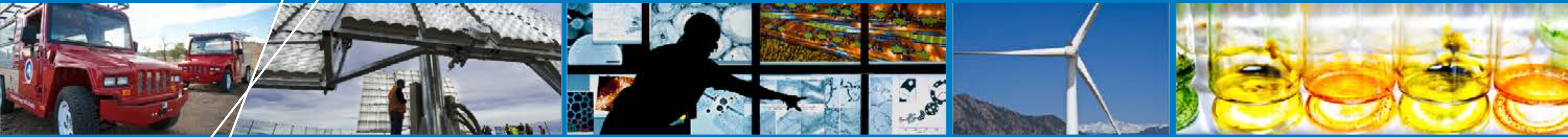
Recommendations on Model Fidelity for Wind Turbine Gearbox Simulations



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Gearbox Reliability Collaborative All-Members Meeting
Boulder, Colorado, February 17–18, 2015

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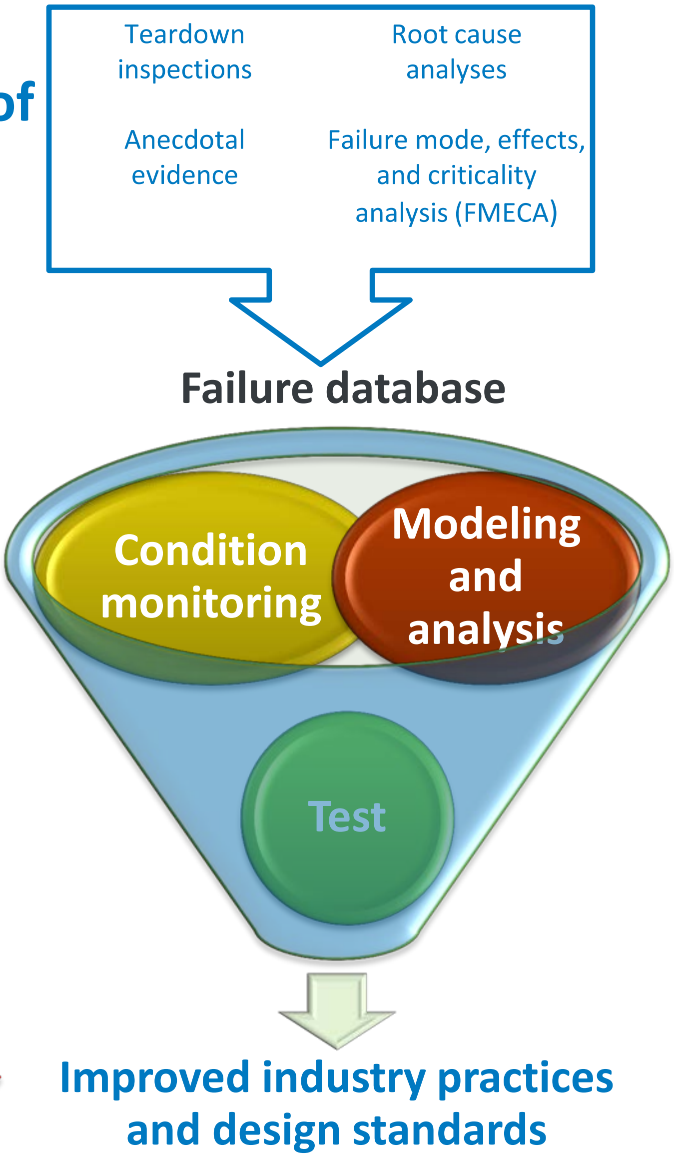
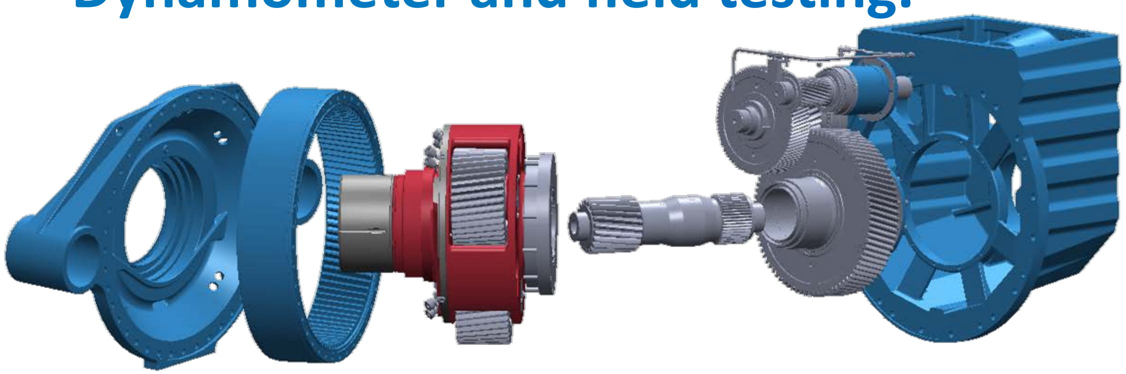
Gearbox Reliability Collaborative (GRC)

- **Many gearboxes do not achieve design life**
- **The GRC, founded by the U.S. Department of Energy (DOE), studies gearbox problems**
  - Do we understand the load environment?
  - Are elements missed in the design process?
  - Are the modeling tools sufficient?
- **GRC modeling "round robin" examines common gearbox modeling practices**
  - Drivetrain complexity
  - Gearbox complexity
  - Excitation sources
  - Imperfections.



Test Articles

- **Two redesigned 750-kilowatt (kW) gearboxes**
  - Modular, three-point mount and two-speed drivetrain
  - One planetary-stage and two parallel-stage gearboxes
  - Avoided proprietary aspects and updated to state-of-the-art design
    - Floating sun, cylindrical roller planet bearings, tapered roller bearings in parallel stages, and pressurized lubrication with offline filtration
  - Significant internal and external instrumentation
    - Planetary section loads, motions, and temperatures
    - High-speed shaft, pinion, and bearing loads recently added
- **Dynamometer and field testing.**



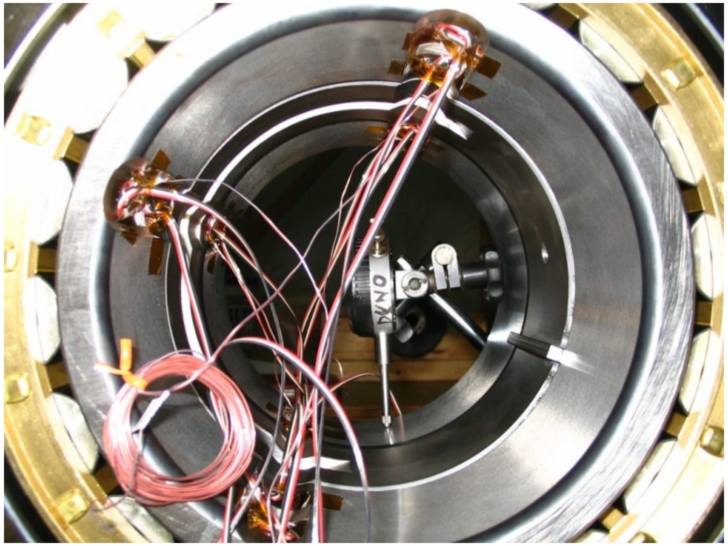
Dynamometer test. Photo by Scott Lambert, NREL 19222

Main Shaft and Planetary Instrumentation

- **Input torque and main shaft bending moment measured by strain gauges**
- **Gearbox internal measurements**
  - Sun motion (two radial)
  - Ring gear tooth root strain (three places)
  - Planet bearing strain (six bearings, six places).

