



Planetary Load Sharing in Three-Point-Mounted Wind Turbine Gearboxes: A Design and Test Comparison

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3rd Conference for Wind Power Drives

Aachen, Germany

March 8, 2017

[NREL/PR-5000-68021](#)

Drivetrain Reliability Collaborative (DRC)

The DRC studies gearbox reliability topics related to:

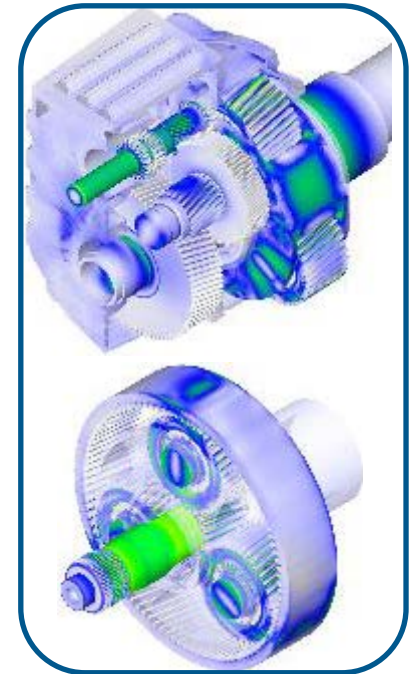
- Design assumptions and modeling methods
- Operational loads and environment
- Validation testing and failure modes.



Photo by Jeroen van Dam, NREL 19257



Photo by Mark McDade, NREL 32734



Current DRC Research Projects

Current DRC research products include:

- Concluding investigation of planet gears, bearings, and splines
 - Research began in 2006 with many participants and all results public



Photo by Mark McDade, NREL 40432



Photo by Jonathan Keller, NREL 36521

- Investigating bearing axial cracking
 - Research began in 2014 with Argonne National Laboratory and industry partners
- Collecting diagnostics, prognostics, and failure statistics
- Investigating main bearings (future).

Planetary Load Sharing Comparison

➤ Testing

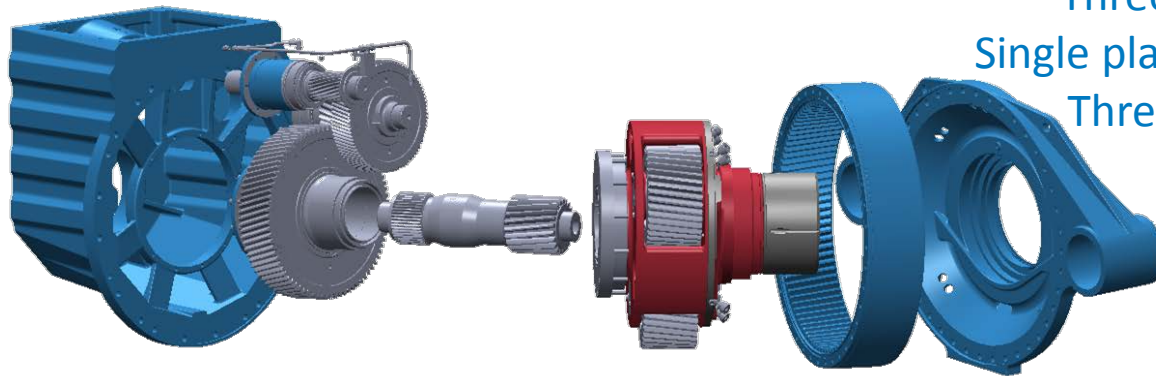
- Planet Bearing Loads
- Parametric Studies
- Summary



Photo by Jonathan Keller, NREL 36521

Planet Bearing Investigation

- Tested commercial, 750-kilowatt drivetrain with custom gearboxes
 - Two different gearbox planetary bearing designs



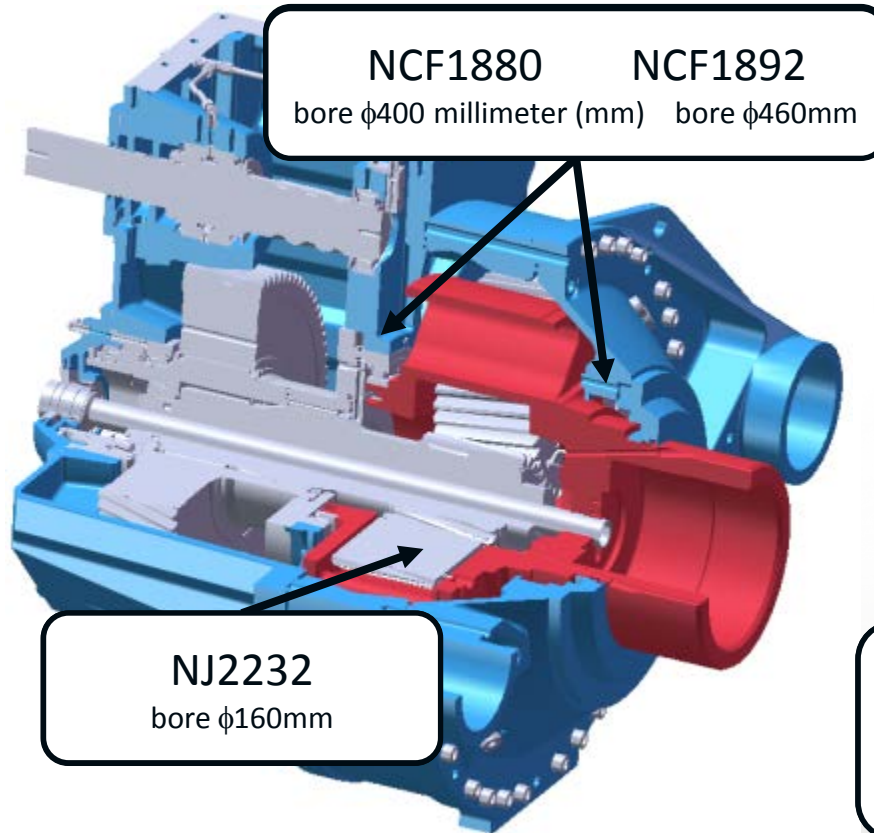
Three-point mounted drivetrain
Single planetary, double parallel gearbox
Three planets with floating sun
14° helical gearing

- Constant torque and speed tests with rotor moments and thrust
- Some field-representative cases, transients, and grid events
- Correlated measured bearing loads to model predictions
 - Finite element, multibody, and lumped-parameter models
 - Validate load-sharing characteristics driving L10 life.

Planet and Carrier Bearing Designs

Gearbox 1 and 2

Cylindrical Roller Bearings (CRBs)



Gearbox 3

Tapered Roller Bearings (TRBs)

