Wind Turbine Drivetrain Reliability Research – Gearbox Bearing Axial Cracking Failure Mode Example

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NREL/PR-5000-85857

IISE Webinar
April 13, 2023

Photo by Dennis Schroeder, NREL 49408

Agenda

- Global Wind Energy
- Drivetrain Reliability Research
- Top Failure Mode Identification
- Benchtop Testing
- Physics-Domain Modeling and Validation
- Reliability Assessment and Prognosis
- Summary
- Q&A

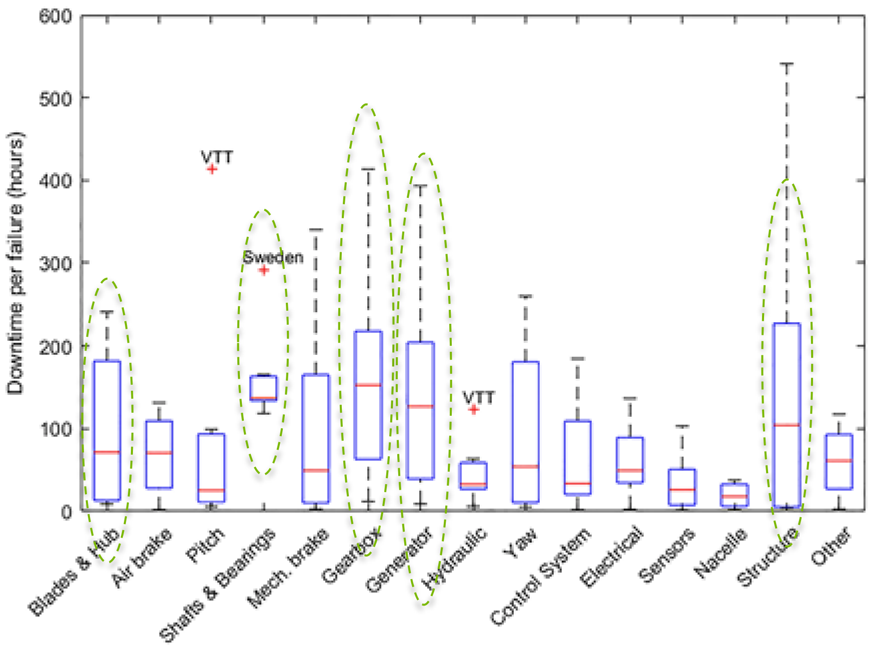
Global Wind Energy

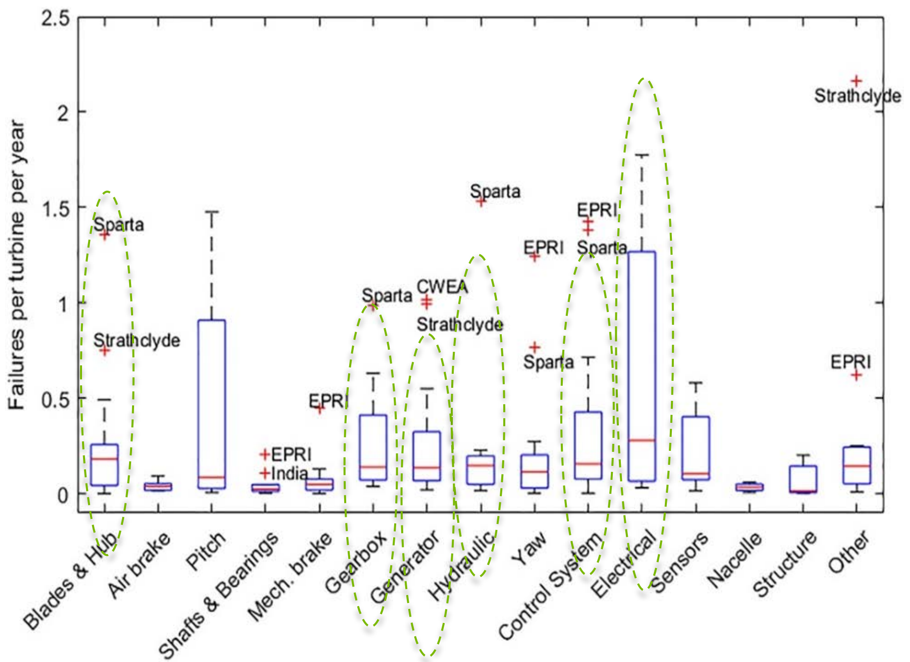
Global Wind Installed Capacity

- Total installed capacity reached 837 GW by the end of 2021 including 57 GW offshore
- Compound annual growth rates (CAGR): slowed down the recent decade still above >10%/year

Source: Global Wind Energy Council, Global Wind Report 2022.

Wind Turbine Reliability Challenge





- **Premature component/subsystem failures, led by gearboxes, challenge the wind industry and result in increased cost of energy for wind power.**

Dao, C., Kazemtabrizi, B., and Crabtree, C. (2019) Wind Turbine Reliability Data Review and Impacts on Levelised Cost of Energy, *Wind Energy*; 22.12: 1848-1871.

Drivetrain Reliability Research

Motivations

- Predominant failure modes ***generally are not***:
  - Accounted for in design standards or predicted by life models
  - Specific to a supplier or due to manufacturing or material quality.
- Need for research to characterize failure modes and:
  - Develop methods to increase reliability and life (coatings, additives, designs, controls)
  - Develop methods to predict remaining useful life and increase availability
  - Reduce drivetrain operations and maintenance (O&M) costs and levelized cost of energy.

Photo courtesy of Argonne National Laboratory (ANL)

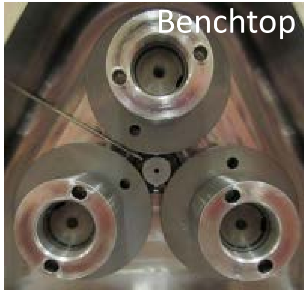


Photo by Mark McDade, NREL 40432

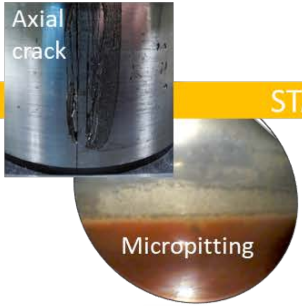
Photo by Dennis Schroeder, NREL 21864

Drivetrain Reliability Research

Pitch, Main, and Generator Bearings and Gearboxes

Source: Keller, J. et al. 2021. Wind Turbine Drivetrain Reliability and Wind Plant Operations and Maintenance Research and Development Opportunities. NREL/TP-5000-80195, [*https://nrel.gov/docs/fy21osti/80195.pdf*](https://nrel.gov/docs/fy21osti/80195.pdf).