Sun motion. Photo by Edward Overly, NREL Photo 26666

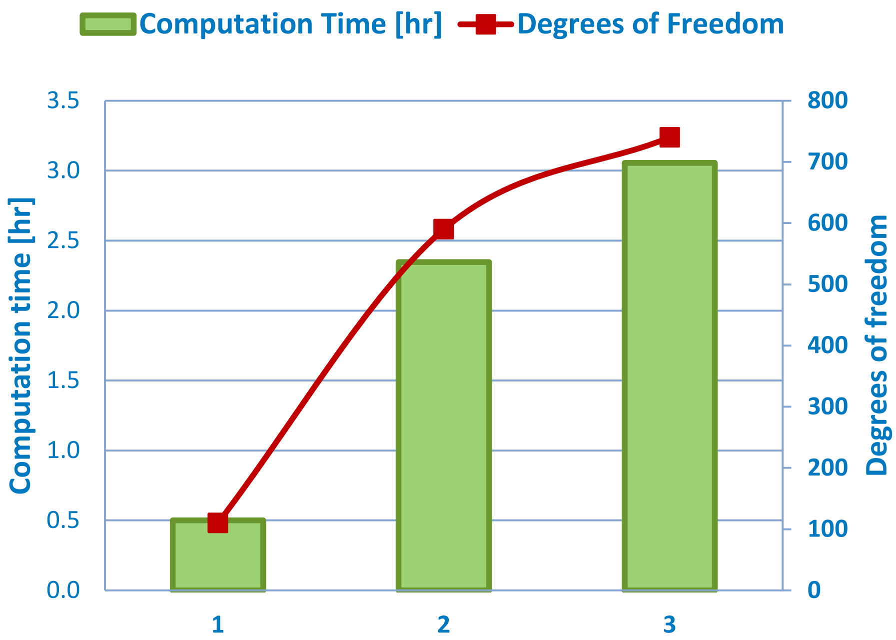
Ring gear strain. Photo by Edward Overly, NREL 19495

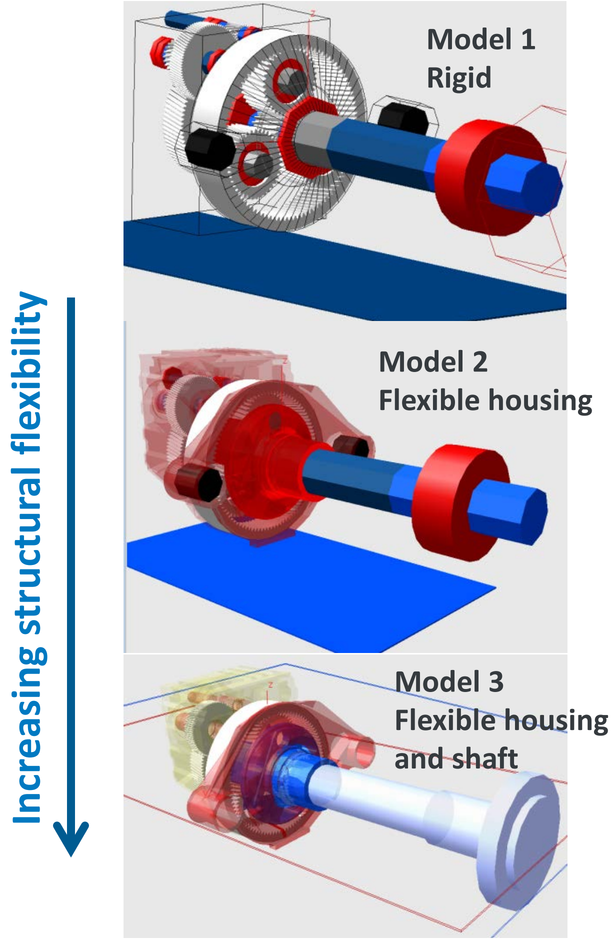


Planet bearing strain. Photo by Jeroen van Dam, NREL 19680

Motivation of Modeling Round Robin

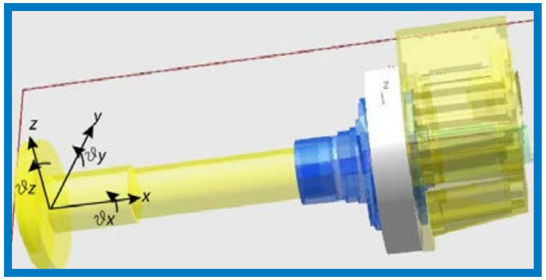
- **Required model fidelity is a balancing act between accuracy and computational efficiency**
  - Fully flexible gearbox models simulate the dynamometer loading conditions better
  - Rigid body models can be considered to have the advantage in computational time.





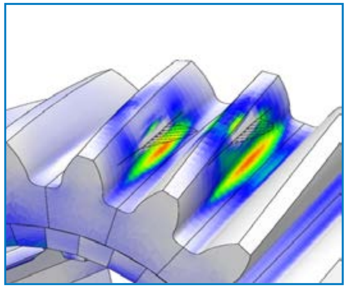
Literature Review of Modeling Approaches

Drivetrain modeling



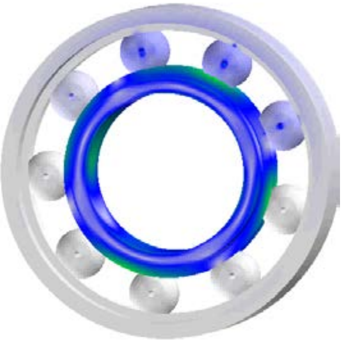
Gear modeling

- Gear body modeled as lumped parameters or finite element (FE)
- Tooth microgeometry typically considered in FE
- Mesh-modeled stiffness or contact mechanics (CM).



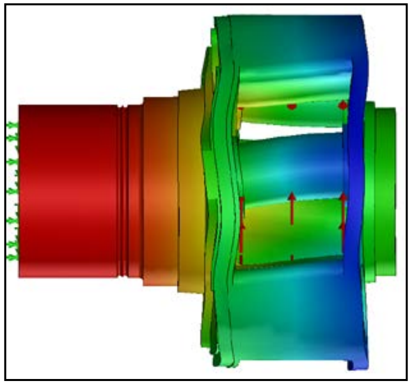
Bearing modeling

- Modeled as global, nonlinear stiffness or FE
- Off-diagonal stiffnesses rarely considered
- Roller microgeometry modeled as CM.



Structural modeling

- Rigid body or FE
- Craig-Bampton modal condensation typically used.