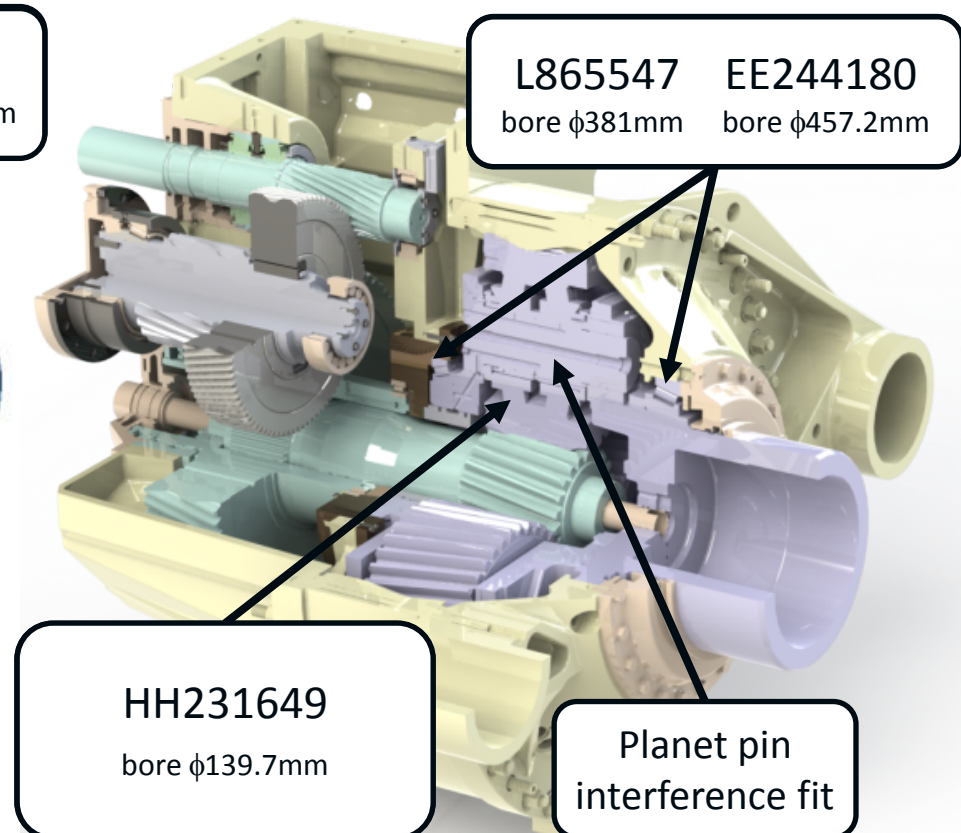
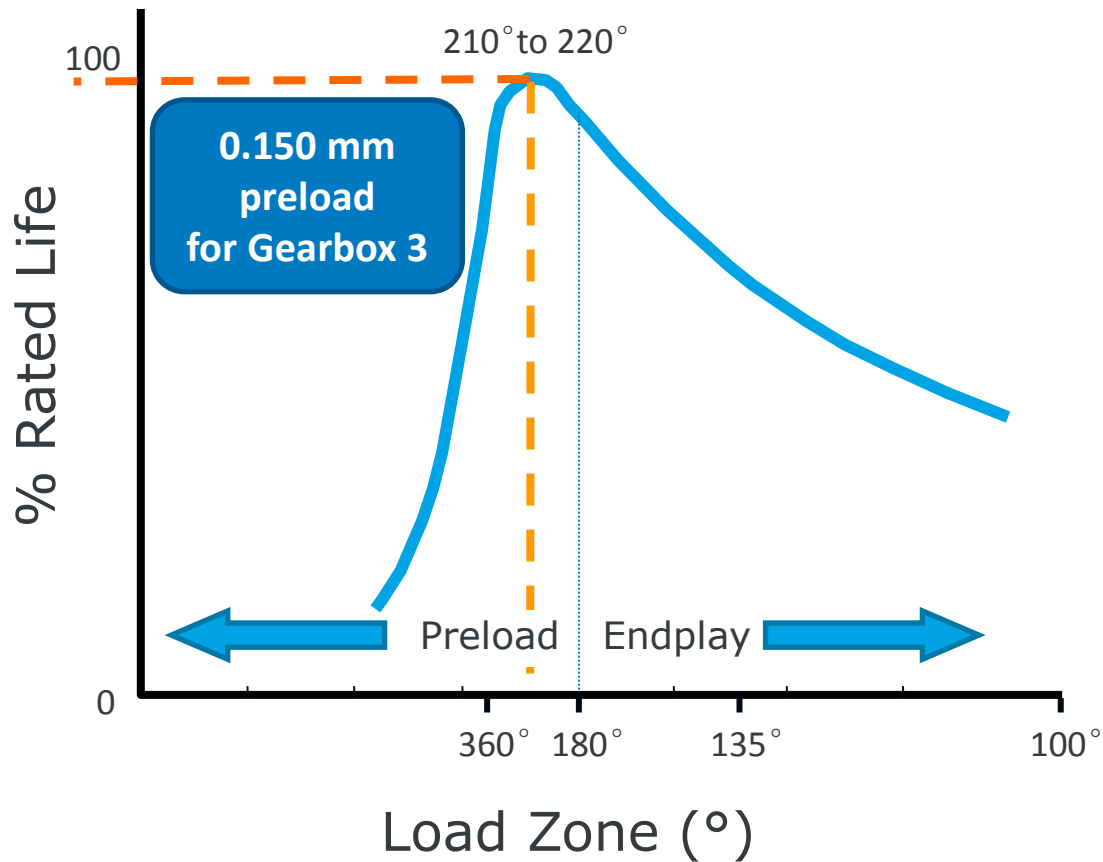
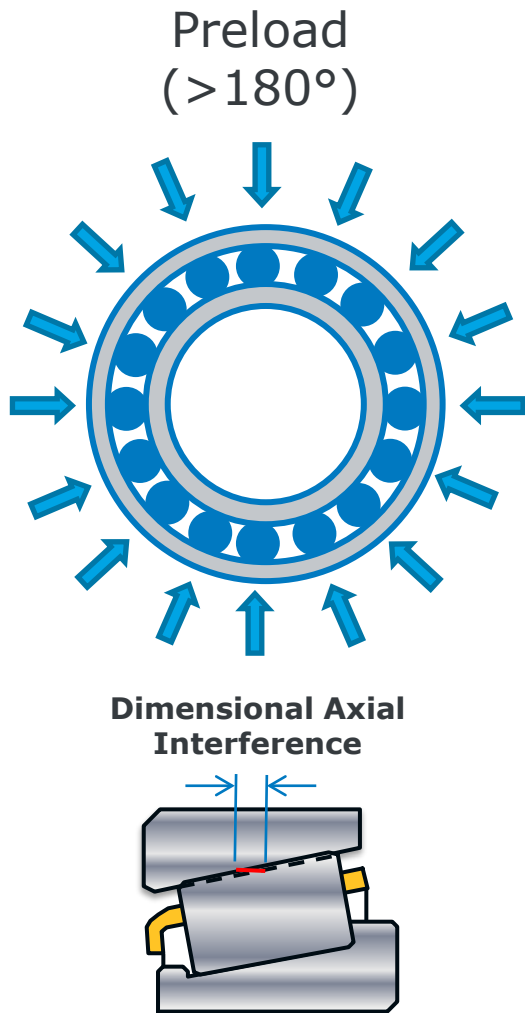