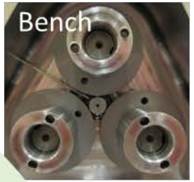
- Identify failure modes
  - Prevalent, costly, and uncharacterized



START

Characterize failures

cracking, wear, micropitting, fretting, …



Quantify damage contributors

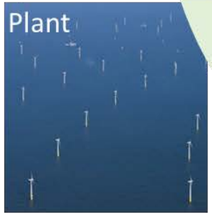
load, stress, cycles, slip, friction, current, …

Develop rating or life model

fatigue, friction energy, …

Verify life model

predictions (hindcast) vs. actual failures (forecast)



- Cooperative R&D Agreements
- Technology Commercialization Funds
- Funding Opportunity Announcements

FINISH

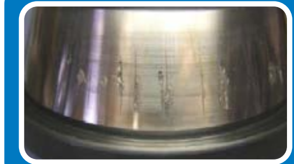
- Improve designs
  - Components, controls, materials, coatings, lubricants…
- Predict Remaining Useful life
- Optimize O&M
- Improve standards
  - AWEA Recommended Practices
  - IEC 61400-4 and AGMA 6006

Drivetrain Reliability Projects

Photo by Dennis Schroeder, NREL 32787

Planetary Load Sharing (New)

- Investigate load sharing in wind turbine drivetrain application
- Quantify differences between drivetrain configurations
- Partners: Romax, SKF, Timken, GEARTECH, Xcel, Brad Foote, Siemens Gamesa



Source: R. Errichello et al. Wind Turbine Tribology Seminar- A Recap. 2012

Gearbox Bearing Axial Cracking (Completing)

- Determine root causes of white-etching cracks (WECs)
- Evaluate effects of lubricant, bearing clearance, and temperature
- Partners: GE, Winergy, SKF, Timken, Afton, Castrol, Klüber, DTU

Source: Windpower Engineering & Development

Main Bearing Reliability (Ongoing)

- Determine root causes of premature wear or surface fatigue
- Evaluate effects of wakes, lubricant, and controller
- Partners: SKF, University of Strathclyde, University of Colorado Boulder

Continue with Plain Bearings?

Source: Windpower Engineering & Development

Pitch Bearing Reliability (New)

- Instrument GE1.5 pitch bearing, validate models, improve rating models
- Update NREL DG03 Pitch and Yaw Bearing Design Guide
- Partner: Fraunhofer IWES and others?

Photo by Dennis Schroeder, NREL 49413

Top Failure Mode Identification

Gearbox Reliability Database

- Started around 2010:
  - No public domain failure statistics available
  - Aim to fill the gap by compiling failure event data through collaborations with partners, emphasizing failure mode and component information.
- Partners:
  - Turbine and gearbox original equipment manufacturers, wind plant owner/operators, gearbox rebuild shops, and consulting companies.
- Major accomplishments:
  - Periodic releases of failure statistics quantitively identifying top failure modes: bearing axial cracking as an example
  - Various failure data collection tools: GearFacts (stand-alone tool)/a postgreSQL database, Excel spreadsheet, portable O&M data collection tool, online portal (including reporting)
  - Standardized terminology and templates.

Gearbox Damage Distribution

- Started around 2010:
  - No public domain failure statistics available
  - Aim to fill the gap by compiling failure event data through collaborations with partners, emphasizing failure mode and component information.
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  - Turbine and gearbox original equipment manufacturers, wind plant owner/operators, gearbox rebuild shops, and consulting companies.
- Major accomplishments:
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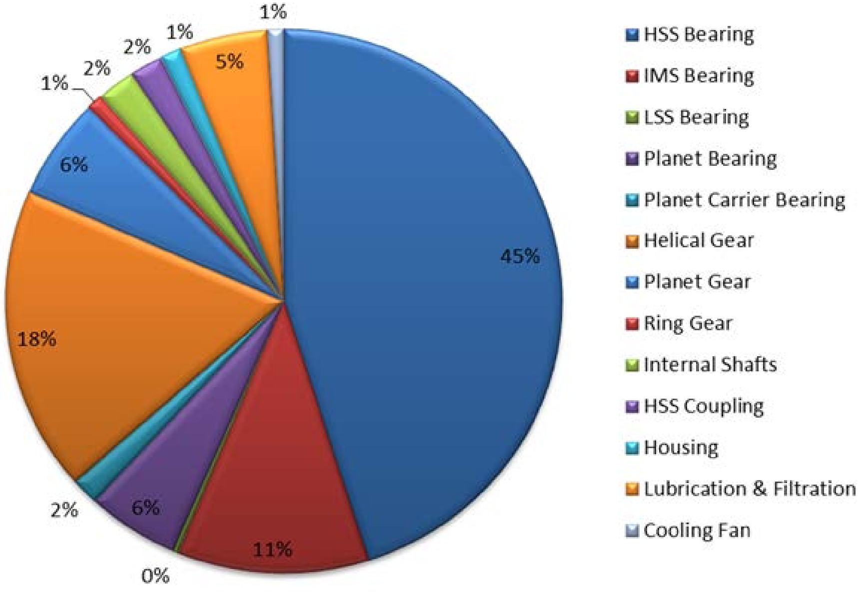


Illustration by NREL

Top Bearing Failure Mode: Axial Cracking

- Samples: about 80 records
- Axial cracks: 71%
- Spalling: 23%
- Pitting: 6%

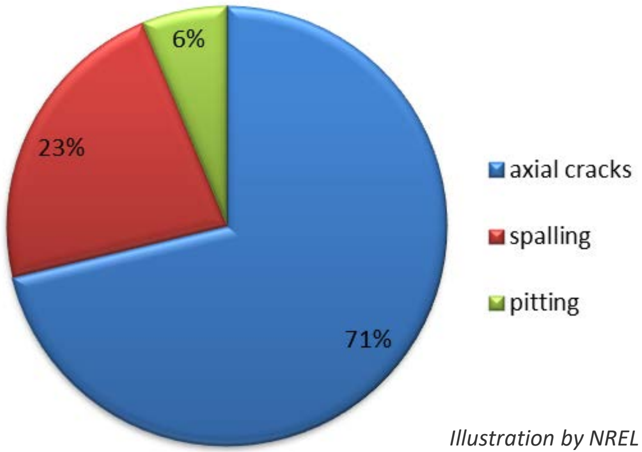
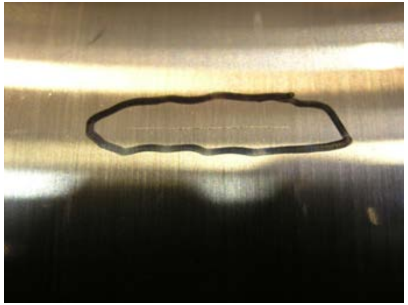
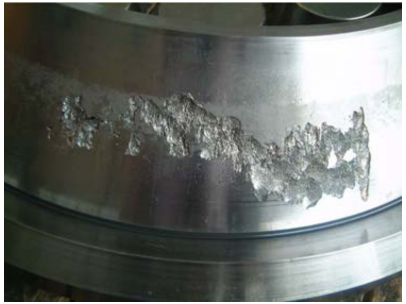


