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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PR-5000-63871
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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.

Improved industry practices and design standards

<table>
<thead>
<tr>
<th>Teardown inspections</th>
<th>Root cause analyses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anecdotal evidence</td>
<td>Failure mode, effects, and criticality analysis (FMECA)</td>
</tr>
</tbody>
</table>
Test Articles

• Two redesigned 750-kilowatt (kW) gearboxes
  o Modular, three-point mount and two-speed drivetrain
  o One planetary-stage and two parallel-stage gearboxes
  o 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
  o 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
  o Sun motion (two radial)
  o Ring gear tooth root strain (three places)
  o Planet bearing strain (six bearings, six places).
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.
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

Increasing computational time
## Model Feature Summary

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

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

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)**

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**

- 100% Crown (178um)
- 50% Crown (90um)
- 25% Crown (45um)
- No Crown

Sun gear orbit with spline tooth modification

**Transmission3D**

Source: Austin 2013

Source: Guo, Y., etc., NREL TP/5000-60641, forthcoming
Gearbox Complexity Fidelity Study

• Studies model fidelity for gearbox components
  o 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.

![Graph showing planet-bearing force over a carrier rotation, SIMPACK](Source: Guo (forthcoming))
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

Load sharing versus bending moment

SIMPACK

Source: Guo et al. 2014

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.

![Graph showing sun gear motion with various planet pin errors](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.

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

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

## Other Important Considerations

<table>
<thead>
<tr>
<th>Other Factors</th>
<th>Effects</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing tolerance</td>
<td>Affects component motions but has limited effect on loads</td>
<td>Medium</td>
</tr>
<tr>
<td>Bearing clearance or preload</td>
<td>Affects component motion and loads; operational values with operating temperature are recommended</td>
<td>High</td>
</tr>
<tr>
<td>Gear tooth micro-geometry</td>
<td>Affects frequency spectrum of component motions and gear tooth load distribution</td>
<td>Low</td>
</tr>
<tr>
<td>Bedplate tilting angle</td>
<td>Causes gearbox axial loads because of gravity</td>
<td>Medium</td>
</tr>
<tr>
<td>Gravity</td>
<td>Affects component motion and loads</td>
<td>High</td>
</tr>
<tr>
<td>Nontorque loads</td>
<td>Affects component motion and loads</td>
<td>High</td>
</tr>
<tr>
<td>Gear mesh stiffness variation</td>
<td>Affects frequency spectrum of component motions</td>
<td>Medium</td>
</tr>
</tbody>
</table>
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 and Water Power Technologies Office.
References