Illustration by Romax Technology



Gearbox 3 Planet Bearing Preload

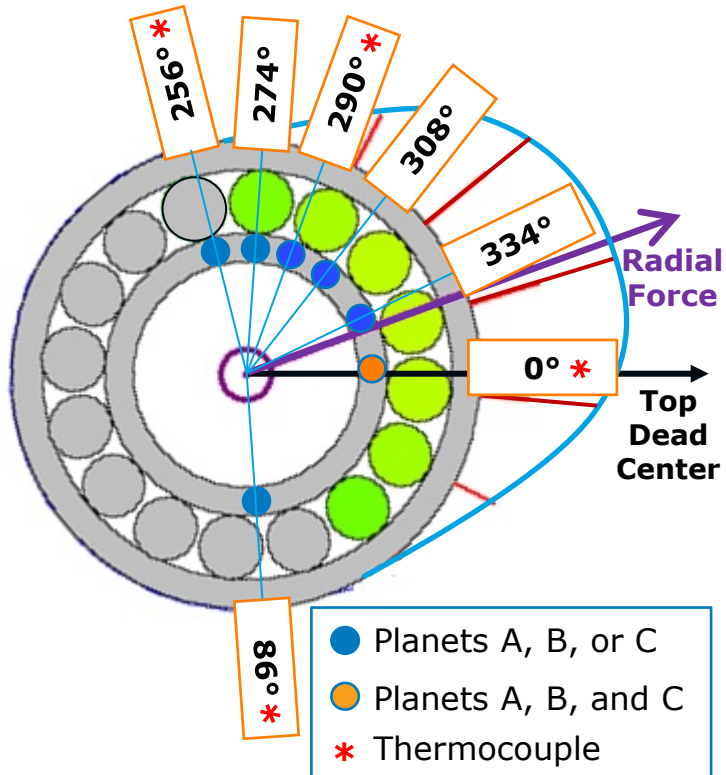


Illustrations by Timken

Planet Bearing Instrumentation

Gearbox 1 and 2

2 axial measurements per row at each location



Upwind row measurements shown
Downwind row measurements *identical*

Gearbox 3

1 measurement per row at each location

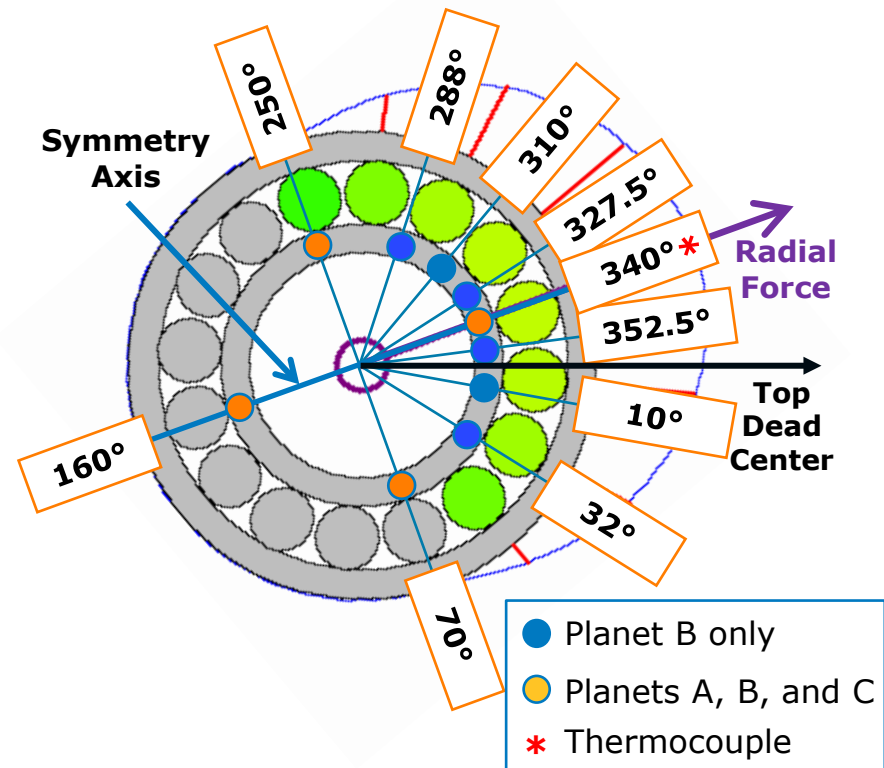
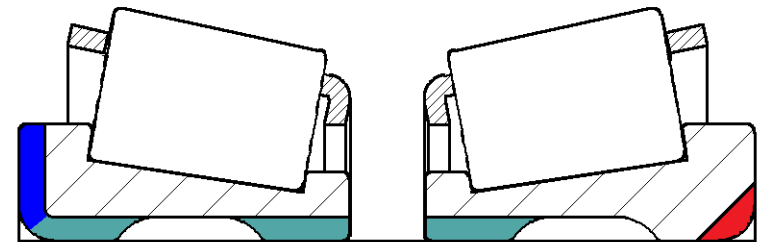
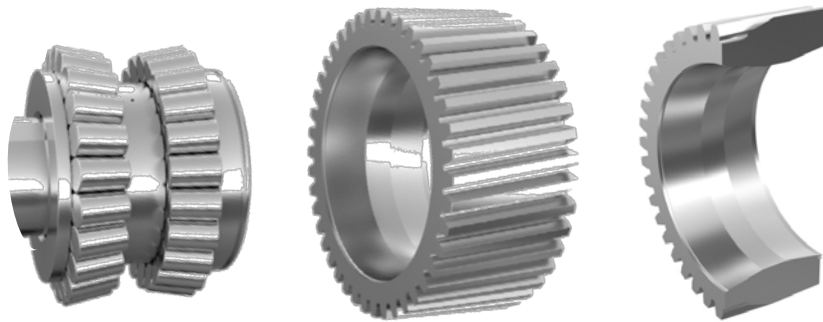
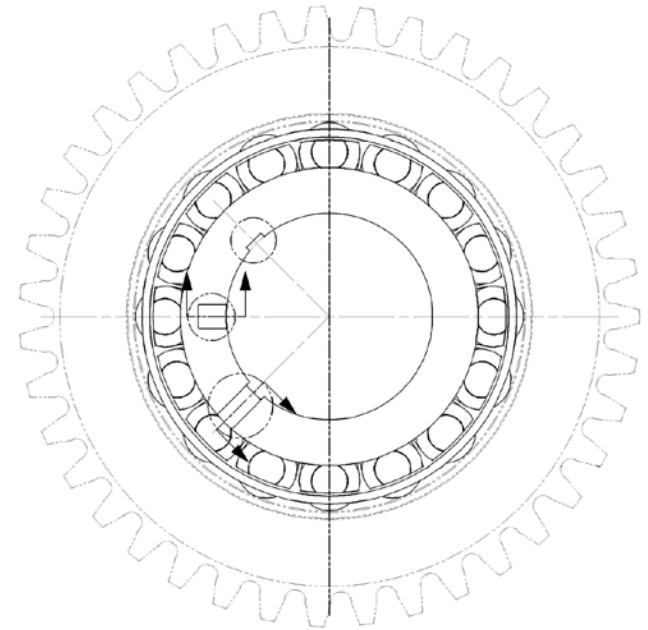
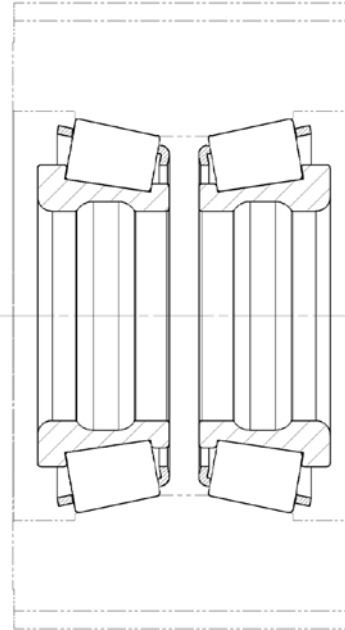


Illustration by Timken

Upwind row measurements shown
Downwind row measurements *symmetric*
about load zone center