Illustration by NREL



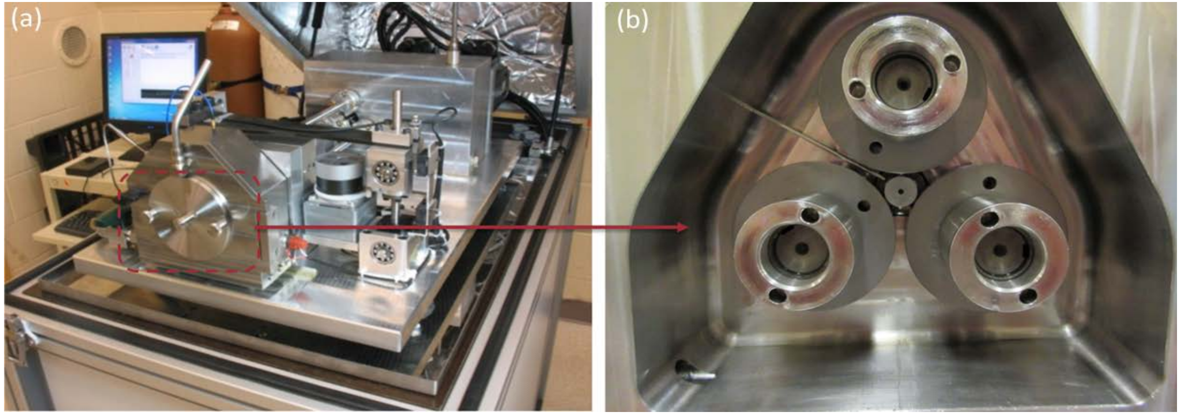


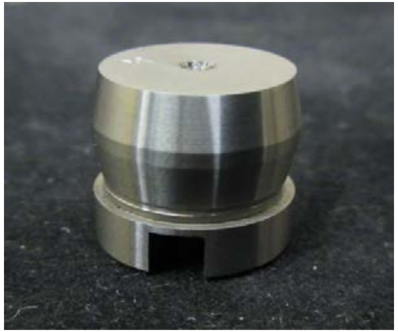
Axial cracks (dominated by high-speed and intermediate-speed stage bearings inner raceway)

Left and middle photos from Gary Doll, University of Akron; right photo from Ryan Evans, Timken

Benchtop Testing at Argonne National Laboratory

Micropitting Rig

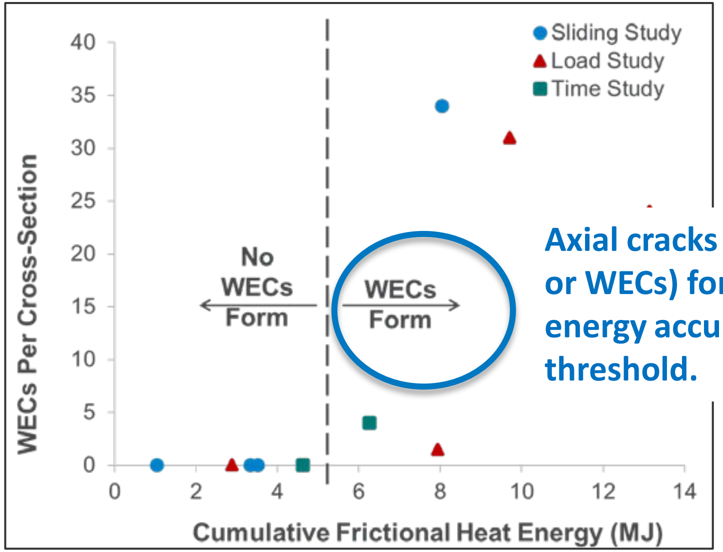




Micropitting Rig Capabilities

- Three rings on roller splash lubricated contact
- Varying levels of sliding
- Speeds up to ~350 contacts per second
- Lubricant temperatures up to 120°C

Gould, Benjamin, and Aaron Greco. 2015. “The Influence of Sliding and Contact Severity on the Generation of White Etching Cracks.” *Tribology Letters* 60(2): 1–13, doi:10.1007/s11249-015-0602-6.



Axial cracks (white etching cracks, or WECs) form when frictional energy accumulation exceeds its threshold.

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.

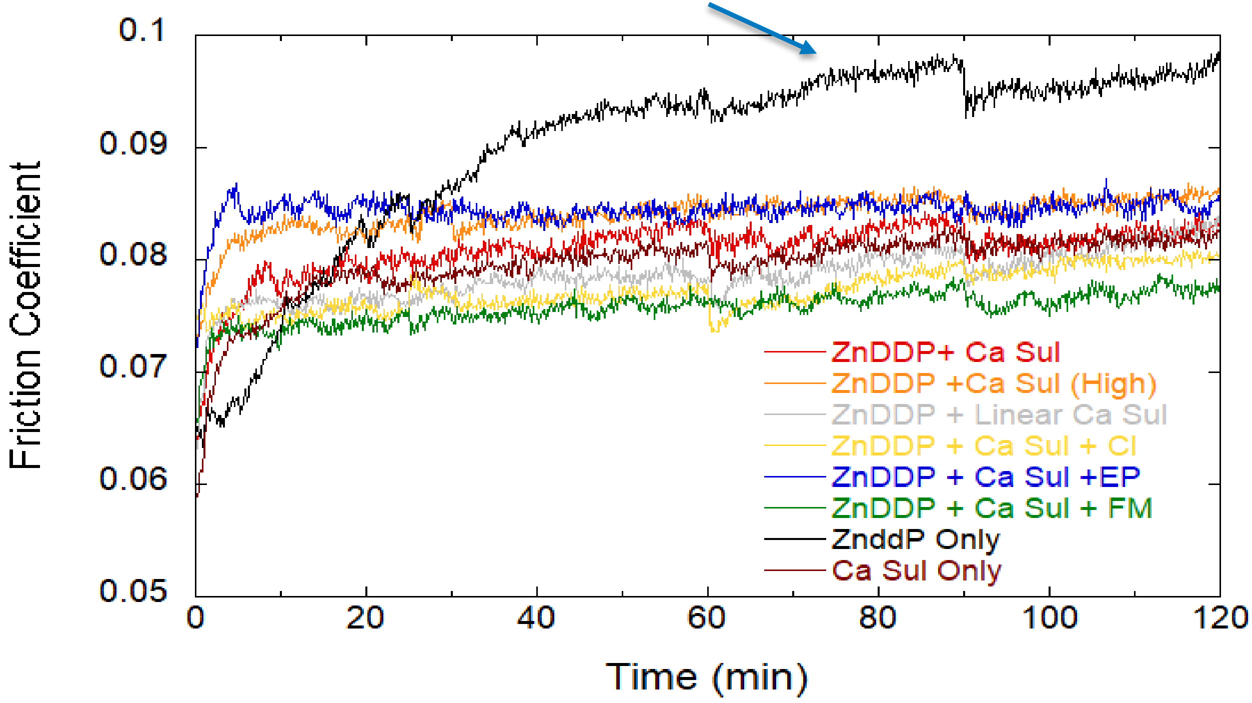
Roller Sliding Under Loaded Conditions Led to Axial Cracking

- Influence of sliding, load, and test duration
- Testing done using "Bad Reference Oil"–known to aid in WEC formation

