Validation of a Generalized Formulation for Load-Sharing Behavior in Epicyclic Gears for Wind Turbines

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Wind Turbine Drivetrain Technology, Operations, and Maintenance

Photo by Dennis Schroeder, NREL 49418

- NREL develops and verifies advanced drivetrain concepts and innovative bearing, gearbox, and generator technologies.
- We lead the Drivetrain Reliability Collaborative to increase drivetrain reliability and turbine availability through improved designs and prognostic technology, thereby reducing operations and maintenance costs.

Areas of Expertise

- Drivetrain innovation
- Drivetrain modeling, analysis, and validation
- Prognostics and health management
- Reliability, operations, and maintenance

Drivetrain Reliability Research

- 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:
  - Increase reliability and life (coatings, additives, lubricants, designs, controls)
  - Predict remaining useful life and increase availability
  - Reduce drivetrain O&M costs.

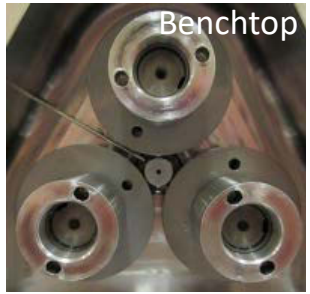

Photo courtesy of Argonne National Laboratory

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Photo by Dennis Schroeder, NREL 21864

Validation of a Formulation for Epicyclic Load Sharing

- Load-Sharing Formulation
- Experimental Validation
- Results and Summary

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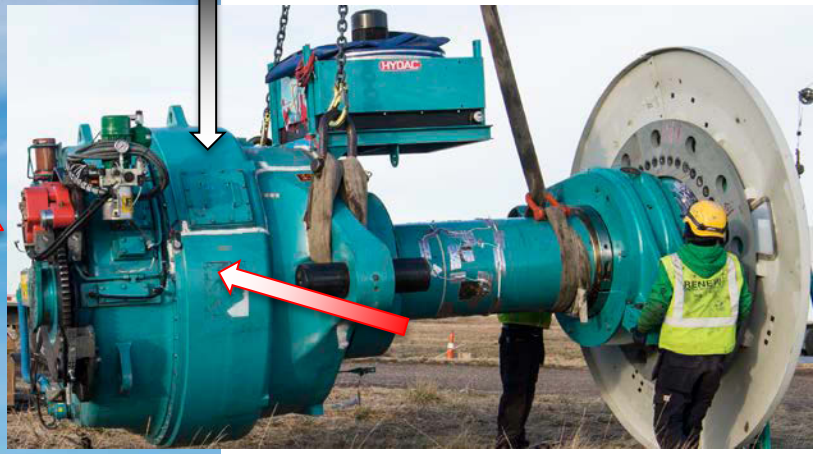


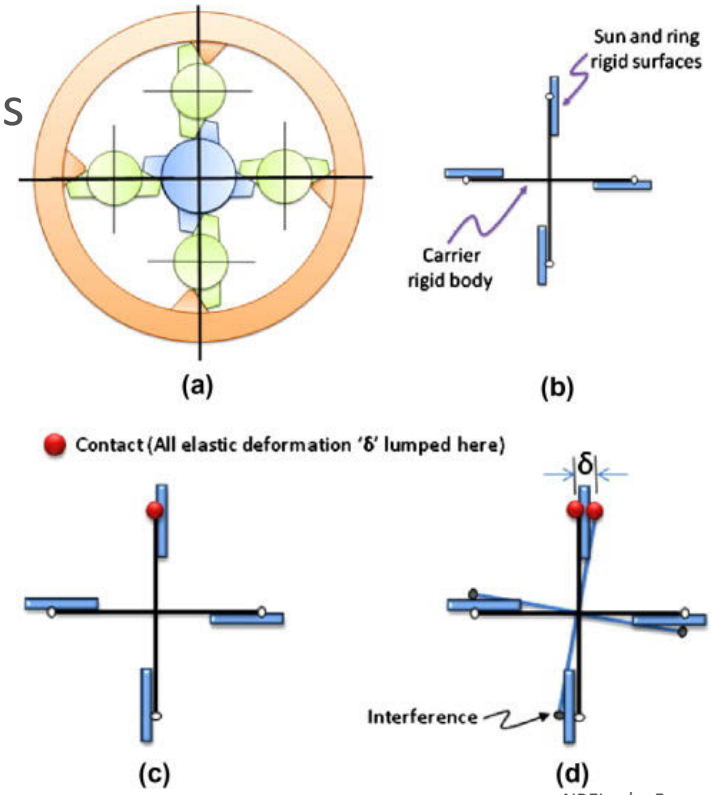
Photo by Dennis Schroeder, NREL 49418

Rotor pitch (nodding) moment

Rotor yaw moment

Epicyclic Load Sharing

- Ideally, all gears transmit equal torque
  - Manufacturing errors create unequal loads
  - Floating central member can compensate
- Singh previously developed an analytic model for load sharing
- This work validates the Singh model that was reformulated for horizontally mounted gearboxes subjected to nontorque loads