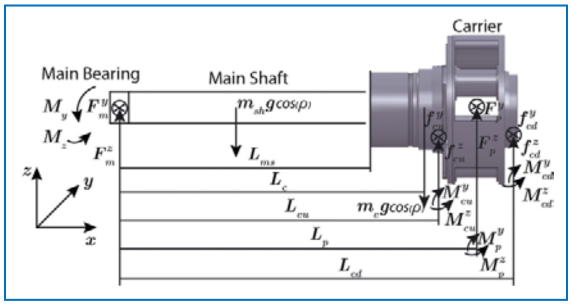
Modeling Tools Studied

Low fidelity (analytical)
- Lumped-parameter, dynamic
- Other analytical tools

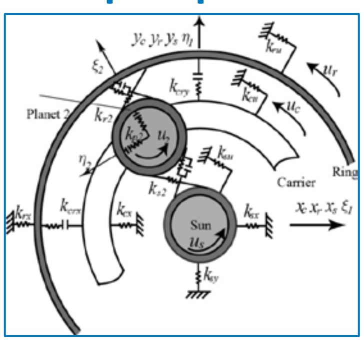
Intermediate fidelity (multibody dynamic tools /MBS)
- SIMPACK, dynamic
- SAMCEF, dynamic

High fidelity (FE)
- Transmission 3D, static
- RomaxWind, static/pseudo-dynamic

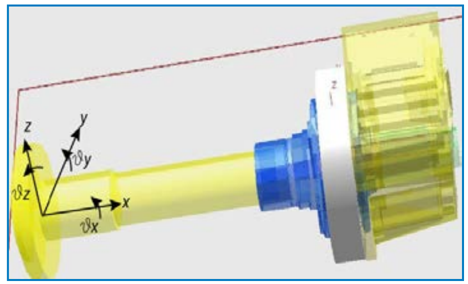
Analytical



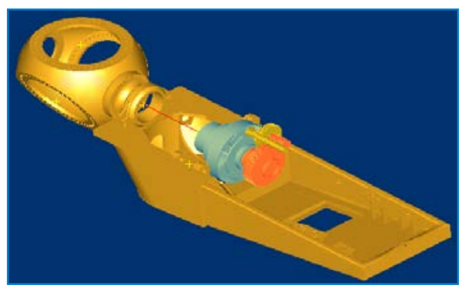
Lumped-parameter



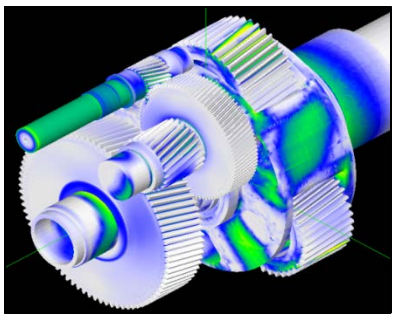
SIMPACK



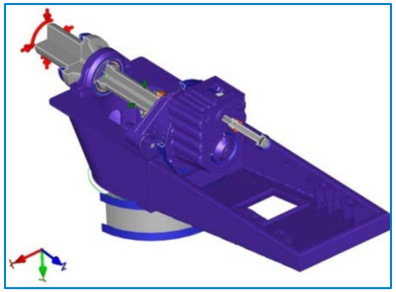
SAMCEF



Transmission3D



RomaxWind



Increasing computational time

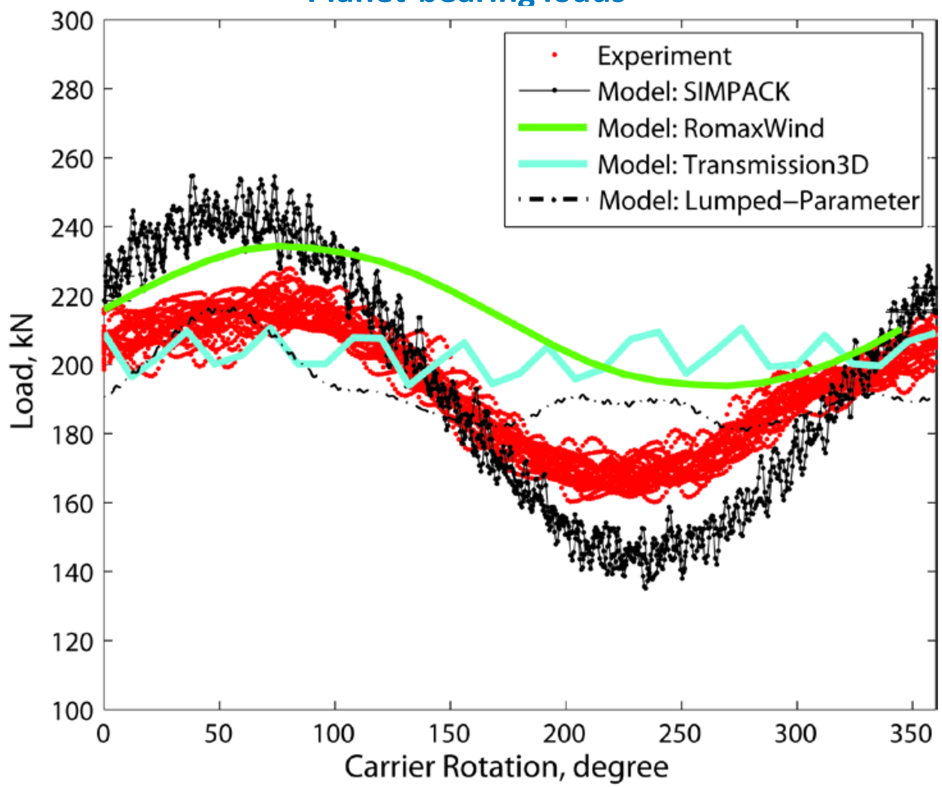
Model Feature Summary

Model Element(s)	Transmission 3D	RomaxWind	SIMPACK	SAMCEF	Lumped-Parameter
Gear teeth, tooth contact	Full FE and contact mechanics	FE-based bending stiffness and contact mechanics	Rigid body with tooth compliance	Rigid body with tooth compliance	Rigid body with tooth compliance
Shafts	Full FE	Flexible beams and condensed FE	Rigid and flexible beams	Flexible nonlinear beams	Rigid body
Bearings, roller contact	Full FE and contact mechanics	Linear and nonlinear stiffness matrices generated via contact mechanics model	Linear and nonlinear stiffness matrices	Linear and nonlinear stiffness matrices	Linear and nonlinear stiffness matrices
Housing, carrier	Full FE	Condensed FE	Rigid and condensed FE	Rigid and condensed FE	Rigid body
Bedplate	Full FE	Condensed FE	Rigid and condensed FE	Rigid and condensed FE	Rigid body
Splines, tooth contact	Full FE and contact mechanics	FE-based bending stiffness and contact mechanics	Stiffness matrices	Stiffness matrices	Stiffness matrices
Generator coupling	Stiffness matrices	Stiffness matrices	Stiffness matrices	Stiffness matrices	Not considered currently
Gearbox support	Stiffness matrices	Stiffness matrices	Stiffness matrices	Stiffness matrices	Stiffness matrices