Additive Impact on Friction

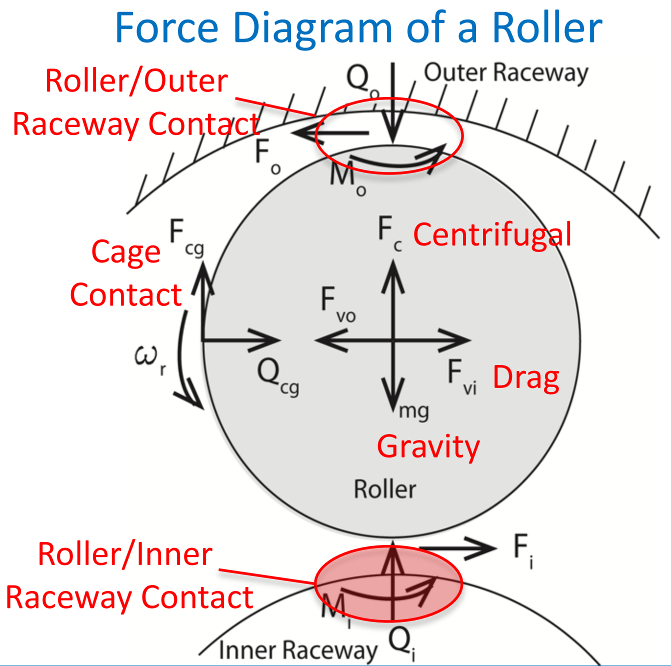
	Bad Reference Oil
ZnDDP	1.82
OB Ca Sul (branched alkyl chain)	2.84
Na Sulfonate	0.75
GMO	0.49
Polysulfide	0.24

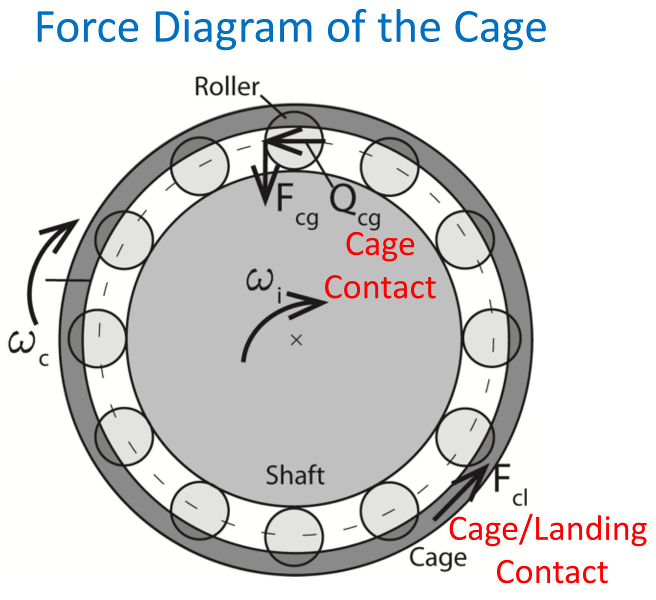
Highest Friction = Earliest Failure



Gould, B., et al. 2019. "The Effect of Lubricant Composition on the Formation of White Etching Cracks." *Tribology Letters* 67. doi:10.1007/s11249-018-1106-y.

Physics-Domain Modeling





Analytical Model Predicts Roller and Cage Slip

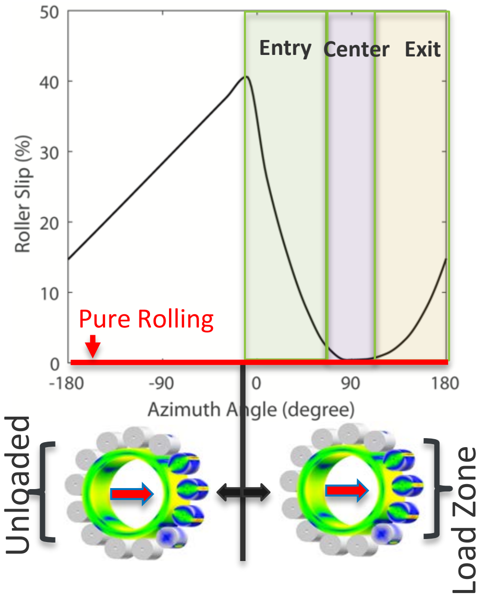
- Target cylindrical roller bearings and consider:
  - ✓ Contact at roller/raceway, roller/cage, and cage/landing
  - ✓ Bearing/lubricant interactions
  - ✓ Gravity, centrifugal, and drag forces.

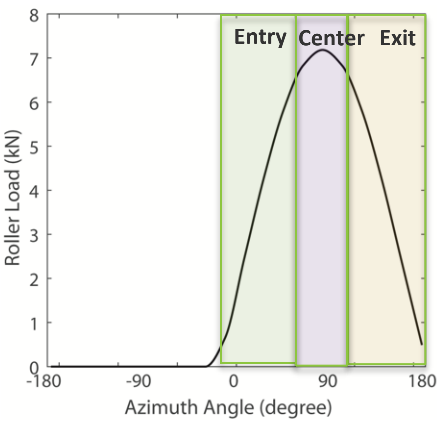
Guo, Y., and J. Keller. 2020. "Validation of Combined Analytical Methods to Predict Slip in Cylindrical Roller Bearings." *Tribology International.* 148:106347. https://doi.org/10.1016/j.triboint.2020.106347

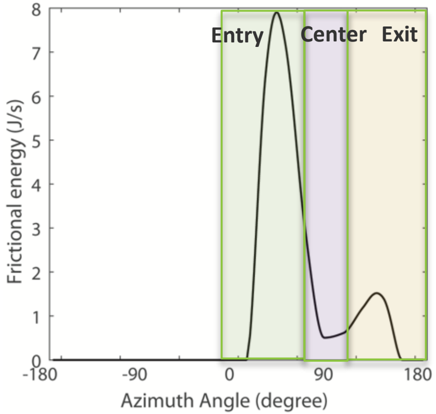
Calculate Frictional Energy From Roller Speed

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

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







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

Test Turbine and Met Tower Instrumentations

- 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 Meteorological (Met) Tower
- Air temperatures and humidity
- Wind speed and direction
- And more…GPS time-stamped