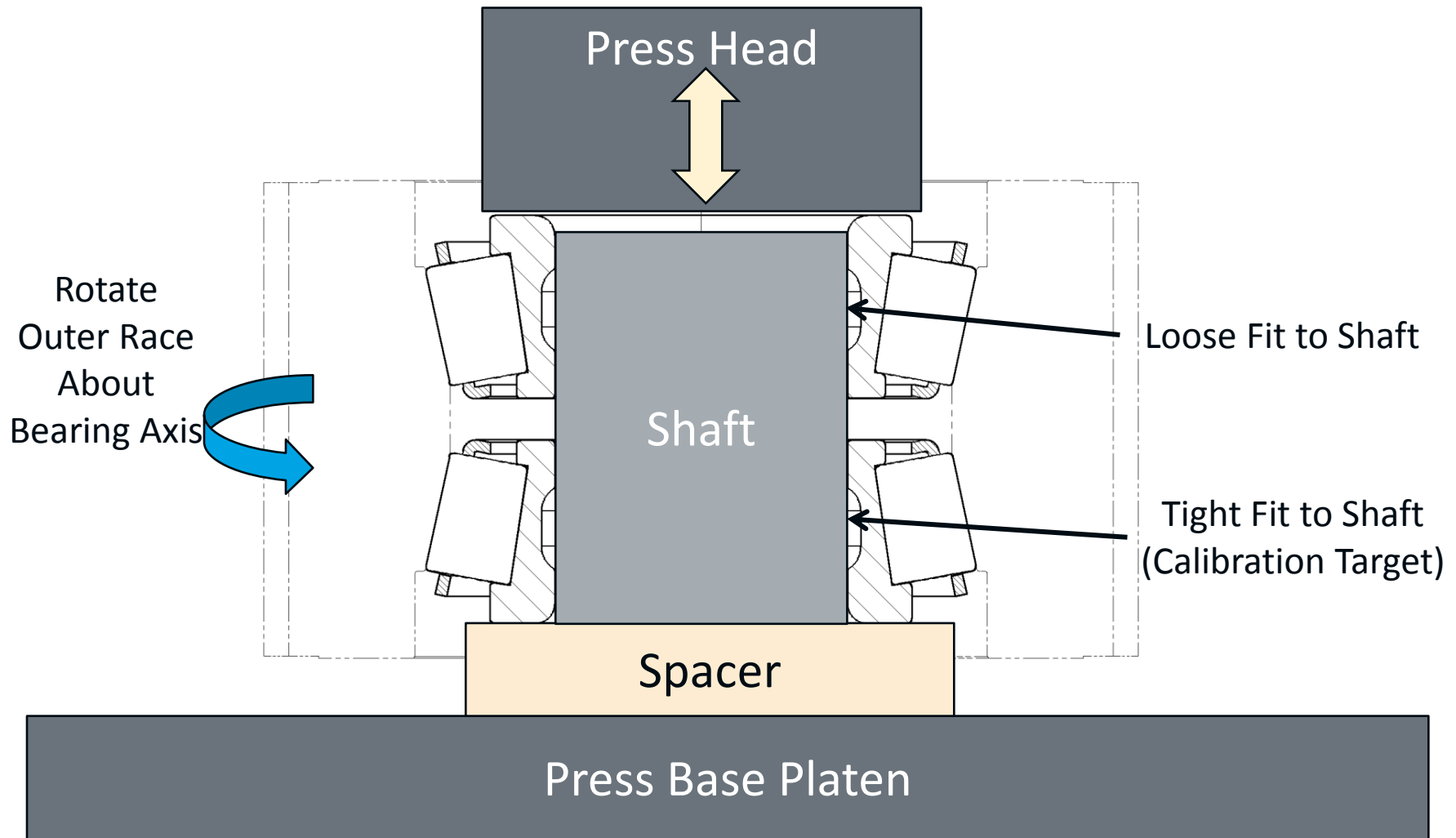
Gearbox 3 Planet Bearing Design

- Finite-element analysis
 - Validate modified-bearing design
- Optimize groove for instrumentation
 - Achieve desired strain
- Cone section
- Stress concentrations.



Illustrations by Timken

Gearbox 3 Planet Bearing Strain Gauge Calibration



Planetary Load Sharing Comparison

- Testing
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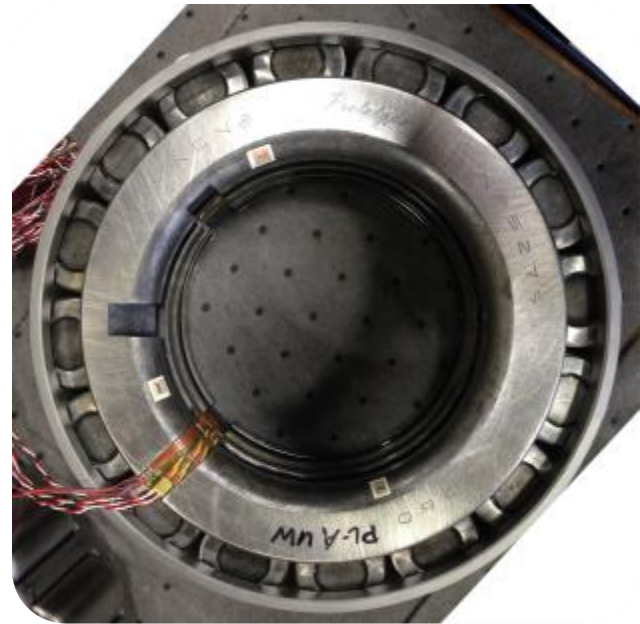


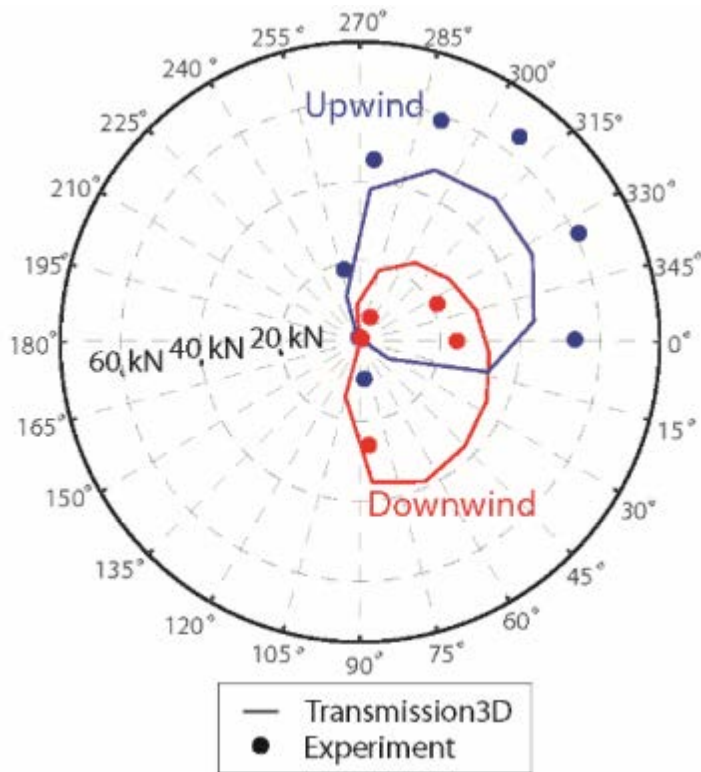
Photo by Jonathan Keller, NREL 36523



Photo by Jonathan Keller, NREL 36524

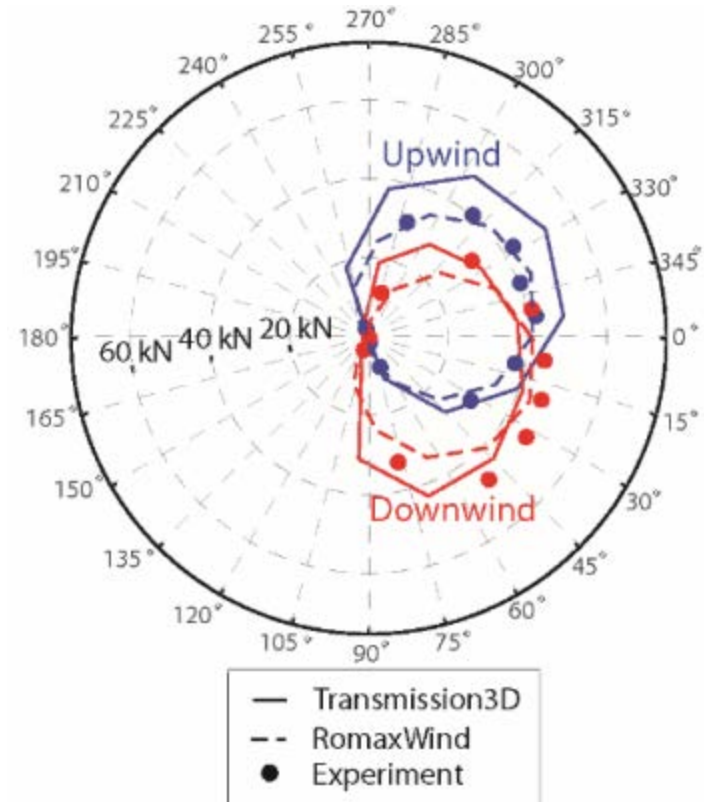
Results – Planet Bearing Load Zones

Gearbox 2 CRBs



**Upwind bearing 50% to 100%
more load than downwind bearing**

Gearbox 3 TRBs

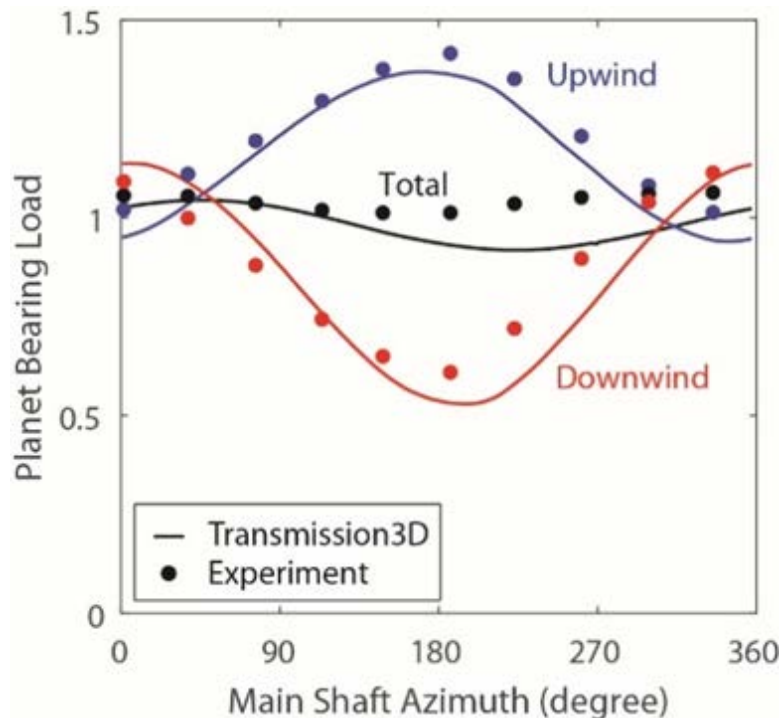


Bearing loads equalized

Loads shown in units of kiloNewton (kN)
Full power, rated torque, no rotor moments

