Webinar – Wind Turbine Dynamics

Steve MULSKI
SIMULIA IPS, Industry Process Expert
Wind Energy Executive
Wind Turbine Engineering | **Agenda**

- Industry Trends
- Technical Challenges
- IPE Wind Turbine Engineering Workflows
- Simpack History
- Fundamentals Multibody System (MBS) simulation
- Wind turbine Analysis
- Flexible Bodies
- Components
- 3DEXPERIENCE Platform
- Summary
Wind Turbine Dynamics | **Trends**

**Increasing Size**

- Deformation
- Loading
- Dynamic Behavior

**Offshore**

- Hydrodynamics
- Control
- Maintenance

**Cost of Energy**

- Minimize CAPEX and OPEX (Capital Expenditure and Operational Expenditure)
Converting turbulent wind to stable electricity

- Large transient forces (wind and waves)
- Connected to ground and grid
- Large flexible bodies
- Acoustics, hydraulics, electronics (high frequencies)
- Multi-disciplinary engineering
- Holistic simulation required
Wind Turbine Dynamics | Onshore
Wind Turbine Dynamics | Offshore
Wind Turbine Engineering | Workflows

- Load Calculations
- Trailing Edge Noise
- Blade Aerodynamics
- WT Aerodynamics and Acoustics
- Thermal Cooling
- Blade Structural Design
- Lightning Strike
- Antenna and Radar
- Hardware in the Loop
- Control
- Drivetrain Resonance Analysis
- Extreme Load Case
- Components
- Structural Noise
- Foundation Design
- Wind Turbine Engineering Workflows
Simpack is a general purpose Multibody System (MBS) simulation software used to predict and visualize motion, coupling forces and stresses, of any mechanical system.
Wind Turbine Dynamics | MBS Simulation

Why Multibody System (MBS) simulation?

• Components behave differently depending upon their surroundings
• In order to accurately predict and minimize loading on components, system simulation is necessary
IMM TU Dresden, Simpack UM 2014

- Investigation of fault scenarios
- System simulation required for accurate loads prediction
Vibration Absorber Example

- How do different parameters influence the dynamics and loading?
- What are the optimal parameters?
- How susceptible is the design to manufacturing tolerances, or how stable is the design?
Wind Turbine Dynamics | Optimization and Sensitivity

Maximum loading and displacements occur at natural frequencies. Sensitivity studies can be carried out in the time and frequency domains.
Wind Turbine Dynamics | Load Calculations

Solver Technology
- Fast, accurate and robust

Simulation Model
- Any type of wind turbine
- Any level of fidelity

Automation
- Template Scripts for all Design Load Cases
- Result and report generation

Integration
- Easy integration into existing workflows
- Reading and writing of any data format type

On Premise  On Cloud

+  +  +  +  +  +  +  +  +  +

Fx  Fy  Fz  Fxyz  Mx  My  Mz  Mxyz
max/min  DLC  SF  [kN]  [kN]  [kN]  [kN]  [kNm]  [kNm]  [kNm]  [kNm]
Wind Turbine Dynamics | Emergency Stop
Simulations of extreme loads must often consider additional effects in order to achieve accurate results:

- Non-linear blade deformation
- Flexibility of major components
Wind Turbine Dynamics | Assembly Load Case

Substantial cost savings can also be achieved through innovation

- Ability to simulate all aspects of all designs, in any level of fidelity
- Anything that can be imagined can be simulated.

Over 50x reduction in hoisting costs
Wind Turbine Dynamics | Resonance Analysis

Critical Resonances
• Identification, comprehension, and elimination
• Automated run-up, resonance detection, and result generation
Wind Turbine Dynamics | Holistic System Simulation

Accurately calculate natural frequencies with higher fidelity models in order to avoid critical resonances that result in faults and down time. Higher accuracy also enables a larger optimization and cost savings potential.