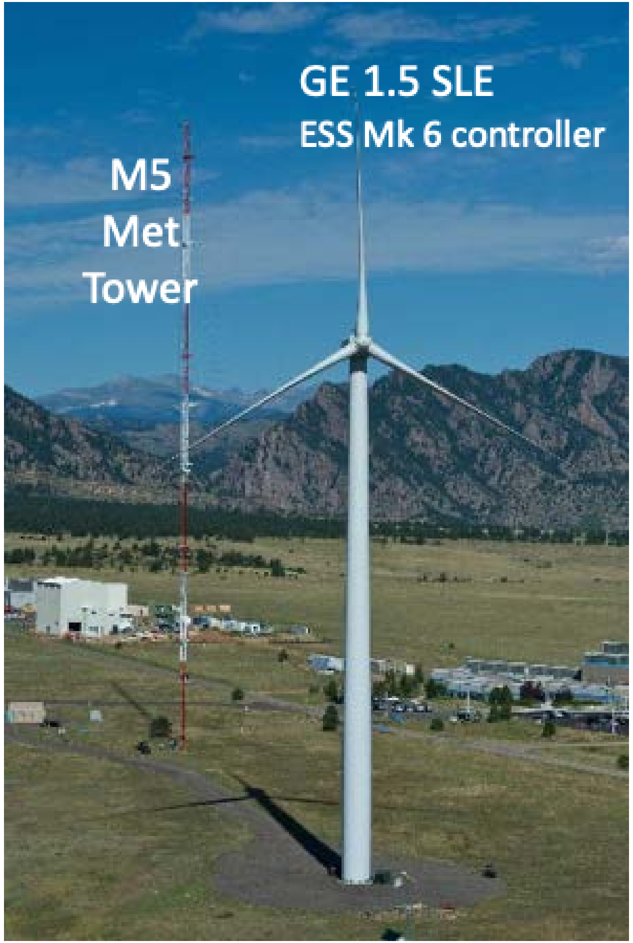
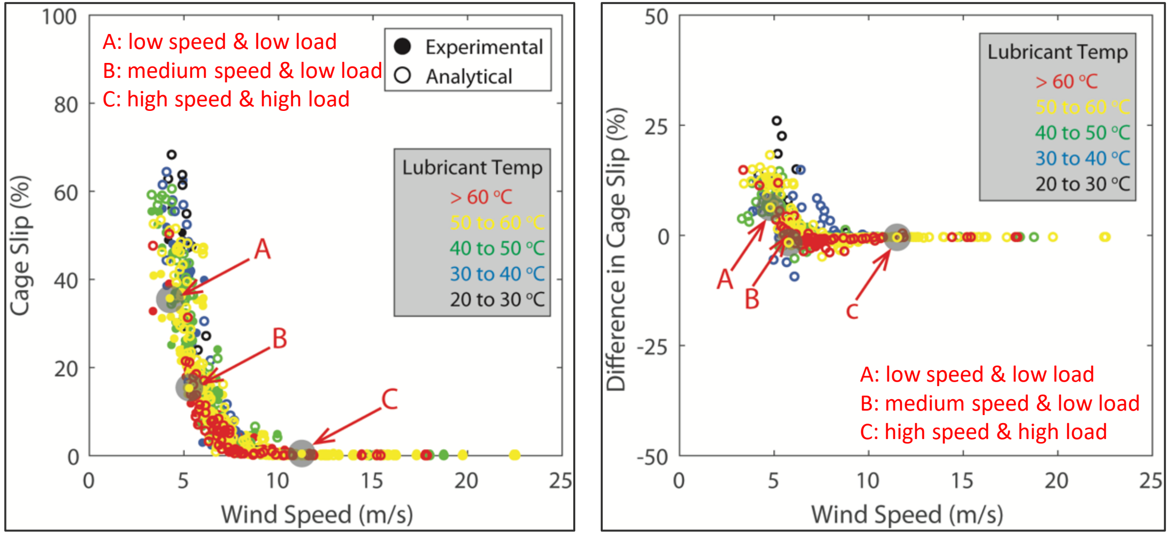


Photo by Dennis Schroeder / NREL, 21884

Validation: Cage Slip

- Developed and validated analytical bearing roller sliding model to evaluate the effect of gearbox, bearing, and lubricant changes on cumulative frictional energy and resultant axial cracking
- Analytical model validated over the full range of turbine operating conditions, power (0% to 120%), speed (60% to 100%), and temperature (20°C to 60°C).

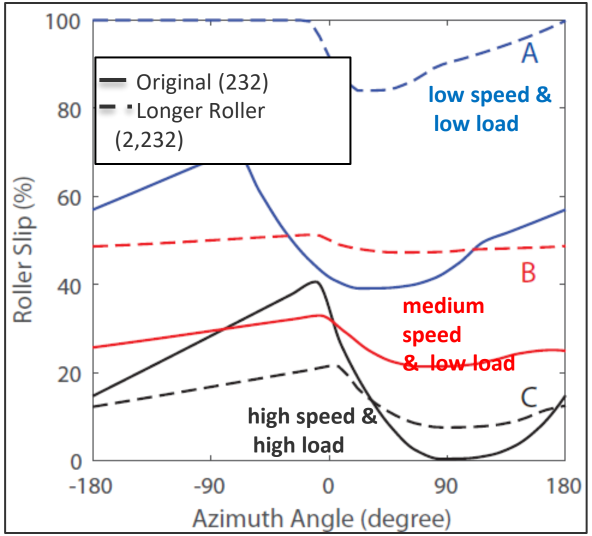


Guo, Y., and J. Keller. 2020. “Validation of Combined Analytical Methods to Predict Slip in Cylindrical Roller Bearings.” *Tribology International.* 148:106347. https://doi.org/10.1016/j.triboint.2020.106347

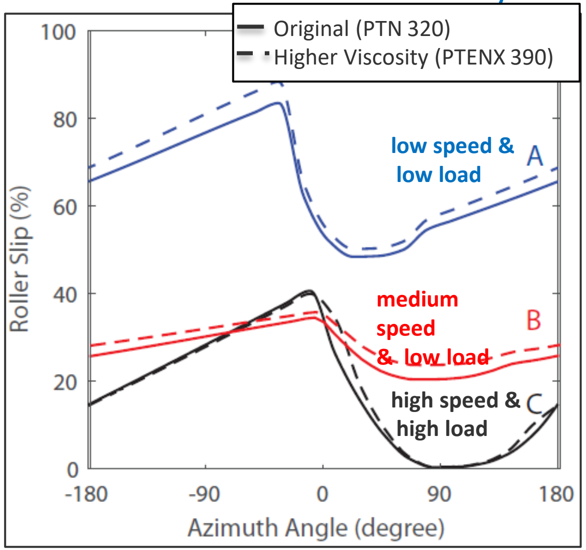
Design Study: Roller Slip

- Model evaluates the effect of gearbox, bearing, and lubricant changes on bearing sliding
  - Examined effects of bearing type and size, and lubricant temperature and viscosity on slip.

Effect of Bearing Size



Effect of Lubricant Viscosity



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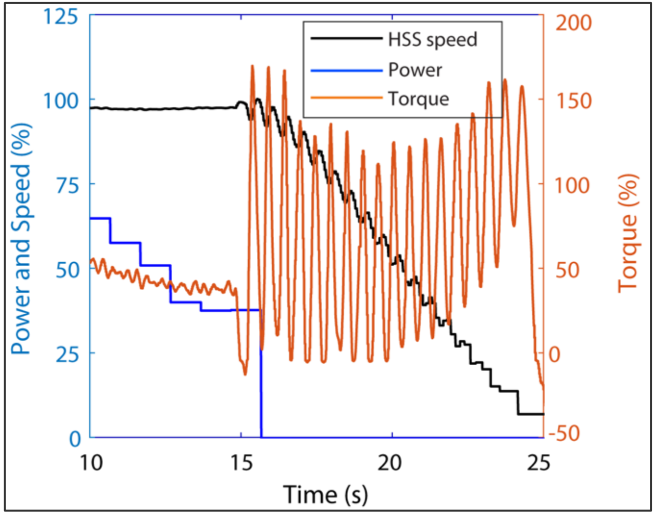
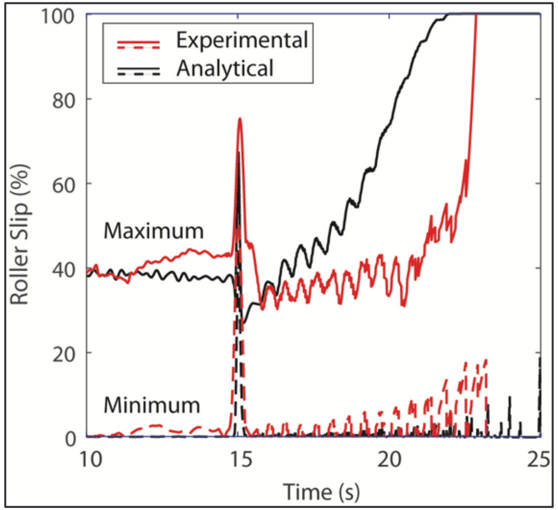
Measured Turbine Responses During An E-Stop