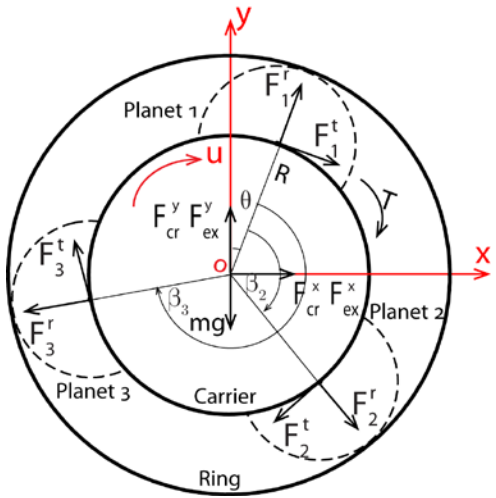
Source: Singh, A., 2010. "Load Sharing Behavior in Epicyclic Gears: Physical Explanation and Generalized Formulation." Mechanism and Machine Theory, 45: 511–530. doi: 10.1016/j.mechmachtheory.2009.10.009.

Epicyclic Load-Sharing Model

- Planetary mesh load factor (K_γ)
  - Actual load/ideal load
  - Varies once per revolution
  - Maximum value (K_γ^*) examined

For a 3-planet floating system:

$$K_\gamma^* = 1 + \frac{K_m \delta_{rp}}{T/3R} + \frac{2R\sqrt{\left(F_{ex}^x + F_c^x\right)^2 + \left(F_{ex}^y + F_c^y - mg\right)^2}}{T}$$



T	Torque
R	Center radius
$K_m \delta_{rp}$	Mesh force
F_{ex}	External force from rotor moment
F_c	Carrier bearing reaction, if in contact, depending on clearance Δ_c
mg	Equivalent system weight

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Photo by Jonathan Keller, NREL 36512

Source: Guo, Y., J. Keller, Z. Zhang, and D. Lucas. 2017. Planetary Load Sharing in Three-Point-Mounted Wind Turbine Gearboxes: A Design and Test Comparison (Presentation). NREL/PR-5000-68021. National Renewable Energy Laboratory (NREL), Golden, CO (US). https://www.nrel.gov/docs/fy17osti/68021.pdf.

Dynamometer Validation

- Full 750-kilowatt wind turbine drivetrain, 2 different gearboxes
- Calibrated strain gauges on planet bearing inners
- Applied nontorque loads with hydraulic actuators
- Measured planet bearing loads and other parameters

Photo by Mark McDade, NREL 32734

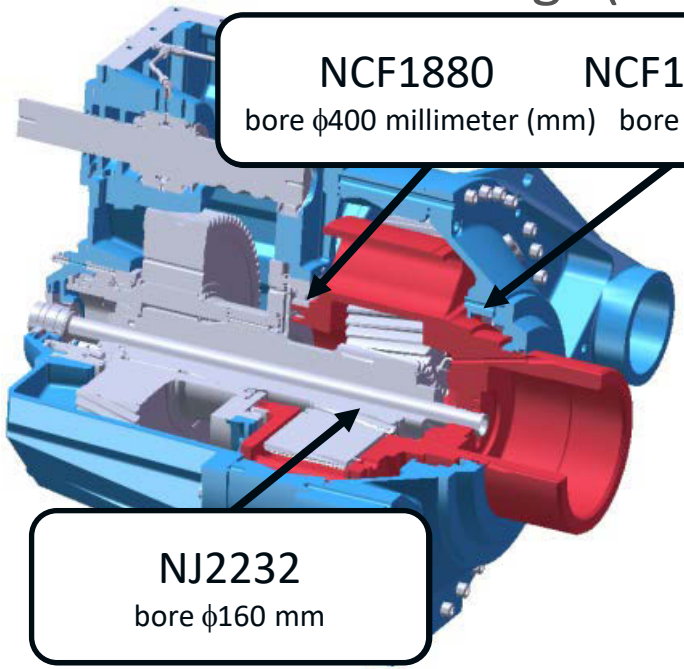
Photo by Mark McDade, NREL 40432

Photo by Jonathan Keller, NREL 36521

Reference: Keller, J. et al. 2018. "Comparison of planetary bearing load-sharing characteristics in wind turbine gearboxes." Wind Energy Science, 3: 947–960. doi: 10.5194/wes-3-947-2018.