<table>
<thead>
<tr>
<th>Model Fidelity Variant</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
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<tbody>
<tr>
<td>Tower flexible</td>
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<td>Main frame flexible</td>
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<td>Gearing flexible</td>
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<tr>
<td>Gearbox housing flexible</td>
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<tr>
<td>Planet carrier flexible</td>
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<tr>
<td>Gearbox housing, 6 DoF</td>
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<td>✔</td>
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<tr>
<td>Shafts flexible</td>
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<td>✔</td>
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</tr>
<tr>
<td>Drivetrain parts, 6 DoF</td>
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<tr>
<td>Rotorblades flexible</td>
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<td>✔</td>
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</table>

Model Natural Freq [Hz]

<table>
<thead>
<tr>
<th></th>
<th>1st torsional</th>
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<th>3rd torsional</th>
<th>4th torsional</th>
<th>5th torsional</th>
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<tr>
<td>1st torsional</td>
<td>11.9</td>
<td>1.9</td>
<td>1.9</td>
<td>1.9</td>
<td>1.5</td>
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<tr>
<td>2nd torsional</td>
<td>179.3</td>
<td>5.2</td>
<td>5.0</td>
<td>3.4</td>
<td>2.7</td>
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<tr>
<td>3rd torsional</td>
<td>424.3</td>
<td>22.9</td>
<td>15.4</td>
<td>8.4</td>
<td>7.8</td>
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<tr>
<td>4th torsional</td>
<td>488.0</td>
<td>180.8</td>
<td>55.2</td>
<td>47.0</td>
<td>32.3</td>
</tr>
<tr>
<td>5th torsional</td>
<td>536.4</td>
<td>424.6</td>
<td>150.7</td>
<td>93.6</td>
<td>97.5</td>
</tr>
</tbody>
</table>

Higher fidelity = risk reduction, optimization and cost savings

Courtesy IMM TU Dresden
Wind Turbine Dynamics | ODS

Operating Deflection Shapes (ODS)
Visualizing of nonlinear model behavior at discrete frequencies

ODS Process
• Input = result of a time domain simulation
• FFT analysis is performed for all states of the model
• Results
  • Amplitudes, phases and kinetic energy of each body
• Viewable animation in Post
Wind Turbine Dynamics | Component Optimization

Analysis and optimization of all mechanical components

Holistic component simulation

- Standalone for plausibility checks
- within test-rig for component validation
- within complete turbine for correct loads
Wind Turbine Dynamics | Foundation Design

Design, investigation, optimization, and risk reduction

- Complete system optimization
- Damage and failure analysis
- Extreme waves
- Soil interaction
- Bolt connections
Wind Turbine Dynamics | **Structural Noise**

Noise reduction is a primary design driver

Noise vibration sources
- Gear wheel meshing
- Pumps
- Motors

From the source the vibration is transferred to emitting surfaces.

**High fidelity models within accurate and capable FEA, MBS and SEA software enable structural noise reduction.**
Wind Turbine Dynamics | Control

Optimization of fully coupled system, including control, power electronics, hydraulics, grid, etc.
Wind Turbine Dynamics | Hardware in the Loop

Coupling of virtual and real world for optimal test campaigns.

Real-time capable MBS, including flexible bodies and high fidelity components is required for realistic conditions.

Courtesy CWD RWTH Aachen
Wind Turbine Dynamics | Flexible Bodies

Different methods for including flexible bodies.