Resulting Roller Slip (Measured/Predicted)

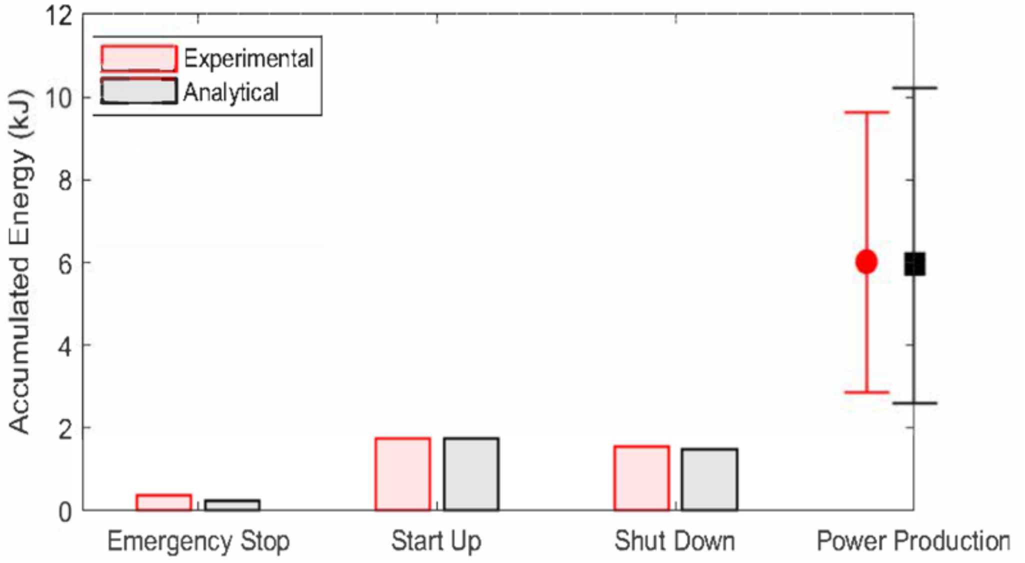


Roller Slip During Transient Events

- Predicted cage and roller slip compared to measured results during start-up, shut-down, and emergency-stop events with reasonable accuracy.

Frictional Energy Comparison

- Compare total sliding energy between turbine operations
- Transients vs. 10-minute projections of normal power
  - Normal power contributes more energy.

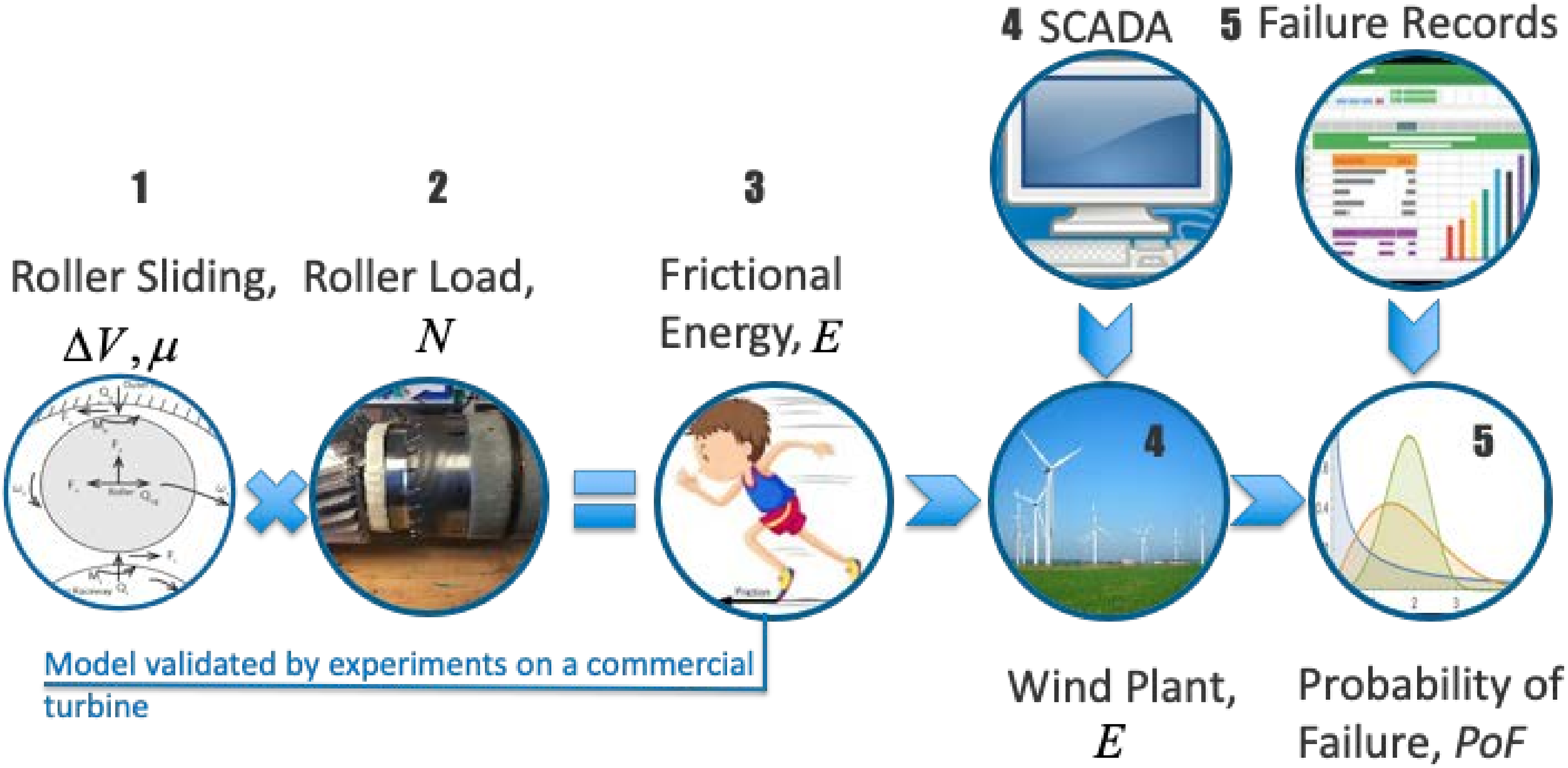


Y. Guo, et, al., 2019. *Quantification of Roller Sliding Energy in Wind Turbine Gearbox High-Speed Shaft Bearings*. Golden, CO: National Renewable Energy Laboratory. NREL/PR-5000-73320.