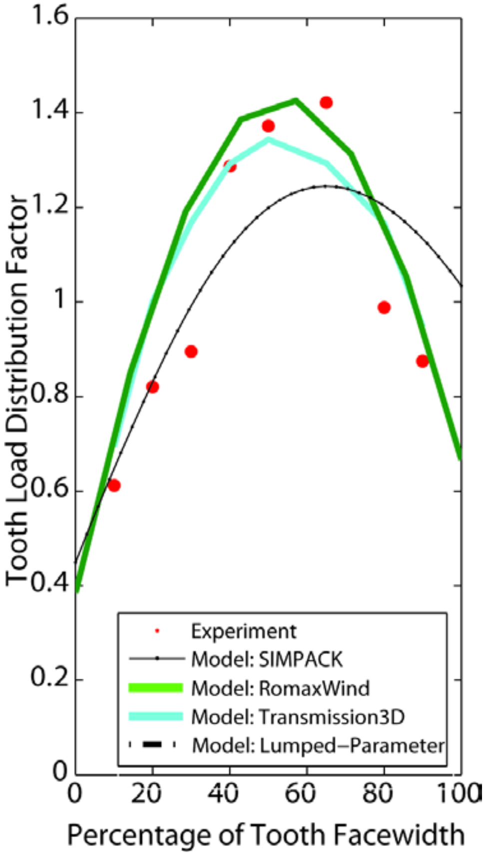
Model Validation by Experiments: Loads

- **Models validated by experiments for planetary loads**
- **Result variances between models caused by differences in:**
  - Modeling approaches
  - Modeling practices.

Planet-bearing loads



Ring gear load distribution factor

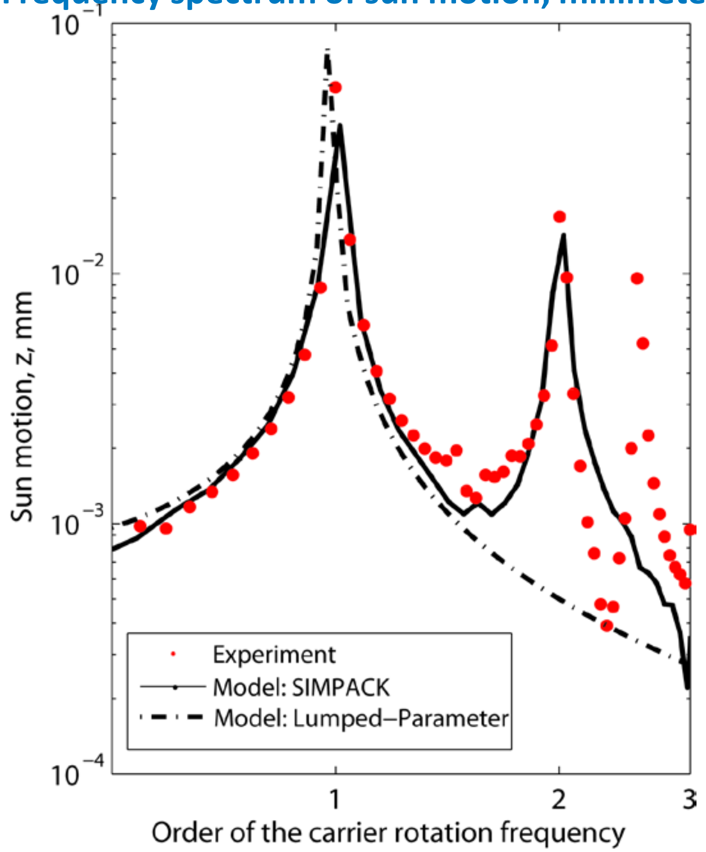


Source: Guo et al. (forthcoming)

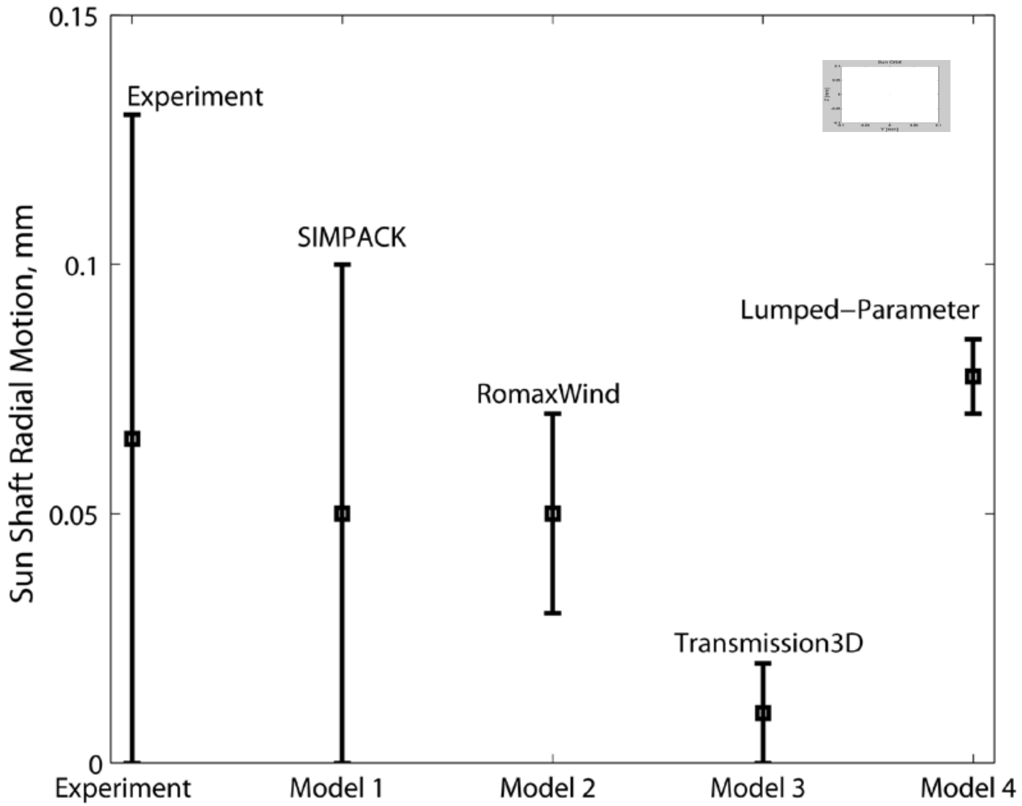
Model Validation by Experiments: Motions

- **Models validated by experiments for sun gear motion**
- **Static models predict smaller sun motion than dynamic models**
  - It is important to consider dynamics to fully capture gearbox motions.

