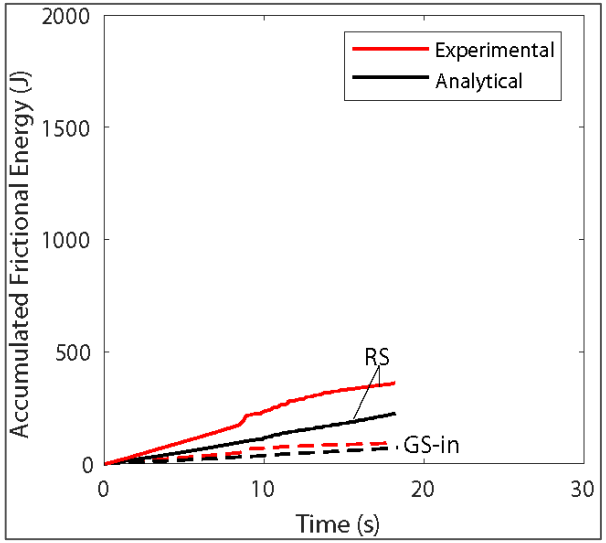
Frictional Energy: Emergency Stop Event

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

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



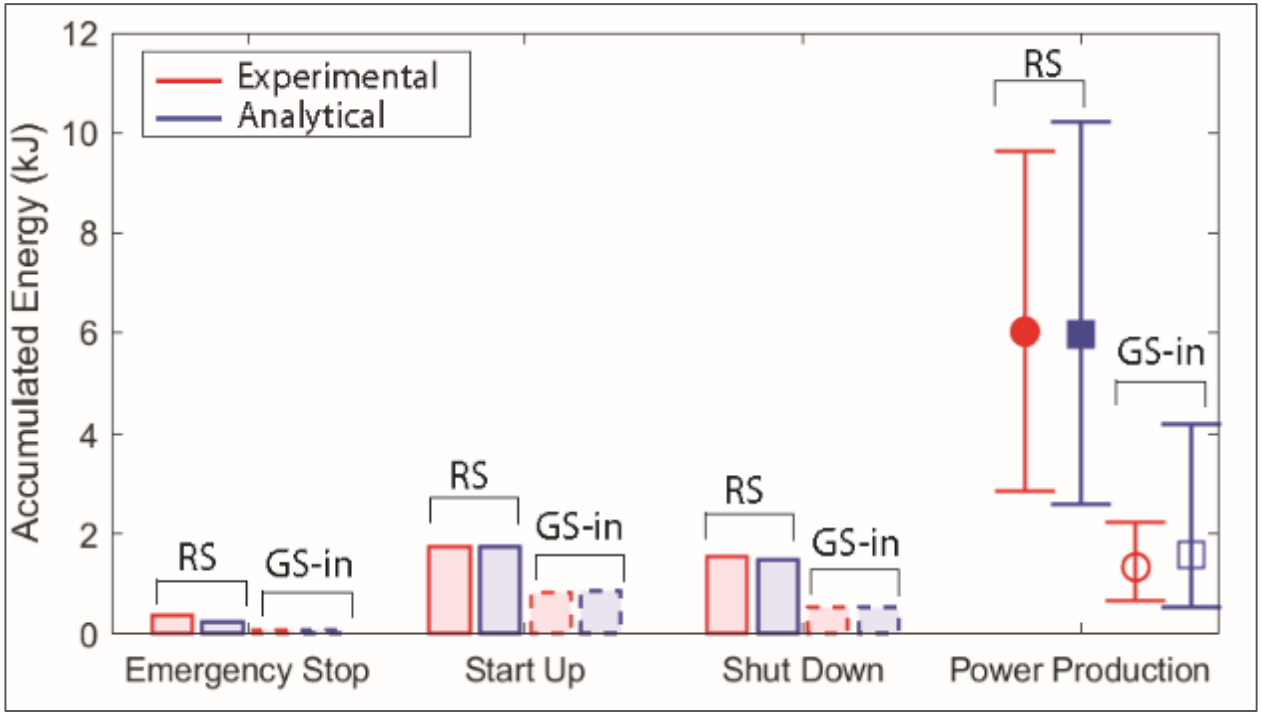




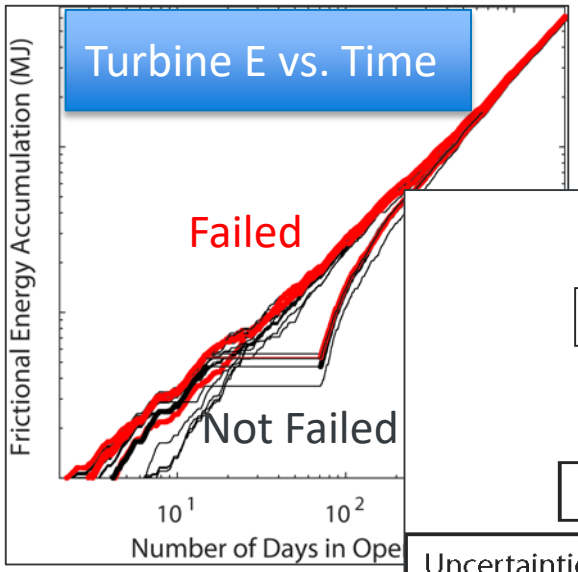
Keller, J., and Y. Guo. 2019. *Analysis of High-Speed-Shaft Bearing Roller Sliding and Frictional Energy in a Wind Turbine Gearbox*. NREL/TP-5000-72415. Golden, CO: National Renewable Energy Laboratory.