Reliability Assessment and Prognosis

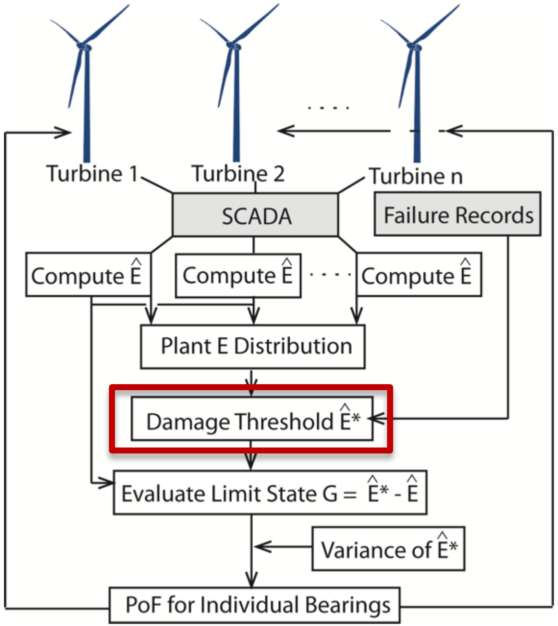
Physics-domain modeling with data domain inputs

Reliability Assessment and Prognosis



Guo, Yi et al. Wind Turbine Drivetrain Reliability Assessment and Remaining Useful Life Prediction. NREL/PR-5000-79004. https://www.nrel.gov/docs/fy21osti/79004.pdf

Flow Chart to Calculate PoF



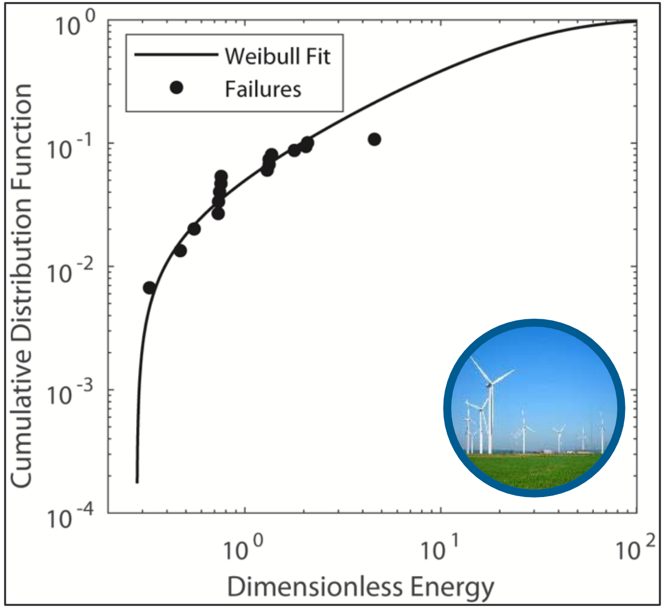
- E – Frictional Energy
- G – Limiting State Function
- PoF – Probability of Failure

Bearing Probability of Failure Predictions

- Interdisciplinary models applicable to various wind plants
- Investigate both high-speed and intermediate-speed stage bearings
- Reliability analysis forecasts individual bearing probability of failure.

Guo, Y., et al., 2020. "A Methodology for Reliability Assessment and Prognosis of Bearing Axial Cracking in Wind Turbine Gearboxes." *Renewable and Sustainable Energy Reviews.* 127: 109888. https://doi.org/10.1016/j.rser.2020.109888.

Weibull Fit of Frictional Energy for Failed Turbines

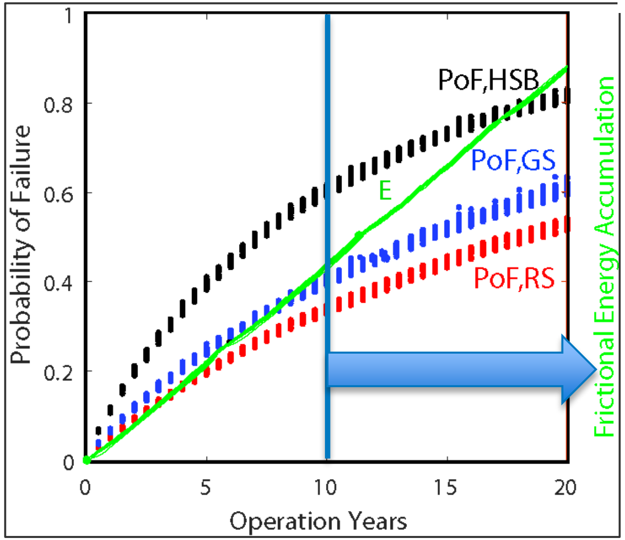


Define Frictional Energy Threshold Distribution

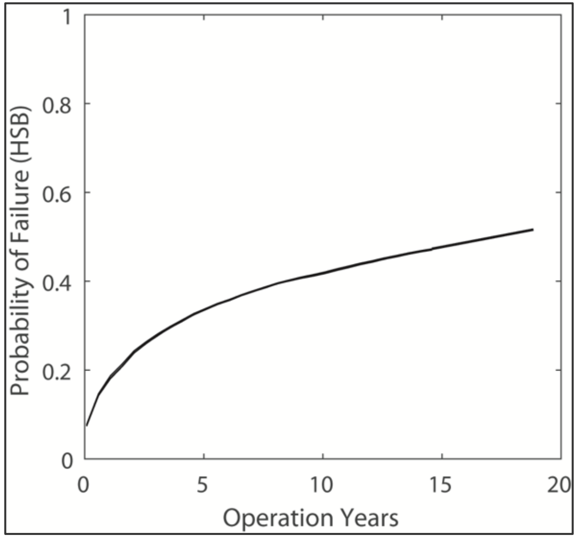
- Weibull cumulative distribution function of frictional energy of failed turbines defines the distribution of energy threshold for the rest of wind plant
- Frictional energy nondimensionalized to consider failures at multiple locations to expand failure records.

Guo, Y., et al. 2020. "A Methodology for Reliability Assessment and Prognosis of Bearing Axial Cracking in Wind Turbine Gearboxes." *Renewable and Sustainable Energy Reviews.*

PoF Using Frictional Energy



PoF Using Power-Hour Accumulations



PoF Predictions Using Frictional Energy and Power-Hour Accumulations

- PoF can be estimated at individual bearings
- Differences in PoFs among turbines insufficient to single out the failed turbines
  - ➢Driven by small E variations among turbines
- The power-hour approach may provide a fast PoF estimate at *plant* level but cannot investigate individual bearings.

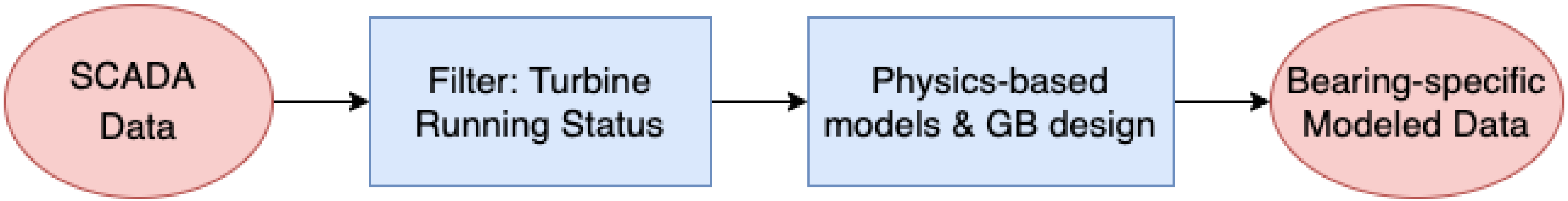
Guo, Y., et al. 2020. “A Methodology for Reliability Assessment and Prognosis of Bearing Axial Cracking in Wind Turbine Gearboxes.” *Renewable and Sustainable Energy Reviews.* 127: 109888. https://doi.org/10.1016/j.rser.2020.109888.