Simpack SIMBEAM
- Full parameterization
- Euler-Bernoulli and Timoshenko beams
- Linear and large deformation bending

FE model import
- Linear substructure, including stress
- Durability analysis with fe-safe
- Non-linear reduction for large deformation for rotor blades
Wind Turbine Dynamics | **Flexible Bodies**

Frequency Content and Interface Modes
Wind Turbine Dynamics | **Flexible Bodies**

Frequency Content and Interface Modes

![Diagram showing frequency response and interface modes](image)

- **Frequency Content and Interface Modes**
  - **Frequency Response [m]**
  - **Reference**
  - **Eigenmodes**
  - **Eigenmodes + Interface Modes**
  - **3 coupling points * 6 directions at each point = 18 interface modes**

- **f_max/1.5**
- **f_max**
- **Frequency [Hz]**
Wind Turbine Dynamics | Flexible Bodies

Stress Recovery From ROM’s – Input to Durability

• Comparison of Different Methods

<table>
<thead>
<tr>
<th>number of modes</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>max Frequency [kHz]</td>
<td>65.2</td>
<td>105.3</td>
<td>232.9</td>
<td>257.1</td>
</tr>
<tr>
<td>Normal Stress X</td>
<td>14.508</td>
<td>18.602</td>
<td>0.082</td>
<td>0.056</td>
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<tr>
<td>Y</td>
<td>70.674</td>
<td>78.889</td>
<td>1.327</td>
<td>1.029</td>
</tr>
<tr>
<td>Z</td>
<td>346.708</td>
<td>320.970</td>
<td>2.250</td>
<td>1.612</td>
</tr>
<tr>
<td>Shear Stress XY</td>
<td>80.358</td>
<td>29.283</td>
<td>4.678</td>
<td>3.315</td>
</tr>
<tr>
<td>YZ</td>
<td>571.447</td>
<td>484.255</td>
<td>9.623</td>
<td>7.150</td>
</tr>
<tr>
<td>XZ</td>
<td>80.250</td>
<td>29.205</td>
<td>4.592</td>
<td>3.232</td>
</tr>
</tbody>
</table>

• Simpack’s combination of eigenmodes and interface modes yields accurate stress with the least number of modes
Wind Turbine Dynamics | Flexible Bodies