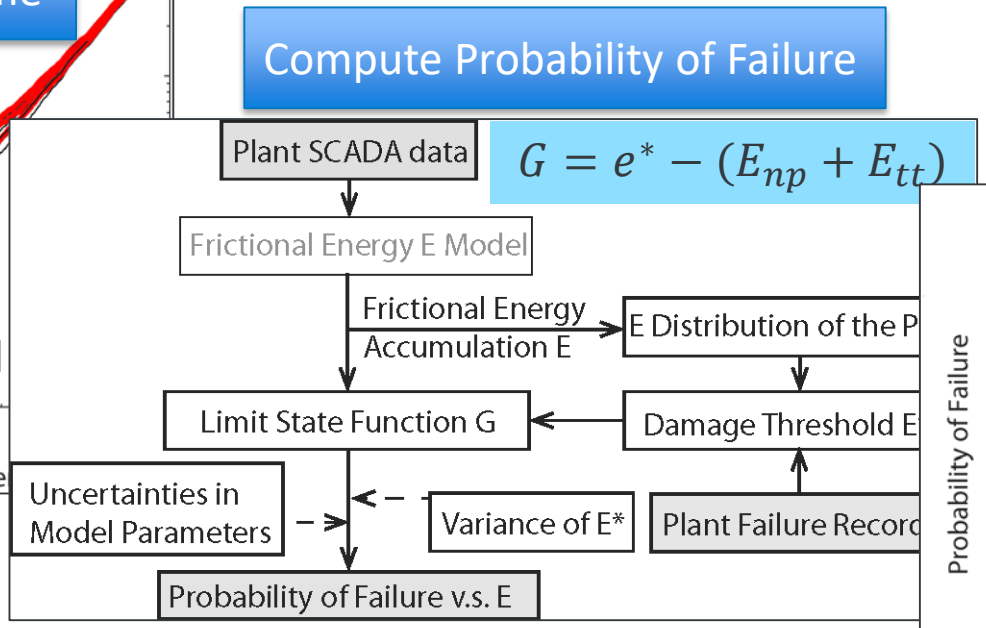
Energy Accumulation Comparison

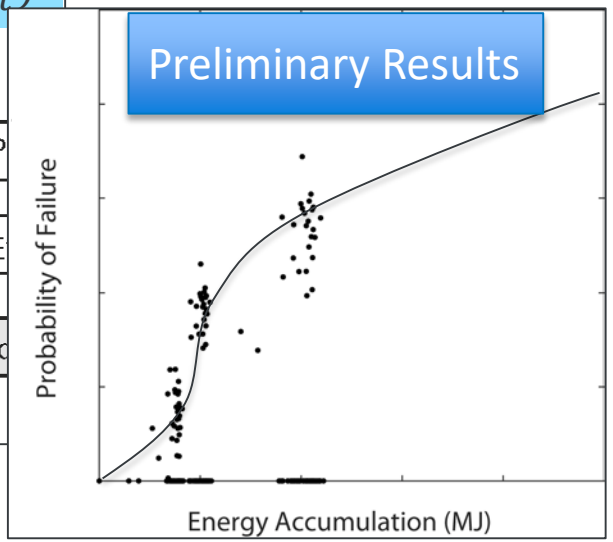
- Compare total sliding energy between turbine operations
- Transients vs. 10-minute projections of normal power
  - Normal power contributes more energy
  - RS (A) has more energy than generator-side inboard (GS-in or B)



Keller, J., and Y. Guo. 2019. *Analysis of High-Speed-Shaft Bearing Roller Sliding and Frictional Energy in a Wind Turbine Gearbox*. NREL/TP-5000-72415. Golden, CO: National Renewable Energy Laboratory.







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

Gould, B., and A. Greco. *The Influence of Sliding and Contact Severity on the Generation of White Etching Cracks*. doi:10.1007/s11249-015-0602-6.

Reliability Assessment and Remaining Life Prediction

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

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

- Bercea, I. et al. *Simulating roller – cage* pocket friction in a tapered roller bearing, European J. Mech. Eng., 1997
- D. Dowson & G. R. Higginson, *The effect of material properties on the lubrication of elastic rollers*, Journal of Mech. Eng. Sci., 1960
- Guo, Y., and J. Keller. 2018. *Investigation of High-Speed Shaft Bearing Loads in Wind Turbine Gearboxes through Dynamometer Testing. Wind Energy*. doi: 10.1002/we.2150.
- Guo, Y., and J. Keller. Forthcoming. *Analytic Formulations of Rolling Element Bearing Sliding in Wind Turbine Gearboxes*. *Mechanism and Machine Theory.*