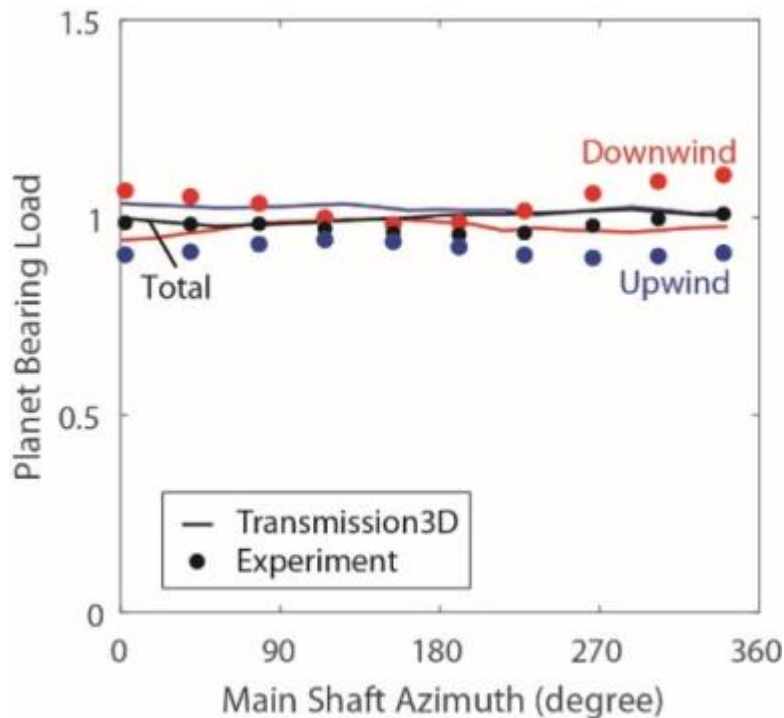
Results – Planet Bearing Loads

Gearbox 2 CRBs



**Upwind bearing
accumulates more fatigue,
downwind risks skidding**

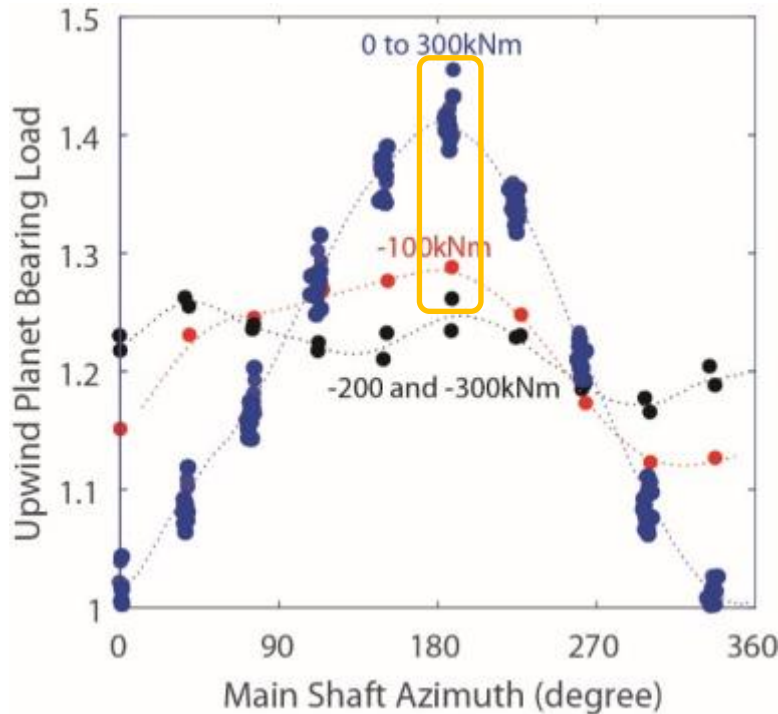
Gearbox 3 TRBs



**Bearing loads
more equalized**

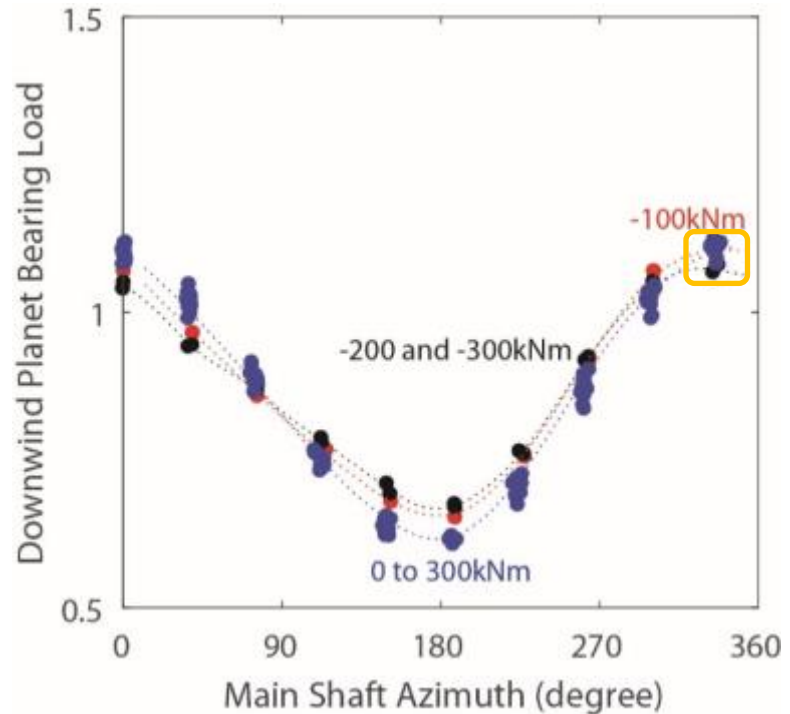
Results – Gearbox 2 Planet Bearing Loads