Simpack Rotor Blade Generator
- ASCII input deck
- Based on Flex5 input Parameters
- Uses SIMBEAM
- Input
  - Basic- bend only
  - Advanced - torsion-bend coupling
  - Linear and large deformations

```plaintext
param.station.begin
i station root pre- flare mass/1 flap struct 3D chord 3D
i ID dist bend sweep [kg/m] [deg] [m] [m] [m] [deg] [deg] [m] [m] [m] [m] [m] [m]
1 1 0.00 0.00 0.00 1445.7 7.00E+09 7.00E+09 19.00 1 2.70 100.80 50.00 59.80
2 1 0.50 0.00 0.00 615.3 6.50E+09 6.30E+09 19.00 1 2.86 98.70 48.50 43.78

param.station.end```

Basic

Advanced
Non-linear deformation of rotorblades

- Rotorblades size is increasing
- Twist-bend coupling now very significant
- Highly non-linear deformation
Wind Turbine Dynamics | Flexible Bodies

Rotorblade generation in Simpack

Different Levels of Fidelity

- Standard Input Data
  - Linear Beam Theory
  - Non-linear Beam Theory
    - Twist-bend coupling
    - Accuracy within 1% of Abaqus
- Non-linear Reduction (deployment phase)
  - Direct use of reduced FE model (from 60,000 to 40 DoF)
Wind Turbine Dynamics | **Flexible Bodies**

A Variety of Choices

**Linear Flexible Bodies**
- Accurate dynamic behavior
- Stress & fatigue
- Noise
- Detailed fluid structure interaction

**Nonlinear flexible Bodies**
- Large deformation
- Reduced Order Formulation

**General Physics**
- collision analyses
- contact
- friction
- plastic deformation

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Reduced order models  
Co simulation

logical scale  
physical scale
Wind Turbine Dynamics | Components

- Large library of Elements
- Cross-industry usage

**General**
- Contact
- Gear pair
- EHD
- Rolling bearing
- Dyn. Bushing
- ....

**Automotive**
- Elkin. sensors
- Tires
- Roads
- Driver

**Engine**
- Dyn. valve spring
- HLA
- Gas forces
- Chain
- Belt

**Rail**
- Rail-wheel contact
- (Flex) track
- Rail wear

**Wind**
- Rotorblade gen.
- AeroDyn IF
- HydroDyn IF
- AeroModule IF
Wind Turbine Dynamics | Components

Rolling Bearings overview
- Linear and non-linear stiffness
- 5x5 Matrices
- Characteristic field data
  - Interface to BEARINX® Map
  - Interface to LAGER2, FVA
- Simpack Rolling Bearing Element
- Simpack general contact

Linear and non-linear stiffness

Coupled linear stiffness
\[
\begin{bmatrix}
c(1,1) & c(1,2) & c(1,3) & c(1,4) & c(1,5) & c(1,6) \\
c(2,1) & c(2,2) & c(2,3) & c(2,4) & c(2,5) & c(2,6) \\
c(3,1) & c(3,2) & c(3,3) & c(3,4) & c(3,5) & c(3,6) \\
c(4,1) & c(4,2) & c(4,3) & c(4,4) & c(4,5) & c(4,6) \\
c(5,1) & c(5,2) & c(5,3) & c(5,4) & c(5,5) & c(5,6) \\
c(6,1) & c(6,2) & c(6,3) & c(6,4) & c(6,5) & c(6,6)
\end{bmatrix}
\]
Rolling Bearings overview

- Rolling Bearing Element
  - 3D Contact Description
  - Based on inner bearing geometry
  - Analytical force description (ISO 16281)
  - Non-linear stiffness and cross-coupling
  - Flexible bearing rings

- Full Body Model
  - Full geometrical and inertial description
  - General Simpack contact Elements
  - Advanced output values (e.g. surface stress)
<table>
<thead>
<tr>
<th>Element</th>
<th>Characteristics</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1D Spring-Damper (FE 6, 43, 185)</td>
<td>• Non-linear 1D stiffness</td>
<td>• Bearing of rigid shafts with linear angular velocity or load</td>
</tr>
<tr>
<td></td>
<td>• Clearance definition</td>
<td>• Simplified NVH driveline analysis</td>
</tr>
<tr>
<td>3D Stiffness Matrix (FE 41, Bearinx ®)</td>
<td>• Linear 3D stiffness</td>
<td>• Bearing of flexible shafts with increasing loads</td>
</tr>
<tr>
<td></td>
<td>• Cross-coupled forces/torques</td>
<td>• NVH without bearing excitations</td>
</tr>
<tr>
<td></td>
<td>• All displacements considered</td>
<td></td>
</tr>
<tr>
<td>3D Contact Description (FE 88)</td>
<td>• Non-linear 3D stiffness</td>
<td>• Flexible bearing of flexible shafts with dynamic loads</td>
</tr>
<tr>
<td></td>
<td>• Cross-coupled forces/torques</td>
<td>• NVH incl. bearing excitations</td>
</tr>
<tr>
<td></td>
<td>• Cage rotation &amp; flexible bearings</td>
<td></td>
</tr>
<tr>
<td>Full Body Model (FE 198)</td>
<td>• Full description of all bearing components and contacts</td>