Frequency spectrum of sun motion, millimeters (mm)



Sun shaft motion amplitude, mm

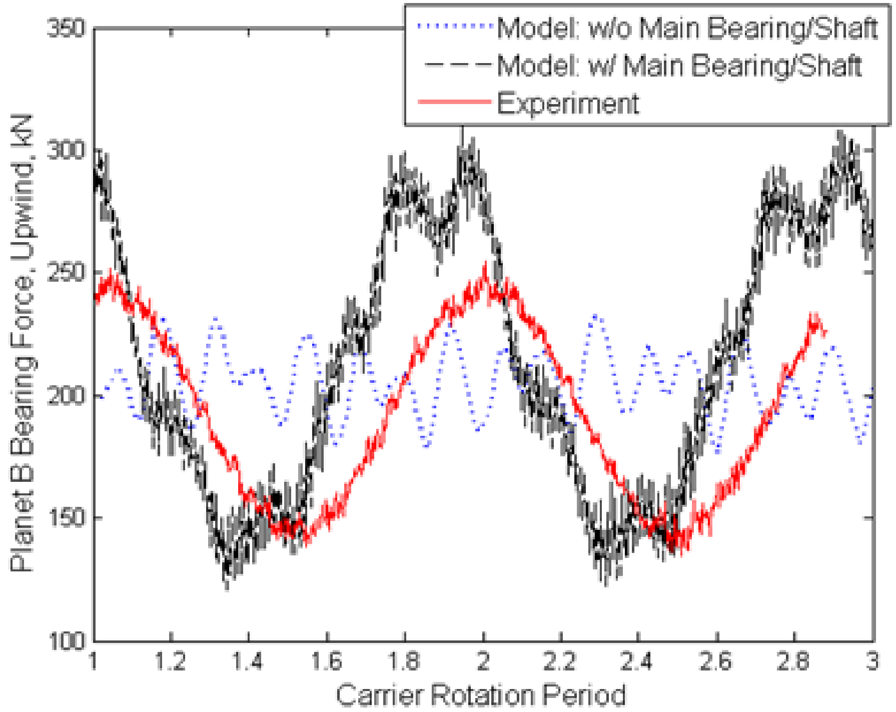


Source: Guo et al. (forthcoming)

Drivetrain Complexity Fidelity Study

- **Determines model boundaries**
  - Should the gearbox be modeled alone?
- **Main shaft and bearing affect gearbox internal loads**
- **Generator coupling has little influence on planet loads.**

Planet-bearing load, kilonewtons (kN)
SIMPACK

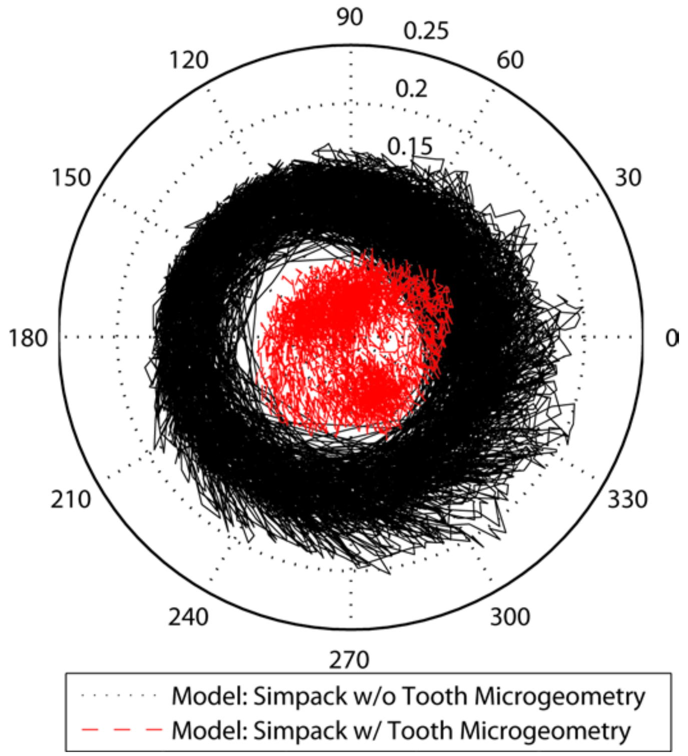


Source: Guo 2015

Gearbox Complexity Fidelity Study

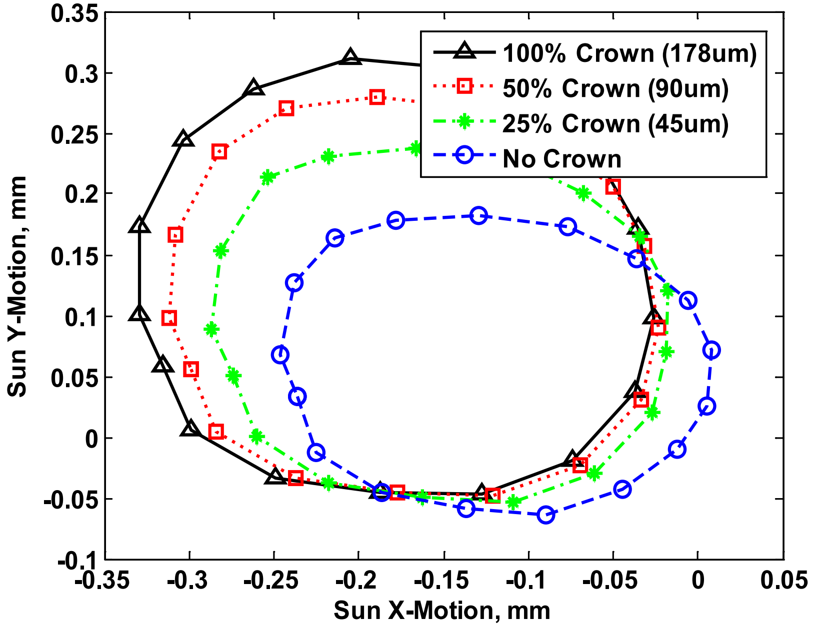
- **Studies model fidelity for gearbox components**
  - ***Gears,*** bearings, and structures
- **Tooth microgeometry affects sun motion.**

