Drivetrain Reliability from Inherent to Operational

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Outline

• Reliability from Two Angles
• Drivetrain Reliability Efforts at NREL
  – Inherent
  – Operational
• A Wishful List
Product Development: Inherent Reliability As the Focus

- Analyze the Problem
  - Specifications
  - Constraints
- Design
  - Block diagrams
  - Data flow graphs
- Development
  - Hardware
  - Software
- Deployment
- Testing
- Done

Wind Turbine Operation and Maintenance: Operational Reliability As the Focus

- Maintenance Strategies
  - Reactive/Corrective/Breakdown /Run-to-failure
  - Preventative/Time-based/Cyclic
  - Predictive/Condition-based
  - Proactive/Reliability-centered

- Operation & Maintenance
  - Operation
    - Performance Monitoring
      - SCADA system data
      - Outlier identification
  - Sensing
    - LIDAR or SODAR
    - Flightleader
    - Maximize Annual Energy Production vs. Minimize Fatigue Loads
  - Control
    - Turbine vs. Plant
  - Logistics Optimization

- Proactive/Reliability-centered
  - Tries to find the optimum point in time for carrying out the required maintenance actions by monitoring the current state of a specific component

- Predictive/Condition-based
  - Tries to find the right time for maintenance measures through analyzing a broad database filled with experiences from the past, supported by an estimated remaining useful life, root cause analysis and mitigation strategies to avoid future occurrences of the same failure
Inherent Reliability

- Gearbox loads:
  - Planet bearings
- Operational conditions:
  - High-speed shaft and main bearings
- Dynamic modeling approaches and recommended practice.
Gearbox Loads Investigation: Planet Bearings

- Compare planet bearing load-sharing characteristics
  - Preloaded tapered roller bearings versus cylindrical roller bearings in clearance.

Project Summary Report

Industry partners: Romax Technology, Powertrain Engineers, Timken, and Brad Foote Gearing

Photo by Mark McDade, NREL 40432

Photo by Jon Keller, NREL 36521
Operational Conditions: High-Speed Shaft Bearings

• Determine turbine operations conducive to crack formation
  – Torque, loads, bearing roller sliding
  – Tribological conditions: temp, moisture, current.

Instrumentation Details

Industry partners: Argonne, SKF GmbH, and Winergy
Operational Conditions: Main Shaft Bearings

- Instrument and install a SKF SRB-Wind main bearing
  - Bearing strain (load), temperature, acoustic emission, vibration
  - Electric current across bearing, axial movement, misalignment
  - Auto-lube system with routine grease sampling.

**Industry Partners: SKF USA**

![Photo from SKF](Photo from SKF)

![Photo by Jonathan Keller, NREL 49379](Photo by Jonathan Keller, NREL 49379)

**Uptower Drivetrain Testing**
Dynamic Modeling Approaches

Gear Contact Analysis
- Gear tooth loading
- Time-varying stiffness
- Tooth contact stress

Structure Finite Element (FE) Analysis
- Torsional windup
- Pin misalignment
- Carrier/pin fit

Bearing Analysis
- Nonlinear stiffness
- Load distribution
- Bearing life

In-House Program
- Gravity/transmission error
- Clearance
- Tooth wedging

Gearbox Analysis
- Deflections
- Misalignment
- Clearance
- Vibration
- Dynamics

Full Turbine Analysis
- International Electrotechnical Commission (IEC) load cases
- Turbulent wind
- Aerodynamics
- Drivetrain dynamics
- Hydrodynamics
- Structural dynamics
Recommended Modeling Practice

Recommended Minimum Model Fidelity

<table>
<thead>
<tr>
<th>Major Drivetrain Components</th>
<th>Recommended Modeling Approach</th>
<th>Requirements for Degrees of Freedom (DOF)</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 DOF</td>
</tr>
<tr>
<td>Main bearing</td>
<td>Stiffness matrices</td>
<td>Five DOF</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 DOF</td>
</tr>
<tr>
<td>Gears</td>
<td>Rigid body with contact stiffness</td>
<td>Six DOF</td>
</tr>
<tr>
<td>Gearbox bearings</td>
<td>Stiffness matrices</td>
<td>Five DOF (except rotation)</td>
</tr>
<tr>
<td>Spline</td>
<td>Stiffness matrices</td>
<td>Two DOF (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 DOF (except rotation)</td>
</tr>
</tbody>
</table>

Recommended Factors to Consider

<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 effects on loads</td>
<td>Medium</td>
</tr>
<tr>
<td>Bearing clearance or preload</td>
<td>Affects component motion and loads. Operational values w/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 due to 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 or transmission error</td>
<td>Affects frequency spectrum of component motions</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Operational Reliability

- Benchmarking
- Performance monitoring
- Condition monitoring
- Remaining useful life prediction
Benchmarking To Identify Gaps

• Performance and reliability based on industry standardized key performance indicators
• Gearbox reliability database as an example: partner-owned data compared with global data.
Performance Monitoring Using Supervisory Control and Data Acquisition Data

- High-speed shaft (HSS) ratio: HSS torque to HSS rpm
- Model developed based on normal operation
- Thresholds established based on a certain allowable false alarm rate
- Two angles: response and residual
- Abnormal: outside of the established thresholds.

Condition Monitoring via Dedicated Instrumentation

- **Stress wave analysis**
- **Vibration analysis**
- **Main filter loop particle counting**
- **Offline filter loop particle counting and oil condition monitoring**
- **Electric signature monitoring**
- **Periodic oil sample analysis.**

*Round robin testing of wind turbine drivetrain condition monitoring techniques.*

Frictional Energy Loss-Based Component Remaining Useful Life Prediction

- High-speed-stage-bearing axial cracking
- Frictional energy loss under both normal and transient operations:

\[ E = E_{np} + E_{tt} \]

\[ E_{np} = f(\mu, N, F, \Delta v) \]
- \( \mu \): friction coefficient
- \( N \): number of cycles (roller)
- \( F \): load
- \( \Delta v \): sliding velocity between roller/raceway

\[ E_{tt} = f(\mu, t, F, \Delta v) \]
- \( \mu \): friction coefficient
- \( t \): time
- \( F \): load
- \( \Delta v \): sliding velocity between roller/raceway

- First- and second-order reliability methods:

\[ G = e^* - (E_{np} + E_{tt}) \]
\[ P_f = P\{G(U) < 0\} \]

Reliability Improvements: A Wishful List

Close the Loop via Root Cause Analysis, etc.

- Standardized and proven parts from both Original Equipment Manufactures (OEMs) and after market distributors
- Optimized operation and maintenance practices considering inventory, technician, and environments
- Reliability-centered maintenance enabled by life data analysis, condition monitoring, and prognostics
- Transparent and standardized benchmarking, consistent maintenance between OEMs and owner/operators
- Damaging operational conditions shared across the industry and mandated to be minimized

- Complete loading spectrum: Representative enough with quantified uncertainties; simulated as close as possible via test rigs
- Material library with detailed information sufficient to evaluate reliability risk under different operational conditions and failure modes
- Major system design via a systematic not isolated component approach: Failure Mode Effects and Criticality Analysis and reliability centered design
- Standardized manufacturing processes, prototype testing, and quality control to minimize possible flaws
- Standardized acceptance testing to ensure minimum deviations introduced during transportation and storage
A Recommended Maintenance Practice

Thank You

www.nrel.gov

The Block Island Wind Farm—the first offshore wind farm in the United States. *Photo by Dennis Schroeder, NREL 40389*

Special thanks go to the U.S. Department of Energy, drivetrain reliability collaborative research partners!