Planet and Carrier Bearing Designs

Gearbox with Cylindrical Roller Bearings (CRBs)



Modified Jahnel-Kestermann PSC 1000-48/60 3-stage gearbox

Gearbox with Tapered Roller Bearings (TRBs)

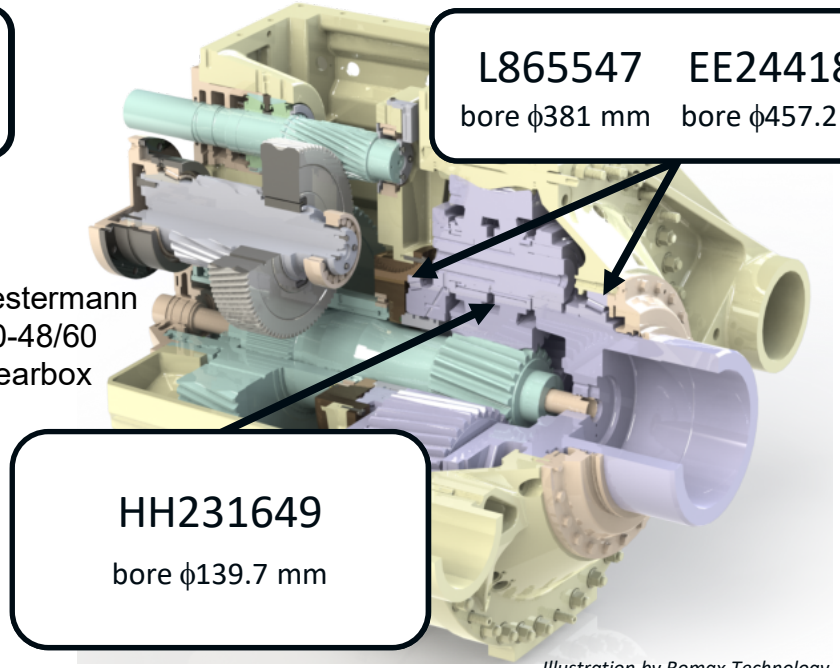


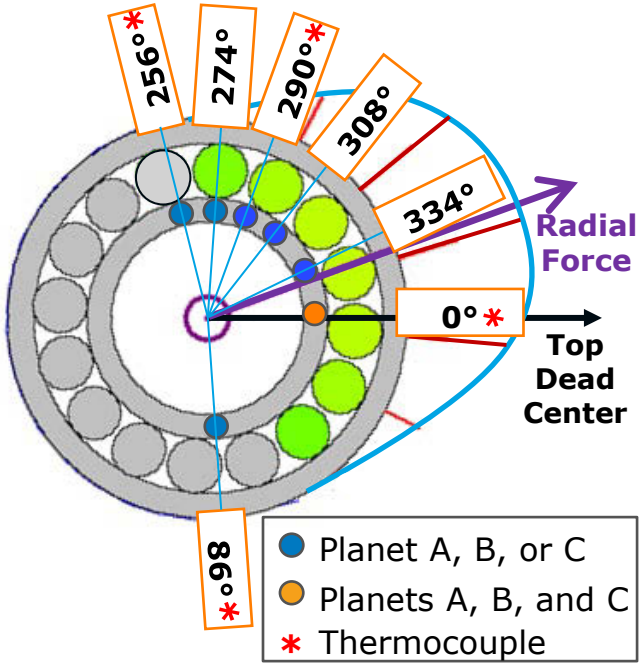
Illustration by Romax Technology

Source: Guo, Y., J. Keller, Z. Zhang, and D. Lucas. 2017. Planetary Load Sharing in Three-Point-Mounted Wind Turbine Gearboxes: A Design and Test Comparison (Presentation). NREL/PR-5000-68021. National Renewable Energy Laboratory (NREL), Golden, CO (US). https://www.nrel.gov/docs/fy17osti/68021.pdf.