Sun gear orbit with gear tooth modification SIMPACK



Source: Guo, Y., etc., NREL TP/5000-60641, forthcoming

Sun gear orbit with spline tooth modification Transmission3D

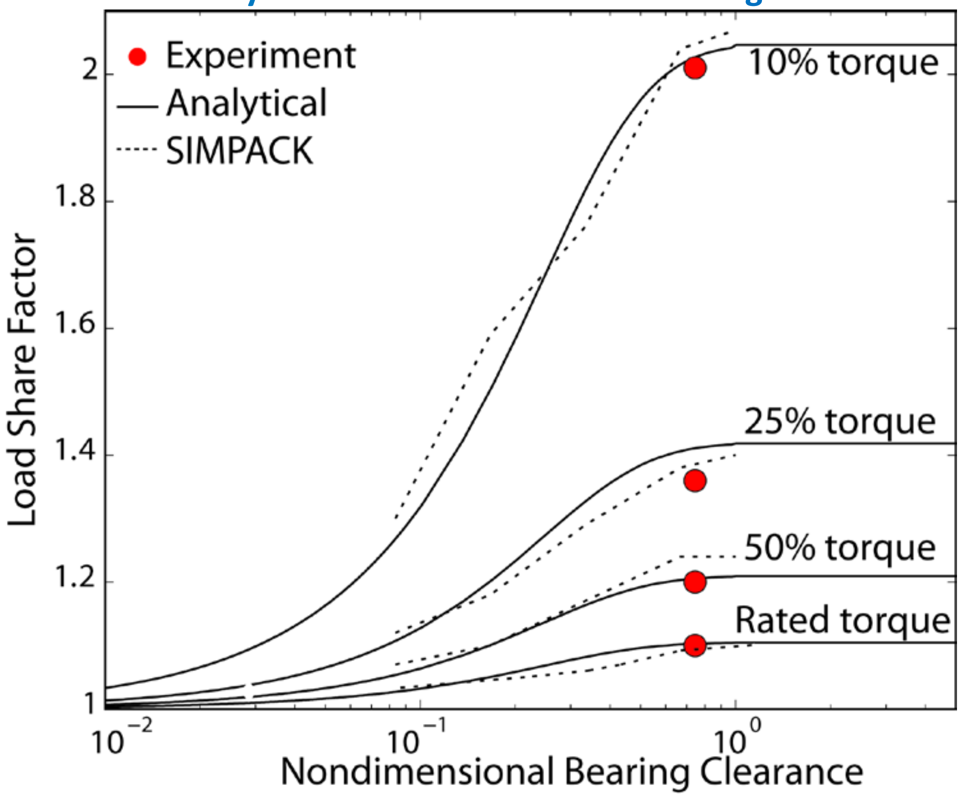


Source: Austin 2013

Gearbox Complexity Fidelity Study

- **Studies model fidelity for gearbox components**
  - Gears, ***bearings***, and structures
- **Clearance and preload in carrier bearings are crucial to characterizing the nontorque load path.**

Planetary load share factor versus bearing clearance

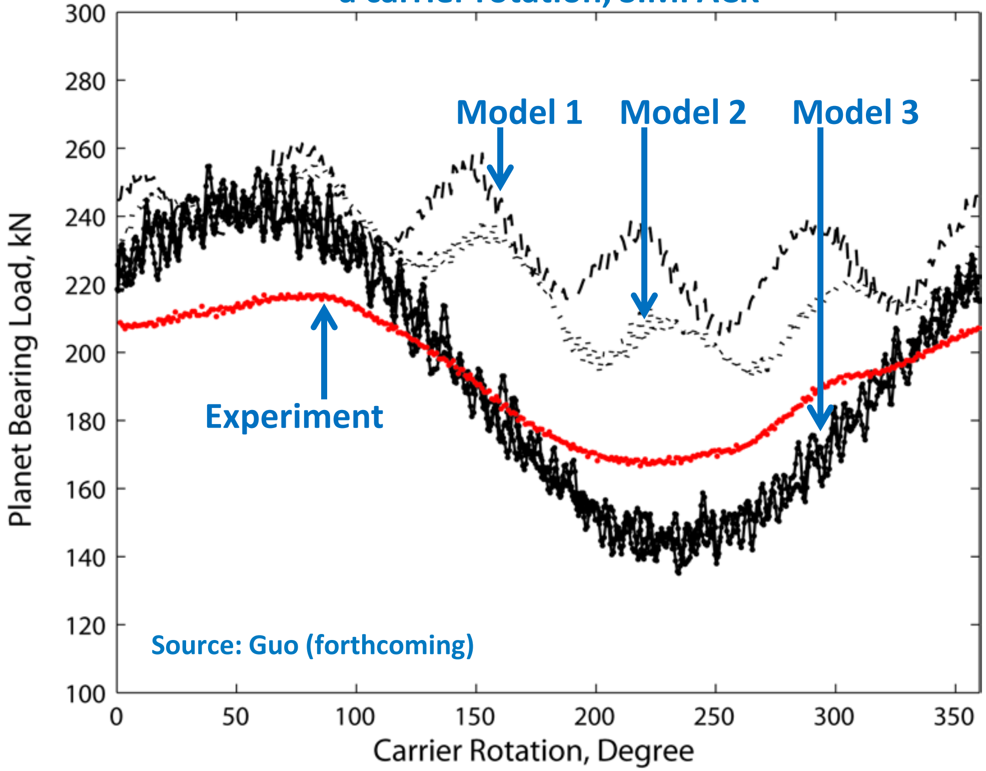


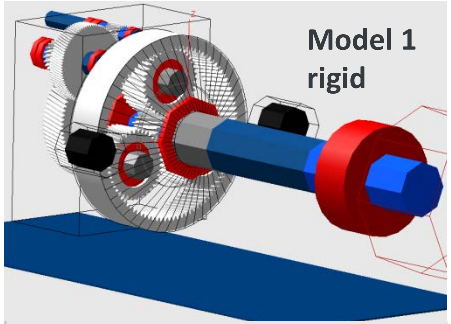
Source: Guo, Keller, and LaCava 2015

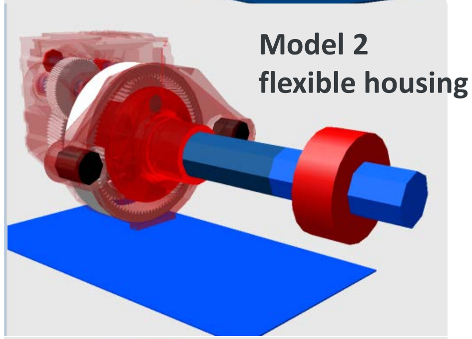
Gearbox Complexity Fidelity Study

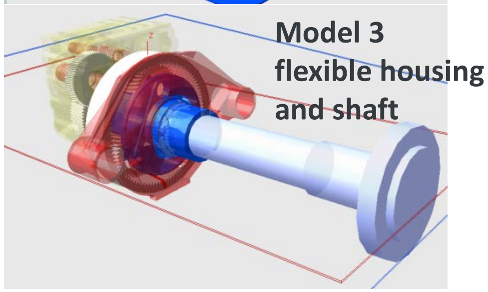
- **Studies model fidelity for gearbox components**
  - Gears, bearings, and ***structures***
- **Best correlation with flexibility of main shaft and gear shafts**
  - Housing and carrier flexibility less important.