Reliability Assessment and Prognosis

Machine learning algorithms using both data and physics-domain features as inputs

Data Description

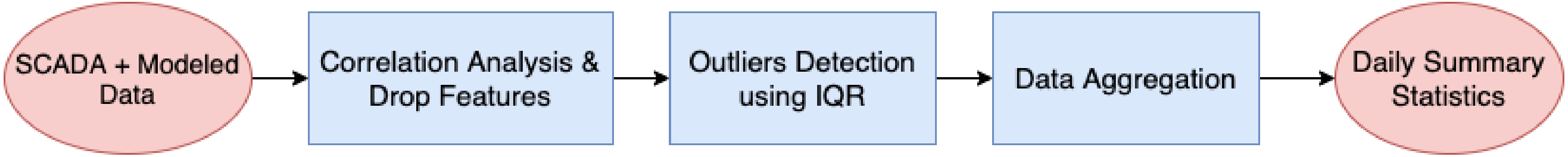
- Consider the data only when a turbine is in running condition and power is produced.
- To represent bearing’s health, additional data are calculated using various physics domain models developed based on gearbox configuration information:
  - Bearing load, roller load, roller deflection, frictional energy, slide-to-roll ratio, etc.



Desai, A., Guo, Y., Sheng, S., Sheng, S., Phillips, C., & Williams, L. (2020). Prognosis of Wind Turbine Gearbox Bearing Failures using SCADA and Modeled Data. Annual Conference of the PHM Society, 12(1), 10. https://doi.org/10.36001/phmconf.2020.v12i1.1292

Data Preprocessing

- Data gaps exist and are not continuous at 10-minute resolution
- Data aggregation and daily summary statistics are found:
  - Minimum, maximum, length of data
  - Mean, standard deviation, root mean square
  - Skewness and kurtosis.



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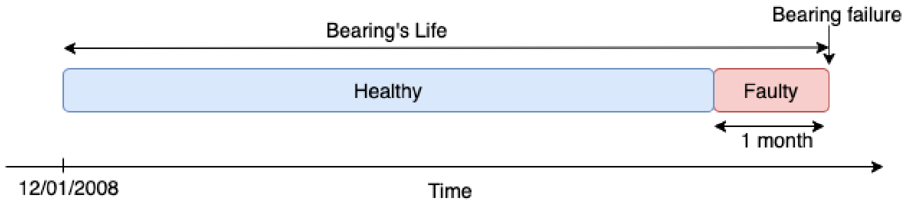
Methodology

- Data Labeling
  - Predicting failure 30 days ahead of its onset
  - Assumption: Data from last month before failure contain strong signal of bearing fault.



- Total of four algorithms are selected for bearing failure prediction:
  - Logistic regression
  - Random forest
  - XGBoost (extreme gradient boosting)
  - LSTM (long short-term memory networks).

Desai, A., Guo, Y., Sheng, S., Sheng, S., Phillips, C., & Williams, L. (2020). Prognosis of Wind Turbine Gearbox Bearing Failures using SCADA and Modeled Data. Annual Conference of the PHM Society, 12(1), 10. https://doi.org/10.36001/phmconf.2020.v12i1.1292

Performance Evaluation

- All four algorithms are trained and tested on two sets of data:
  - SCADA data
  - SCADA data + modeled data.

		Prediction	
		Healthy	Faulty
Actual	Healthy	True Negatives (TN)	False Positives (FP)
	Faulty	False Negatives (FN)	True Positives (TP)

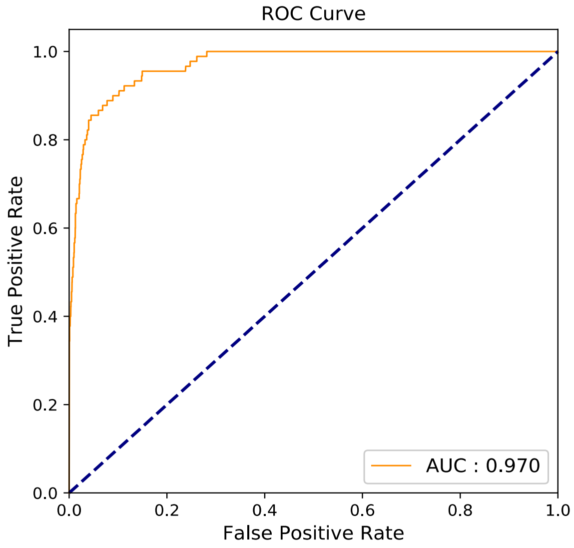
- Modeling performance metrics: Precision, Recall, F1 score and AUC (area under ROC [receiver operating characteristic] curve).

Metric	Formula
Precision	TP/(TP + FP)
Recall or TPR	TP/(TP + FN)
F1 score	2 × Precision × Recall/(Precision + Recall)
FPR	FP/(FP + TN)

Desai, A., Guo, Y., Sheng, S., Sheng, S., Phillips, C., & Williams, L. (2020). Prognosis of Wind Turbine Gearbox Bearing Failures using SCADA and Modeled Data. Annual Conference of the PHM Society, 12(1), 10. https://doi.org/10.36001/phmconf.2020.v12i1.1292

Results

- When physics-domain modeled data were added in addition to SCADA data, model performance increases in terms of F1 score and AUC.
  – Precision increases (~ false alarms decrease), which improves overall F1, as it is a harmonic mean of precision and recall.
  – LSTM models perform the best (not surprising, as they are best among investigated for time series classification).
- Further work on prognosis using hybrid data and physics domain modeling continues.



Desai, A., Guo, Y., Sheng, S., Sheng, S., Phillips, C., & Williams, L. (2020). Prognosis of Wind Turbine Gearbox Bearing Failures using SCADA and Modeled Data. Annual Conference of the PHM Society, 12(1), 10. https://doi.org/10.36001/phmconf.2020.v12i1.1292

Summary

Drivetrain Reliability Research

- Overall drivetrain reliability methodology and related projects presented
- Detailed steps illustrated using bearing axial cracking failure mode as an example
  - Top failure mode identification
  - Benchtop testing
  - Physics-domain modeling and validation
  - Reliability assessment and prognosis.
- Future work continues in drivetrain reliability and broad wind plant O&M
  - Supporting U.S. onshore wind energy industry needs
  - Staying ahead through R&D in reliability and O&M to help minimize U.S. offshore wind energy O&M costs and maximize the potential to meet ambitious development goals.

Q&A

Photo by Dennis Schroeder, NREL 49413

Thank you!

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