Gearbox 2 Upwind Bearing



**Upwind bearing loads
bounded by pure torque and -200 kNm
rotor pitch moments**

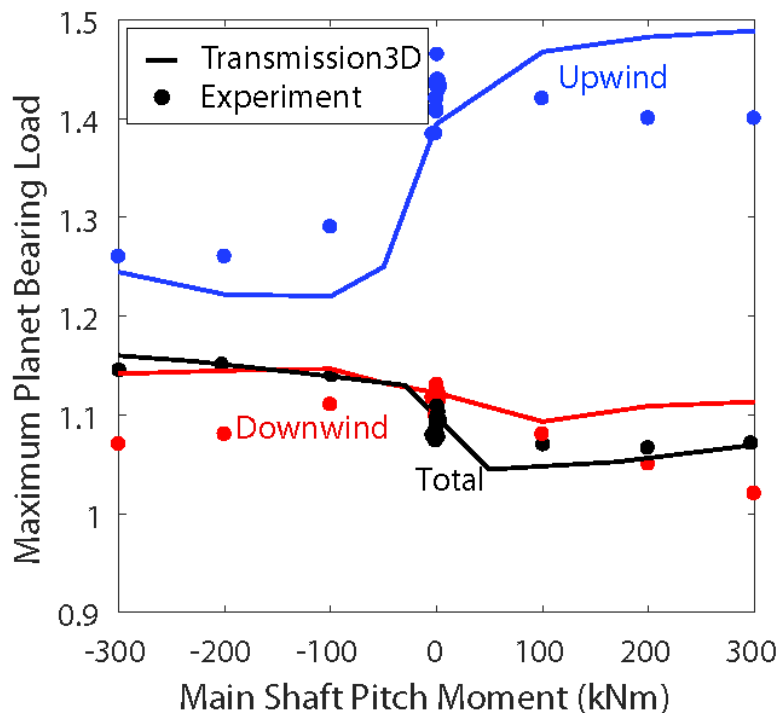
Gearbox 2 Downwind Bearing



**Downwind bearing loads
unaffected by
rotor pitch moments**

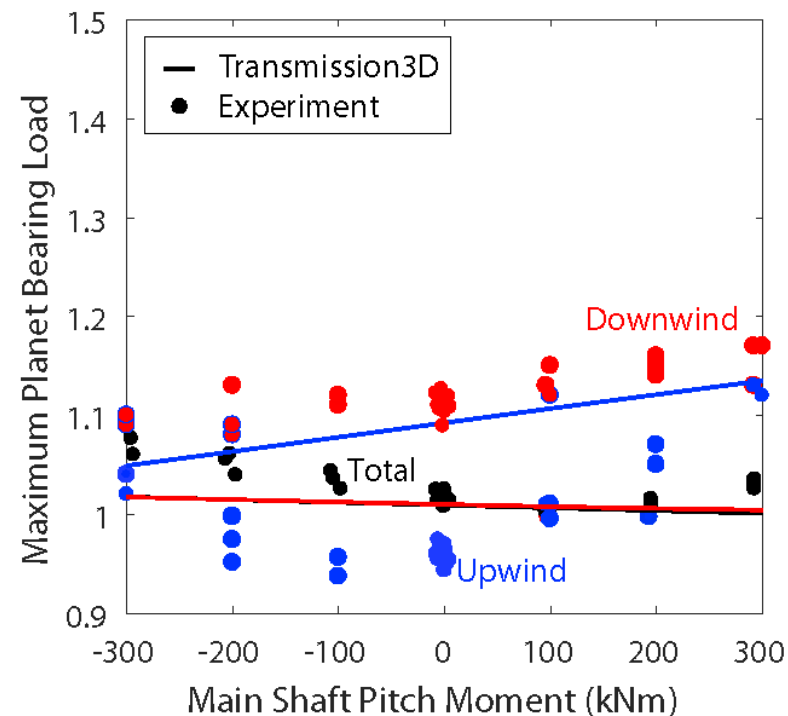
Results – Planet Bearing Load Sharing

Gearbox 2 CRBs



Upwind bearing loads up to 47% higher than expected

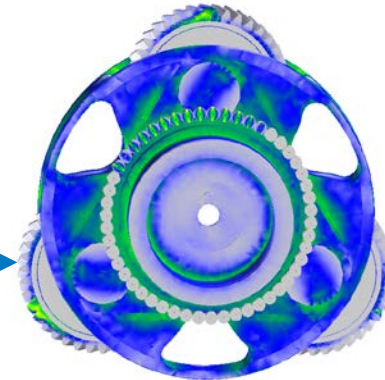
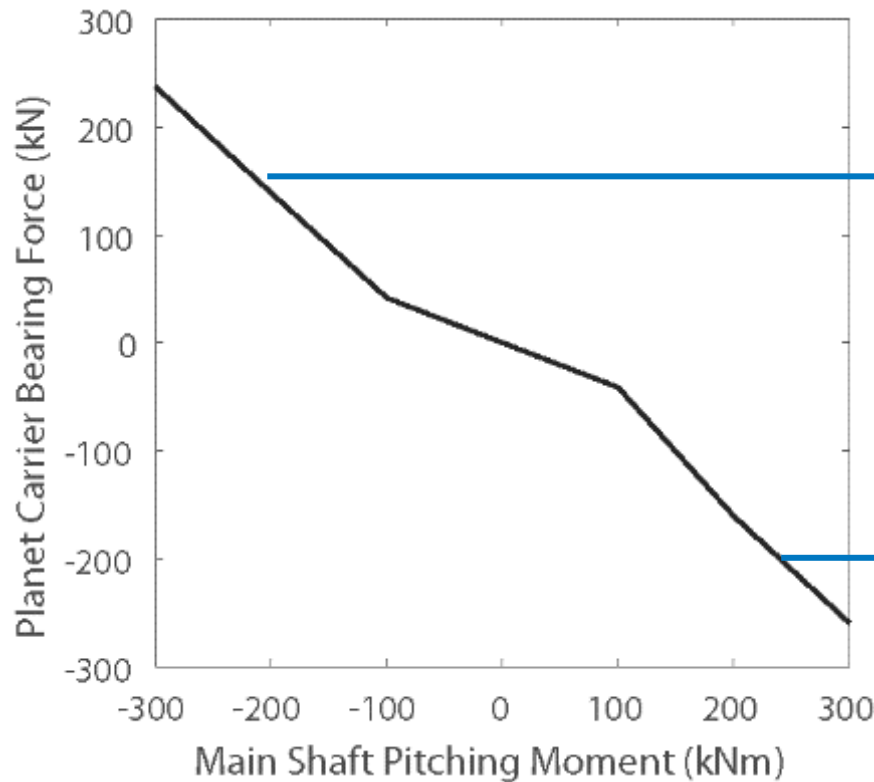
Gearbox 3 TRBs



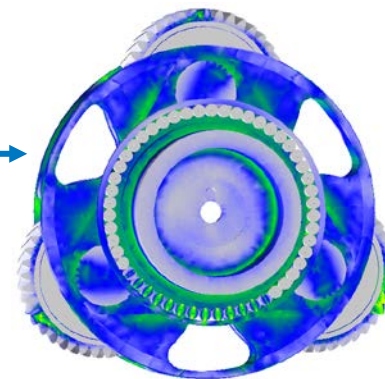
Bearing loads more equalized

Results – Carrier Bearing Loads

- Carrier bearings are not in contact in pure torque/low moments
- Bearing load changes directions with pitching moment.



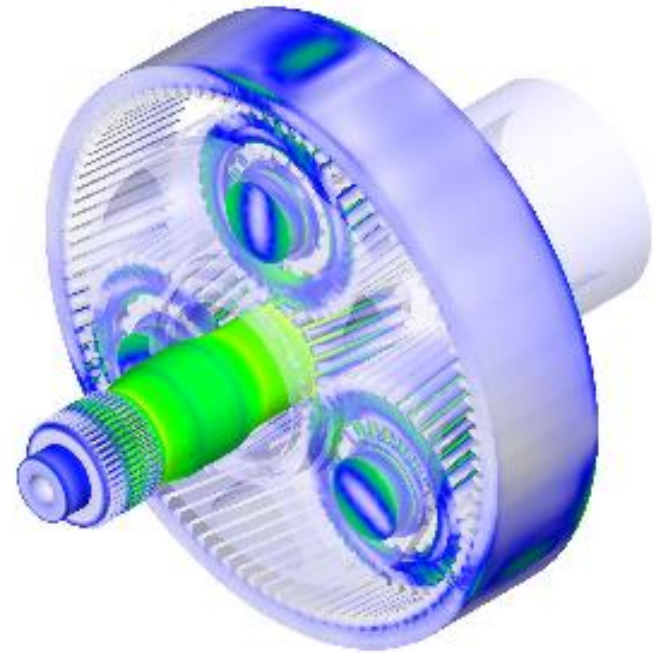
Contact at the top



Contact at the bottom

Planetary Load Sharing Comparison

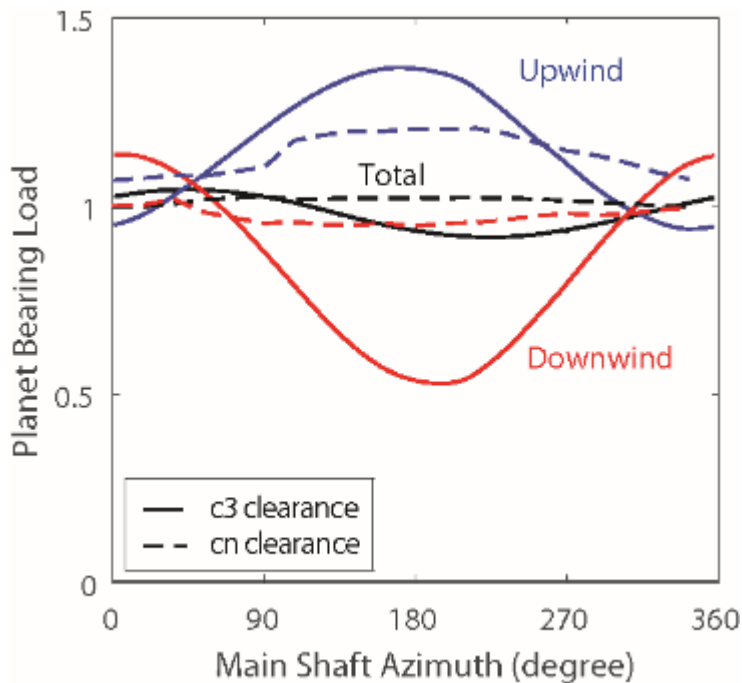
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Parametric Study – Bearing Clearances