Planet-bearing force over a carrier rotation, SIMPACK





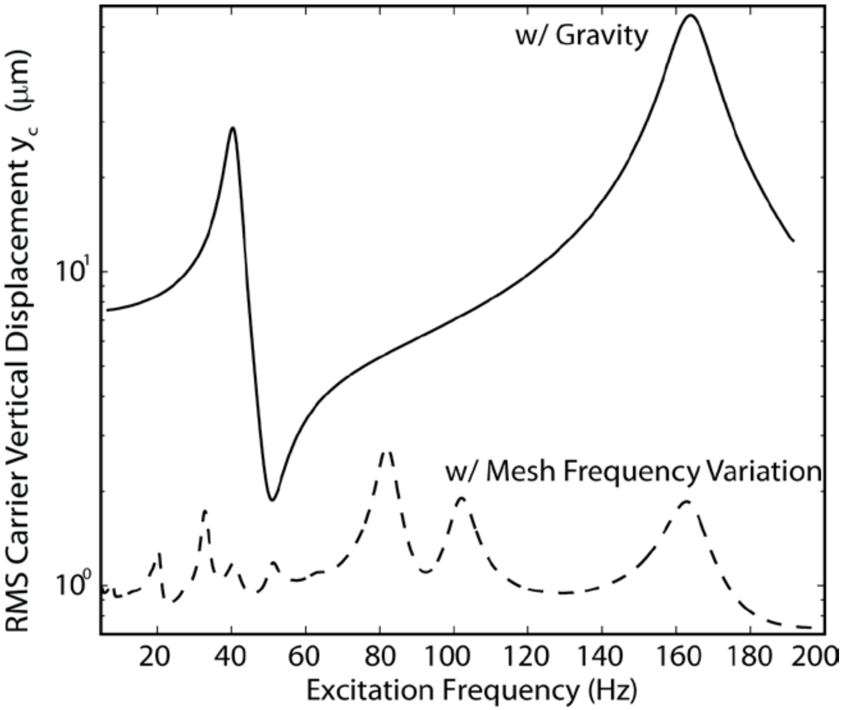




Excitation Source Fidelity Study

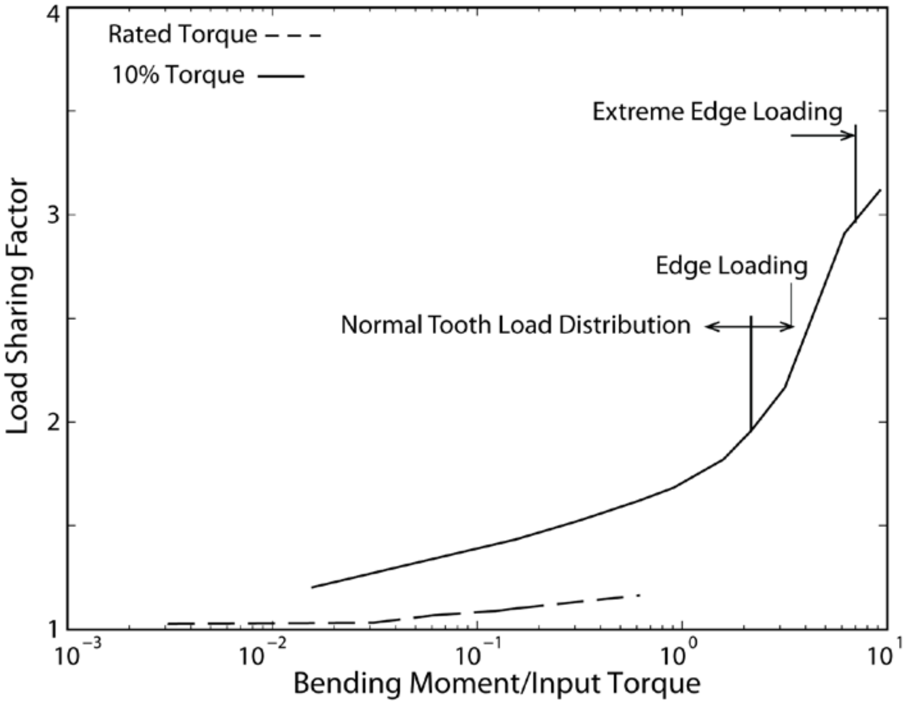
- **Investigates the relative effects of various excitations**
  - Gear mesh variation (internal), gravity, and nontorque loads
- **Nontorque loads significantly affected gearbox internal loads**
- **Gravity has a much greater influence than gear mesh forces.**

Carrier vibration excited by gear mesh and gravity
Lumped-parameter



Source: Guo et al. 2014

Load sharing versus bending moment
SIMPACK

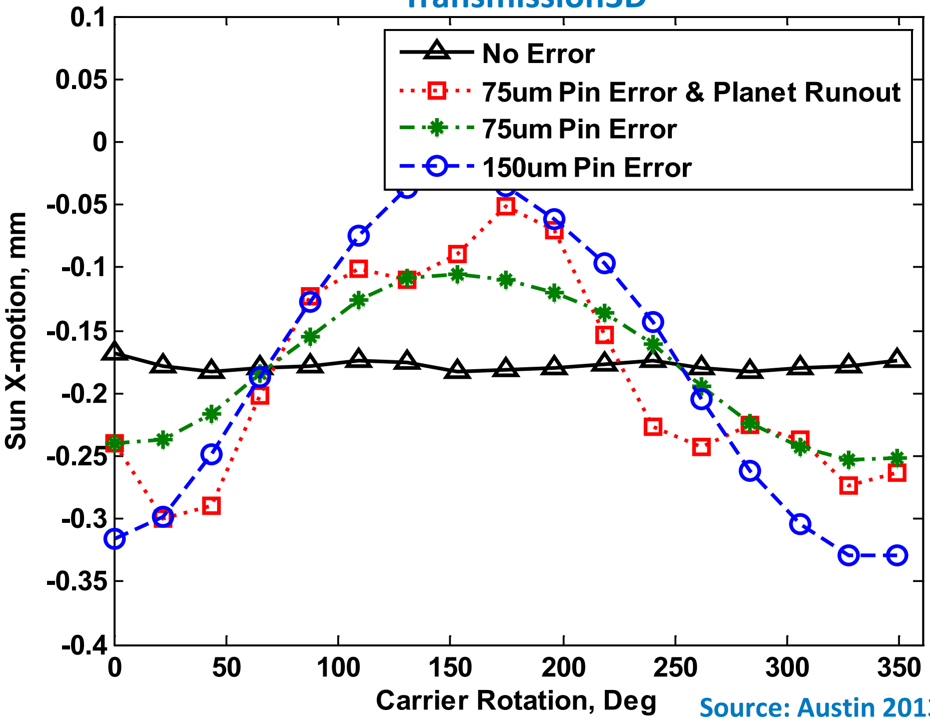


Source: Guo et al. 2015

Imperfection Fidelity Study

- **Considered gearbox imperfections during manufacturing, assembly, and transportation**
- **Imperfections affected component motion**
  - Motion as a result of pin error was larger than that caused by planet runout.