Planet Bearing Instrumentation

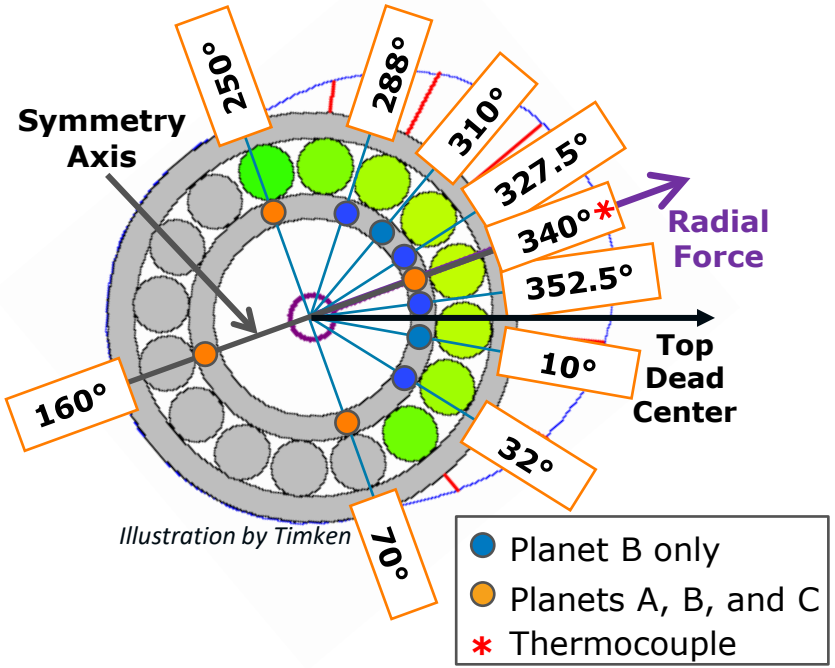
Gearbox with CRBs

2 measurements per row at each location



Gearbox with TRBs

1 measurement per row at each location



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Validation of a Formulation for Epicyclic Load Sharing

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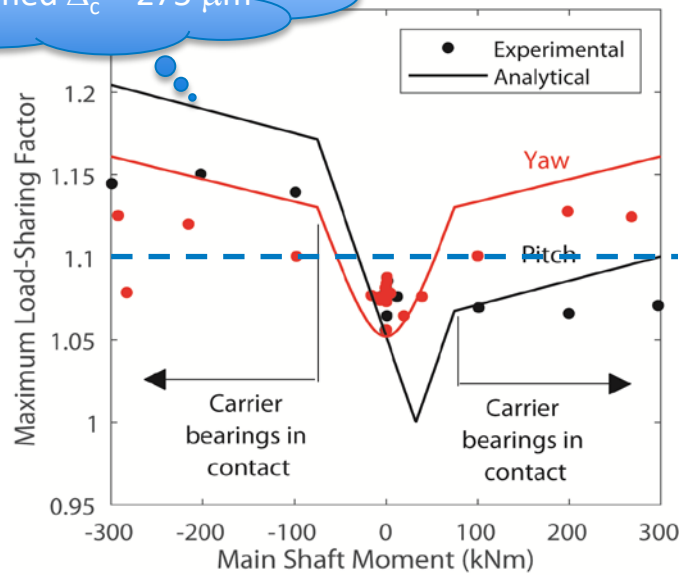
Photo by Jonathan Keller, NREL 36525