- Keller, J., and S. Lambert. 2018. *Gearbox Instrumentation for the Investigation of Bearing Axial Cracking*. NREL/TP-5000-70639. Golden, CO: National Renewable Energy Laboratory.
- Keller, J. 2018. *Investigating Main and High-Speed Shaft Bearing Reliability Through Uptower Testing.* NREL/PR-5000-70958. Golden, CO: National Renewable Energy Laboratory.
- Keller, J., Y. Guo, and L. Sethuraman. 2018. *Main and High-Speed Shaft Bearing Reliability Uptower Test Report*. NREL/TP-5000-71529. Golden, CO: National Renewable Energy Laboratory.
- Keller, J., and Y. Guo. 2019. *Analysis of High-Speed-Shaft Bearing Roller Sliding and Frictional Energy in a Wind Turbine Gearbox*. NREL/TP-5000-72415. Golden, CO: National Renewable Energy Laboratory.
- Keller, J., Y. Guo, Z. Zhang, and D. Lucas. 2018. "Comparison of Planetary Bearing Load-Sharing Characteristics in Wind Turbine Gearboxes." *Wind Energy Science*. doi: 10.5194/wes-2018-36.
- Sheng, S., and Y. Guo. 2019. *A Prognostics and Health Management Framework for Wind Energy*. ASME Turbo Expo GT2019-91533.
- T. A. Harris, *An analytical method to predict skidding in high speed roller bearing*, ASLE Transaction, 1966
- T. A. Harris and M. H. Mindel, *Rolling element bearing dynamics*, Wear, 1972
- Vaes, D., Y. Guo, P. Tesini, and J. Keller. 2019. *Investigation of Roller Sliding in Wind Turbine Gearbox High-Speed Shaft Bearings*. NREL/TP-5000-73286. Golden, CO: National Renewable Energy Laboratory.

Acknowledgments

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office and CRADAs 17-694 with Flender Corporation and 16-608 with SKF GmbH. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.