Gearbox 2

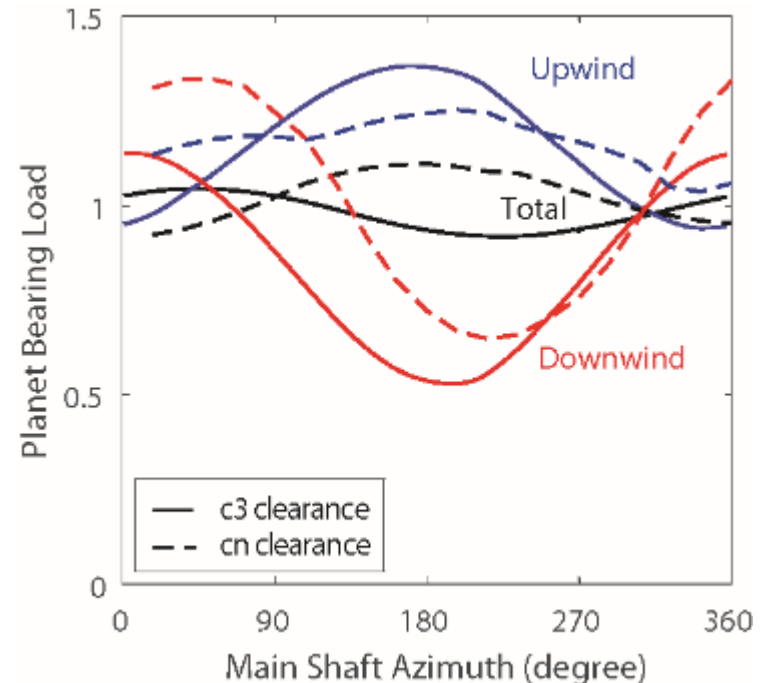
Changing Carrier Bearing Clearance



Reducing carrier bearing clearance improves load sharing

Gearbox 2

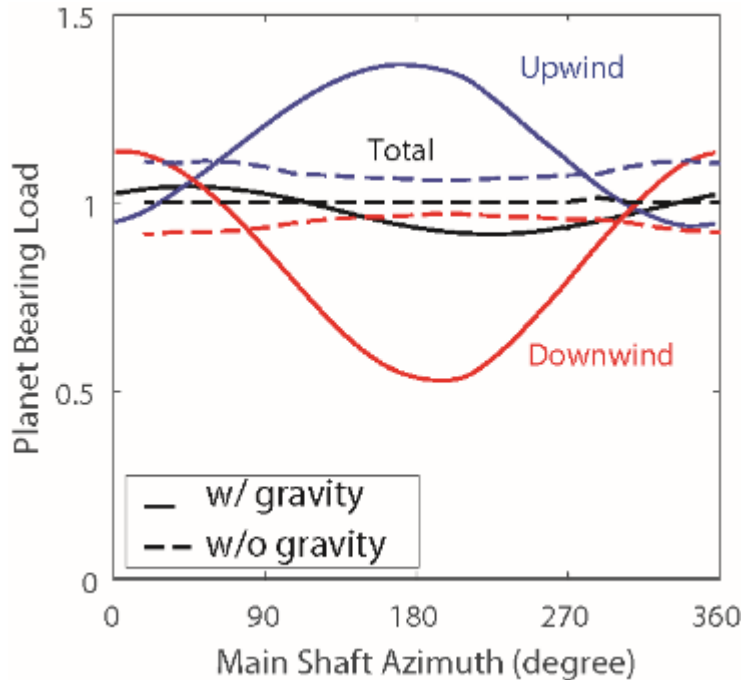
Changing Planet Bearing Clearance



Reducing planet bearing clearance has a smaller benefit

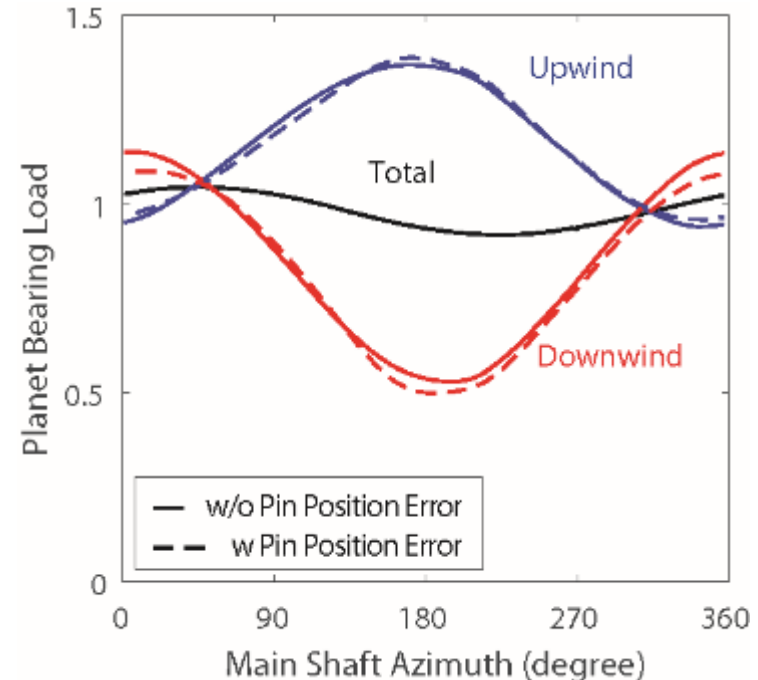
Parametric Study – Gravity and Pin Position Error

Gearbox 2 Effect of Gravity



Gravity disturbs load sharing

Gearbox 2 Effect of Pin Position Error



Pin position error has little effect on load sharing

Planetary Load Sharing Comparison

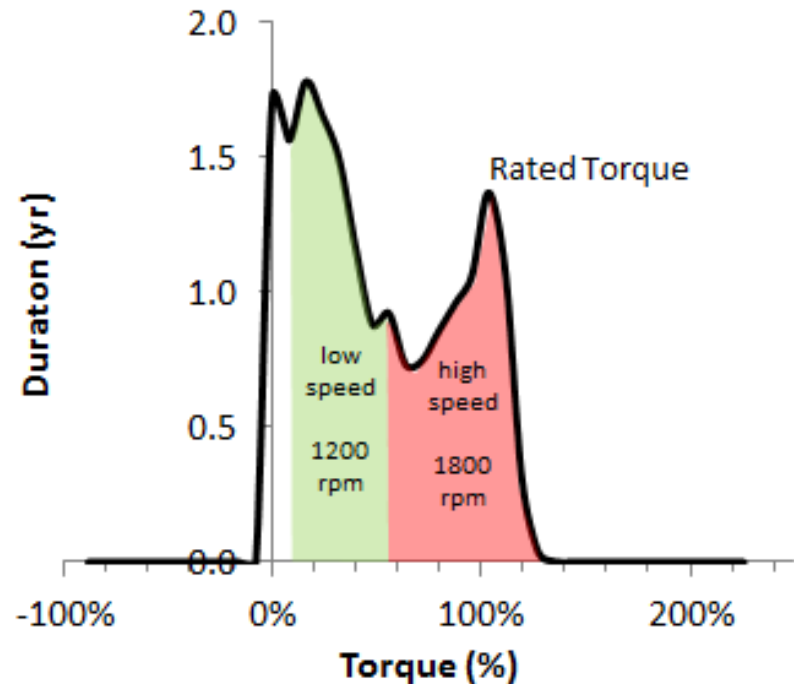
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Photo by Jeroen van Dam, NREL 19257