<td>• Detailed bearing analysis (e.g. normal stress and cage interaction)</td>
</tr>
</tbody>
</table>
Wind Turbine Dynamics | Components

Journal Bearings overview

- Easy setup
- Cylindrical or planar bearings
- Analytical HD, online HD or one- / double-sided EHD (floating ring)
- Fluid flow coupling of bearings
- Transient oil temperature by a global thermal balancing
- Wear calculation
## Wind Turbine Dynamics | Journal Bearings Overview

<table>
<thead>
<tr>
<th>Element</th>
<th>Characteristics</th>
<th>Use</th>
</tr>
</thead>
</table>
| **Approximating Hydrodynamics (FA)** | • Analytical approach  
• All forces/torques  
• Mixed friction | • Fast cylindrical bearing with friction torque  
• Durability calculations of holistic models |
| **Hydrodynamics (HD) or Rigid dry contact** | • Online solution  
• All forces/torques/ friction regimes  
• Lokal design elements | • Geometry optimization (crowning, grooves etc.)  
• Oil flow analysis |
| **Elasto-Hydrodynamics (EHD) or Rigid elastic contact** | • HD / Rigid dry contact +  
• local deformations on one or both bodies | • Friction and wear analysis  
• Micro geometry optimization |
Wind Turbine Dynamics | Components

Gear Wheels

- Basic Gear Pair
  - No meshing excitations
  - Recommended for linearization tasks

- Gear Pair 225
  - Meshing excitations
  - Profile and flank micro geometry
  - Pre Plots: check plot, load intensity, mesh contouring

- Gear Pair 225 with Flexible Bodies

- Non-standard gear profiles
Wind Turbine Dynamics | Components

Gear Pair 225

- DIN 3990

- Weber Banaschek
  - Clear separation of stiffnesses (body, tooth and contact)
  - Recommended for use with flexible gears and ring gears

- Extended tip contact

- Contact pattern plot
Wind Turbine Dynamics | Components

Optimization of tooth load distribution

- Gear tooth modification
- Gearbox support stiffness
- Planet pin shit, tangential and radial

Face load factors, $K_{H\beta}$, optimization by varying:

- helix angle modification
  $f_{H\beta} = 90 \, \mu m$

Wind Turbine Dynamics | **Components**

Flexible Spline Coupling

- Rigid
  - Detailed contact
- Flexible
  - Beam elements
  - FEA Bodies
Wind Turbine Dynamics | Components

Electric Machine Interface

Allows for Full System Drivetrain Analysis including:

• Gear Meshing
• Roller Bearing
• Nonlinear Bushings
• Spatial Electric Loads
Wind Turbine Dynamics | Components

Aerodynamic Methods

- Blade Element Momentum (BEM)
  - AeroDyn from NREL
  - AeroModule from ECN
  - Flex5 (customer implementation)

- Free Vortex Wake
  - AeroModule from ECN
  - S4 from DLR (customer implementation)

- CFD (Navier Stokes, Lattice Boltzmann)
  - 3DEXPERIENCE, PowerFLOW, XFlow
  - Customer implementations
Wind Turbine Dynamics | Components

Hydrodynamic Methods

- Morrison Equations (HydroDyn)
  - Slender cylinders
  - Offshore fixed and floating structures

- Linear hydrodynamics (HydroDyn)
  - Hydrostatic, waves/currents, added mass, radiation/diffraction

- CFD
  - Detailed Loading
  - Extreme events
  - Optimization
Wind Turbine Dynamics | Components

Offshore mooring lines

- Quasi-static mooring line
  - MAP (NREL)
  - Multi-Segmented
  - Seabed contact and friction

- Dynamic mooring
  - Morrison equations (HydroDyn)
  - Multi-body line
  - Contact, friction, etc.
Wind Turbine Engineering | 3DEXPERIENCE Platform

Concurrent Engineering

Components
- gearbox,
- pitch system,
- yaw system,
- ....

Structural parts
- hub,
- bedplate,
- ....

Blades & Aerodynamics

Control

Certification

Electrical System

Tower

Foundation

3DEXPERIENCE
Wind Turbine Engineering | 3DEXPERIENCE Platform

The Digital Thread

Full digital continuity from design to validation to manufacturing eliminates translations and other sources of data loss.
Wind turbine Dynamics | **Summary**

- Dynamics and load prediction of any wind turbine type, and at any level of fidelity.
- Unified solution
  - Design Load Calculations
  - Component Optimization
  - Stress, durability
  - Acoustics
  - Realtime
  - ...
- Transparent simulation environment
- 3DEXPERIENCE

THANK YOU FOR YOUR ATTENTION!