Load-Sharing Factors

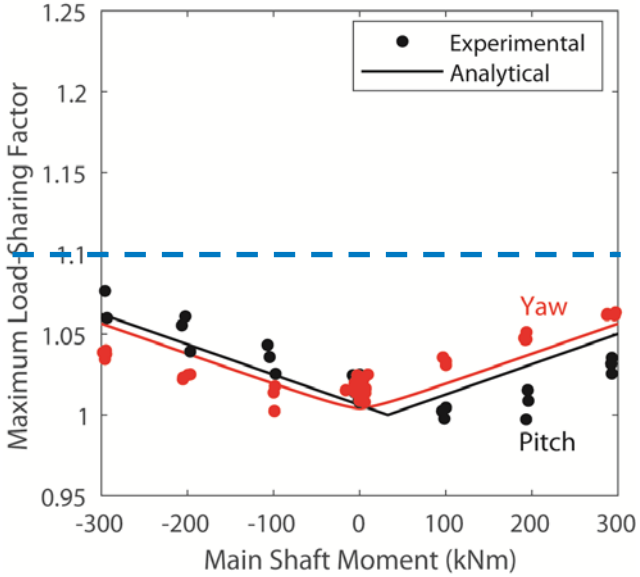
Gearbox with CRBs

Assumed Δ_c = 275 μm



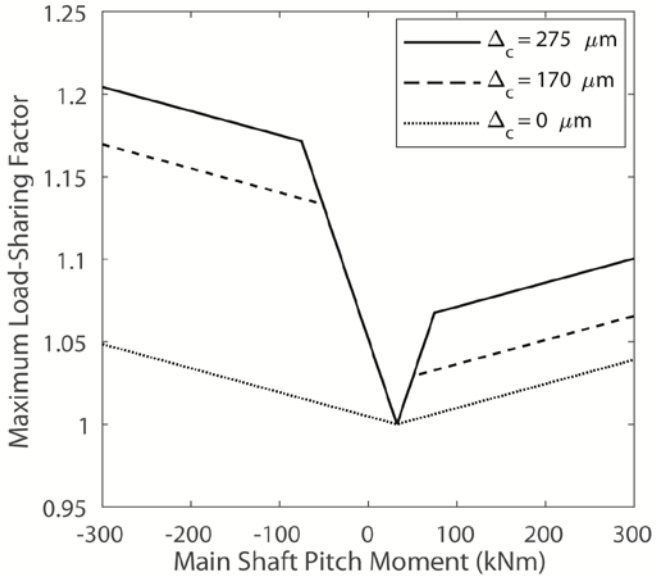
Design K_γ

Gearbox with TRBs



Carrier Bearing Clearance

Gearbox with CRBs



Reducing clearance improves load sharing

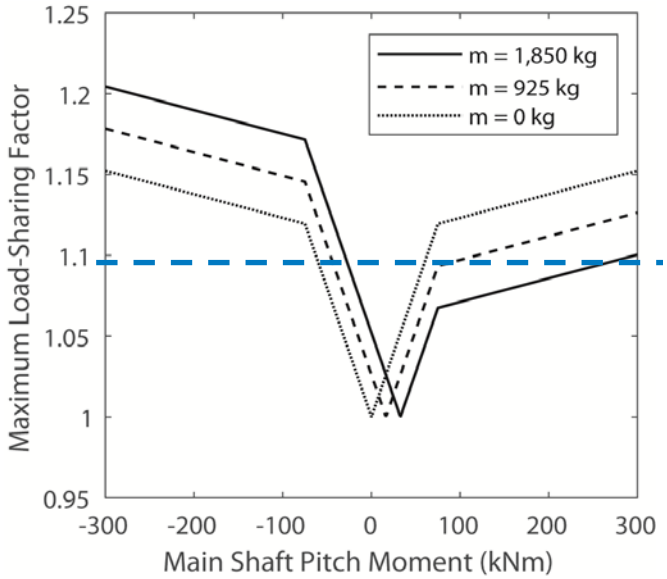
Model does not include preload

Difficult to determine carrier bearing operational clearance (Δ_c) for full complement bearings

Load sharing sensitive to Δ_c

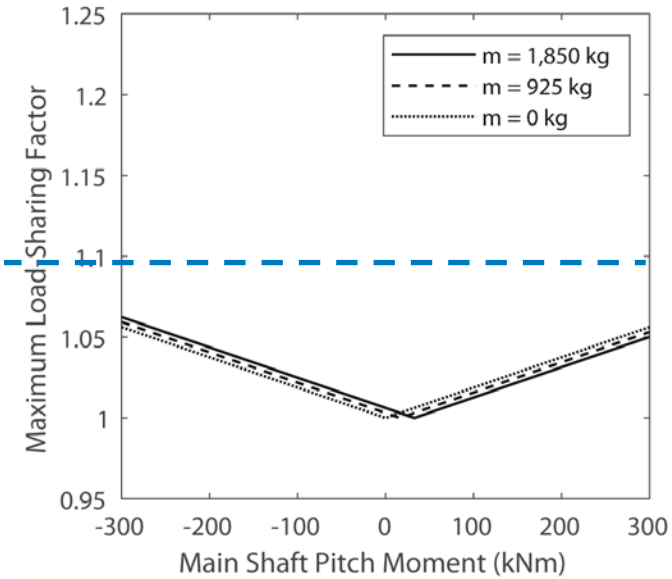
Planetary System Mass

Gearbox with CRBs



Lightweighting improves load sharing

Gearbox with TRBs



Lightweighting has no effect

Design K_γ

Summary and Conclusions

- Validated load-sharing model for horizontal gearboxes
  - Accounts for nontorque loads, gravity, and clearance
- Equal load sharing cannot generally be achieved
  - With zero nontorque load $K_{\gamma}^{*} = 1.08$
- Carrier bearing clearance has strong influence on load sharing
- Equivalent system weight only influences load sharing for systems with clearance

Photo by Dennis Schroeder, NREL 49413

Thank you!

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www.nrel.gov

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