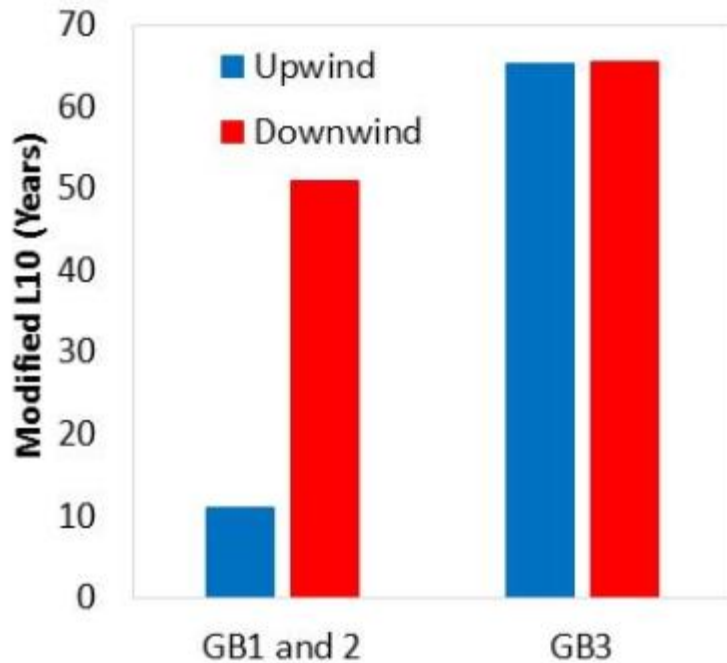
Design Load Spectrum

- Torque spectrum, plus constant rotor thrust and weight
 - Based on 3-month field test
 - Much time spent at low torque
 - Rated torque: 325 kNm
 - Rotor thrust: 94 kN
 - Rotor pitch: -100 kNm
- Rated torque and thrust plus combinations of extreme pitch and yaw moments used for strength check.



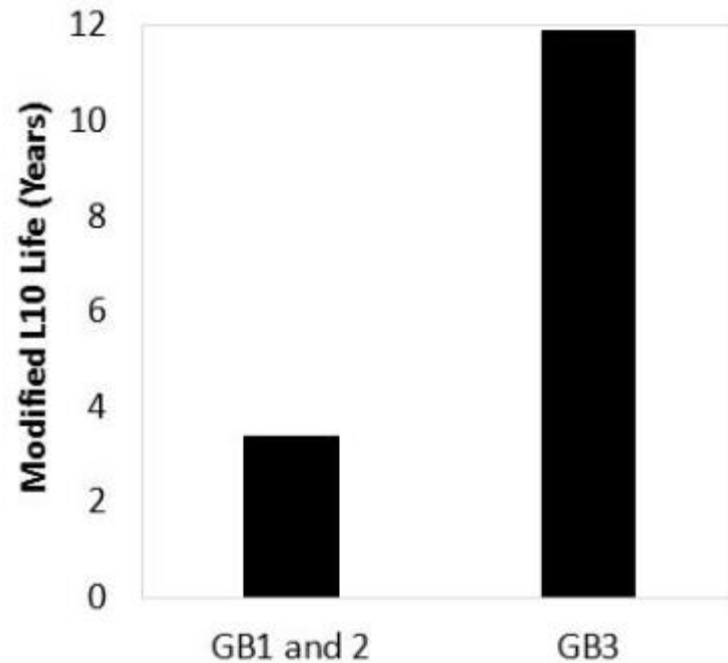
Bearing Fatigue Life

Planet Bearings Only



Load equalization and small capacity increase due to semi-integrated design

All 8 Planetary Bearings (6 Planet and 2 Carrier)



3.5x increase!

Summary

- Designed, built, and tested custom 750-kilowatt gearboxes
 - Designed planetary sections with CRBs and TRBs
 - Determined load spectrum through field tests
- Correlated measured loads to model predictions
 - Validated load-sharing characteristics driving L10 life
 - Reduced misalignment and improved load sharing
- Demonstrated improved load sharing with TRB design
 - Predicted 3.5x increase in L10m life.

Acknowledgments

This work was funded by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding for this work was provided by the DOE Office of Energy Efficiency and Renewable Energy, Wind Energy Technologies Office.

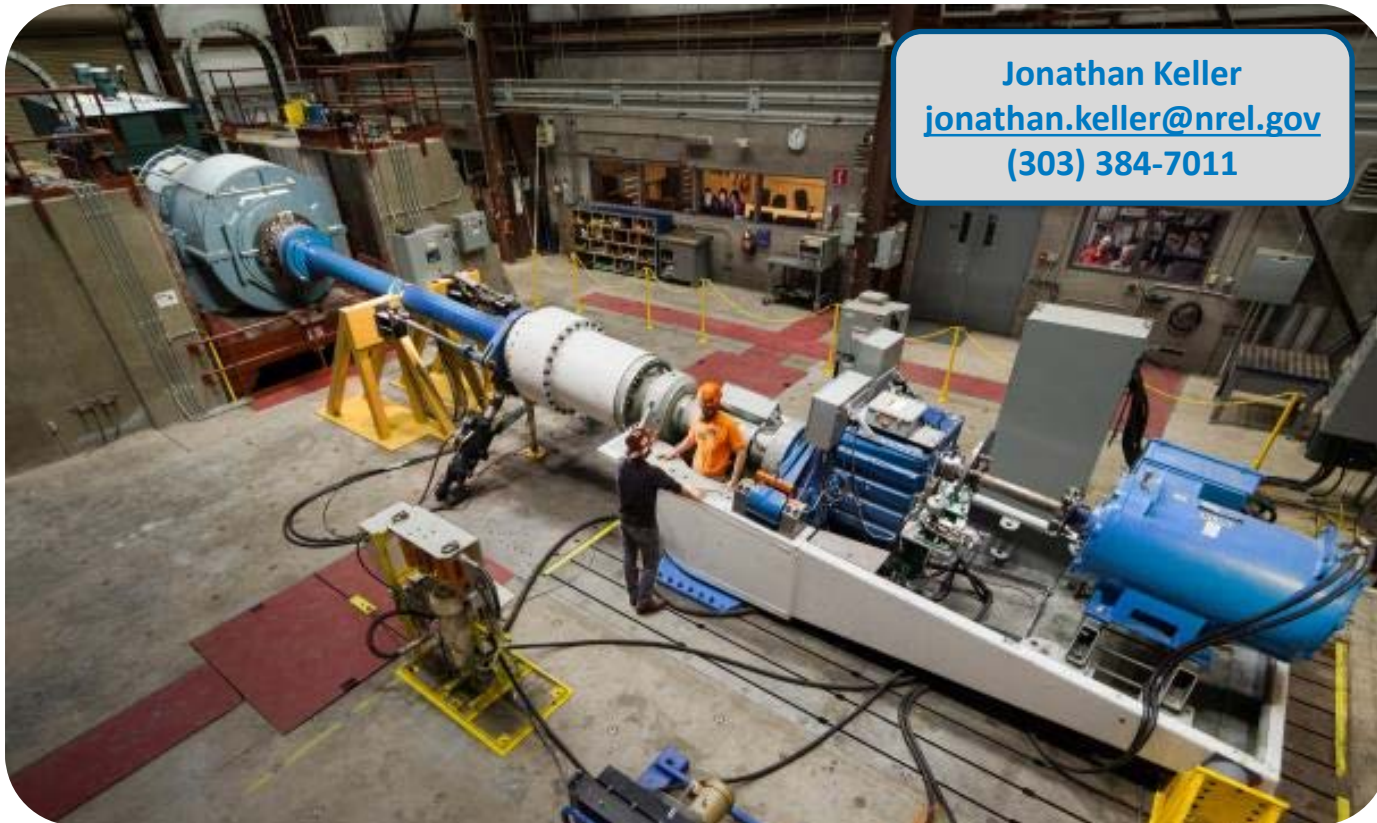


Photo by Mark McDade, NREL 32734