Sun gear motion with various planet pin errors
Transmission3D

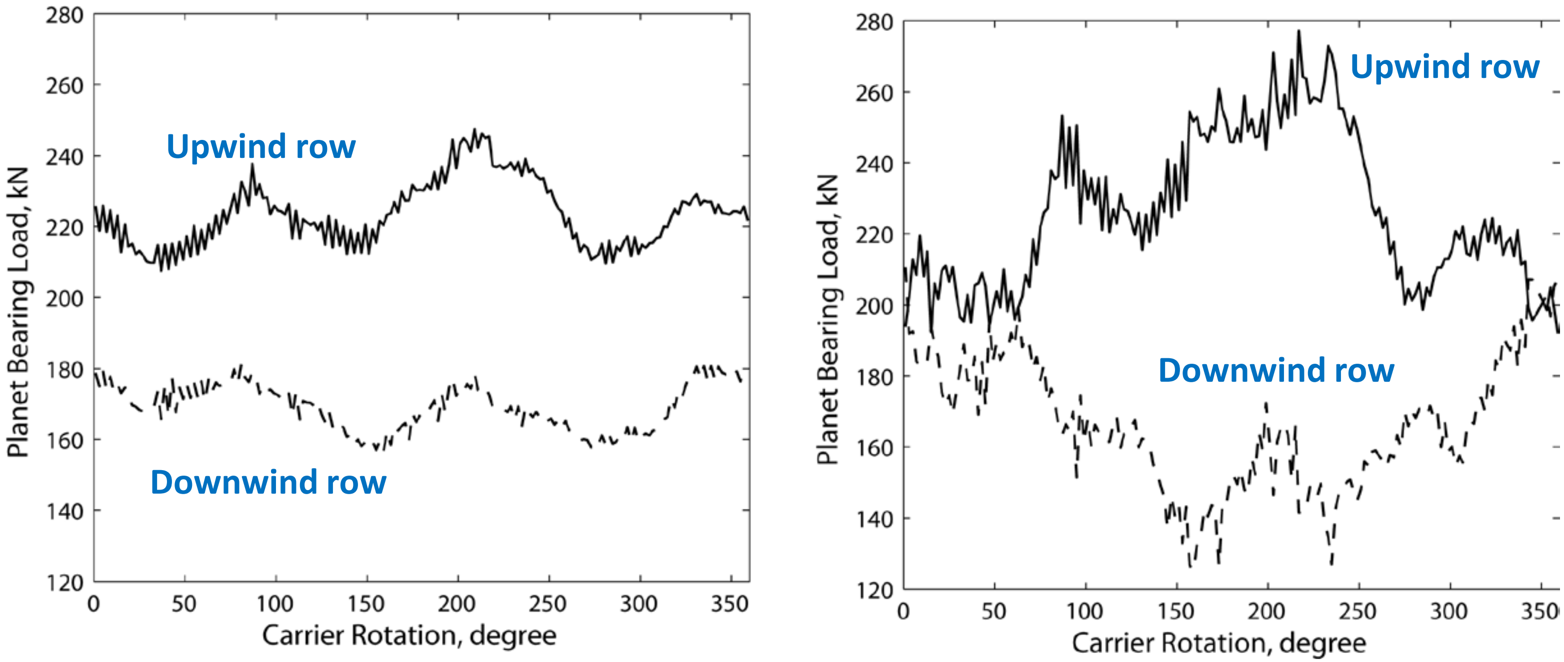


Source: Austin 2013

Imperfection Fidelity Study

- **Planetary carrier pin connection affects planet-bearing loads**
  - Soft connection reduces planet peak loads
  - With rigid connection, upwind and downwind bearing loads out of phase.

Planet-bearing loads with soft (left) and rigid (right) carrier pin connection
SIMPACK



Source: Guo (forthcoming)

Conclusions

- **GRC modeling "round robin" examines common gearbox modeling practices and assumptions**
- **Gears, bearings, and structure—key elements for modeling**
- **Drivetrain complexity**
  - Gearbox alone is insufficient for capturing component loads and motion
  - Main bearing and generator coupling are important
- **Gearbox complexity**
  - Bearing clearance and preload can change the nontorque load transfer path
  - Housing and carrier structure affect tooth misalignment and bearing loads
- **Excitation sources**
  - Nontorque loads and gravity are the dominating external excitation sources
- **Imperfections can affect gearbox component loads and motion.**

Recommended Practice for Gearbox Simulations

Recommended Minimum Model Fidelity

Major Drivetrain Components	Recommended Modeling Approach	Requirements for Degrees of Freedom (DOFs)
Rotor/hub	Rigid body with lumped weight	N/A
Main shaft	Flexible, FE beams	Six DOFs
Main bearing	Stiffness matrices	Five DOFs
Gearbox housing	Flexible, condensed FE	N/A
Planetary carrier	Flexible, condensed FE	N/A
Gearbox shafts	Rigid shaft with correct bearing locations	N/A
Gearbox support	Stiffness matrices	Six DOFs
Gears	Rigid body with contact stiffness	Six DOFs
Gearbox bearings	Stiffness matrices	Five DOFs (except rotation)
Spline/gear coupling	Stiffness matrices	Two DOFs (tilting)
Bedplate	Rigid body or condensed FE	N/A
Generator coupling	Stiffness matrices	Five DOFs (except rotation)

Other Important Considerations

Other Factors	Effects	Priority
Manufacturing tolerance	Affects component motions but has limited effect on loads	Medium
Bearing clearance or preload	Affects component motion and loads; operational values with operating temperature are recommended	High
Gear tooth micro-geometry	Affects frequency spectrum of component motions and gear tooth load distribution	Low
Bedplate tilting angle	Causes gearbox axial loads because of gravity	Medium
Gravity	Affects component motion and loads	High
Nontorque loads	Affects component motion and loads	High
Gear mesh stiffness variation	Affects frequency spectrum of component motions	Medium

Acknowledgments

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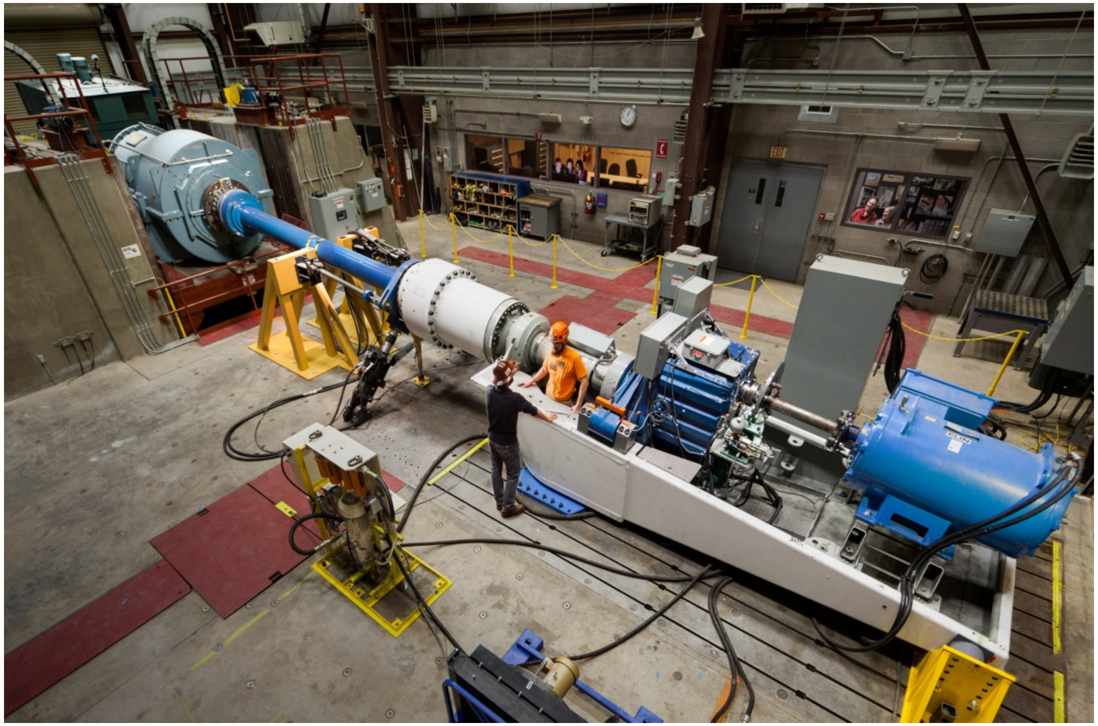

Dynamometer test. Photo by Mark McDade, NREL 32734

Field test. Photo by Jeroen van Dam, NREL 19257

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