Simulation of Drive Trains in Wind Turbines with SIMPACK

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Introduction and Overview

• Wind power is eco-friendliness and has been steadily improved
• Annual grow rates of 35 % in Germany
• 10 years ago power-output per unit less than 300 kW
• Today standard output 1.5 MW
• Turbines with 2.5 MW are in operation
• Off-Shore-Turbines with 5 to 6 MW output are in development stadium
• Operational experience with that turbine size is not yet available
Introduction and Overview
Introduction and Overview

• Operational load situation is characterized by:
  – High load peaks
  – Load alternations in the drive train
  – High light load periods (harmful to gearing)
  – Aeroelastic vibrations at the rotor blades

• Especially the drive train has to withstand:
  – Dynamics of the wind loads
  – Dynamics of the electrical network
  – Deformations of the tower and the nacelle structure
Drive train concepts in Wind Turbines

Fig. 8.27. Rotor shaft and bearings integrated into the gear box

(FLENDER)

Fig. 8.30. Variations of rotor bearing shaft and assembly [7]
Drive train concepts in Wind Turbines

Fig. 8.30. Variations of rotor bearing shaft and assembly [7]

Fig. 8.25. Rotor shaft and bearing assembly of the VESTAS V66
Drive train concepts in Wind Turbines

Long shaft with separate bearings, gearbox supported by the shaft with torque restraints.

Rear bearing integrated into the gearbox, "three point suspension" of shaft/gearbox assembly.

Rear bearing integrated into the gearbox, gearbox foot-mounted on the bedplate, front bearing integrated in the load carrying structure of the nacelle.

Rotor bearings completely integrated into the gearbox.

Rotor bearings on a stationary hollow axle, power transmission by a torque shaft.

Fig. 8.30. Variations of rotor bearing shaft and assembly [7]

Fig. 8.26. Three point suspension of the rotor shaft / gearbox assembly of the NORDEX N 80
Actual and future problems

• The natural frequencies (Bending and Torsion) of tower and nacelle of today’s wind turbines up to 2.5 MW output are between 0.5 and 2 Hz.
• The lowest natural frequencies (Bending and Torsion) of the rotor blades are in a similar scale up to 3 Hz.
• The lowest torsional natural frequencies are normally above 3.5 Hz.
• Possible excitation frequencies on the rotor side are in the same scale with regard to multiples of the operational number of revolutions (3P – threefold, 6P – sixfold).
• Necessity to calculate all frequencies exactly to avoid unwanted excitations.
Actual and future problems

- Due to changing relations of mass and stiffness in the Multi-Megawatt-Turbines the natural frequencies of the drive train will be lowered into the area of the natural frequencies of the structure.
- An additional problem to excite natural frequencies results from the variable speed to optimize the operational management of the turbine.
- Measures have to be taken to operate the turbine not in resonance areas.
- This could be achieved by „Blocking“ or rapid „Crossing“ of speed areas.
- The exactly knowledge of all natural frequencies is an absolutely must.
Creating a simulation model of the drive train

- A prerequisite for dimensioning a drive adequately for the expected strain is to know the kind of strain action as a function of time.

- If you can’t measure it you have to calculate (simulate) it.

- Therefore we created a Multi-Body-System-Model of the complete Drive Train of a Wind Turbine.
Creating a simulation model of the drive train

First of all we have the following conditions:

- The model must represent the conditions of the real system as accurately as possible.

- The connection between the real system and the reduction in the model should be noticeable at each point.

- It should be possible to calculate the system parameters on which the model is based from the technical documents or from the real system itself with sufficient accuracy.
Creating a simulation model of the drive train

- A simple 3-Mass-Torsional-System for the complex drive train is not sufficient. Such models are in use to simulate the complete Wind Turbine with
  - Aerodynamics at the rotor
  - Oscillations of tower, nacelle and complete structure
  - Dynamics of drive train and electrical system
Creating a simulation model of the drive train

The created model has the following features:

• 11 rigid bodies with:
  – 13 torsional and
  – 7 translational degrees of freedom

• System boundaries:
  – at the rotor hub 3 forces and 3 moments out of a wind simulation program FLEX4
  – at the generator characteristic line of the air gap moment (Kloss equation)

• Model creation and determination of main parameters is the most important aspect, therefore we used the programme SIMOFFICE (available at TU Dresden)

• Calculation with SIMPACK and MATLAB / SIMULINK
Creating a simulation model of the drive train
Creating a simulation model of the drive train

Flow of Torque

<table>
<thead>
<tr>
<th></th>
<th>axial</th>
<th>radial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>
Creating a simulation model of the drive train

Flow of Torque

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<td></td>
</tr>
<tr>
<td>100%</td>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>50%</td>
<td>50%</td>
<td></td>
</tr>
</tbody>
</table>

Force Elements:
- Toothing
- Coupling
Creating a simulation model of the drive train

Windsimulationprogram FLEX 4 transforms given (measured) wind loads into 3 forces and 3 moments at the hub.
Creating a simulation model of the drive train

\[ \frac{M}{M_K} = \frac{2}{S} + \frac{S_K}{S} \]
Creating a simulation model of the drive train

Simulation Results Flex4

Measured Data of Wind Turbine

Matlab/Simulink-Model for Characteristic Curve of Generator and to Simulate Switch Operations and Preparation of Measured Data

Rotational Speed Rotor
Axial Force
Brake Torque
Generator Torque

Simpack-Model

Evaluation and Visualisation of the Simulation Program Simpack
Results of the Simulation

Natural modes and frequencies of the linearized model

- Discretizing the drive train into rigid masses and massless rigidities allows an exact assignment of frequencies to the respective component of the drive train. This allows to draw conclusions on the excitability of undesirable vibrations.

- Comparison between torsional, translatorial and combined modes (as given in the following table)

- Campbell-Diagram
## Results of the Simulation

Natural modes and frequencies of the linearized model

<table>
<thead>
<tr>
<th>No. of natural frequency</th>
<th>SIMPACK</th>
<th>Torsional Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 Hz</td>
<td>0 Hz</td>
</tr>
<tr>
<td>2</td>
<td>1,65 Hz</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>3,05 Hz</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>3,43 Hz</td>
<td>4,844 Hz</td>
</tr>
<tr>
<td>5</td>
<td>23,09 Hz</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>23,22 Hz</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>24,98 Hz</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>36,16 Hz</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>59,93 Hz</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>67,36 Hz</td>
<td>67,126 Hz</td>
</tr>
</tbody>
</table>

Remark: This table shows very clear the advantages of a full Multi-Body-System-Simulation compared to a Torsional-Simulation.
Results of the Simulation

Natural modes and frequencies of the linearized model:

3.43 Hz: Torsional
Results of the Simulation - Campbell Diagram

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### Results of the Simulation

Natural modes and frequencies of the linearized model

<table>
<thead>
<tr>
<th>No. of eigenfrequency</th>
<th>SIMPACK</th>
<th>Torsional Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>130,10 Hz</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>202,80 Hz</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>242,62 Hz</td>
<td>236,16 Hz</td>
</tr>
<tr>
<td>14</td>
<td>259,11 Hz</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>390,60 Hz</td>
<td>380,64 Hz</td>
</tr>
<tr>
<td>16</td>
<td>573,72 Hz</td>
<td>566,30 Hz</td>
</tr>
<tr>
<td>17</td>
<td>621,83 Hz</td>
<td>604,73 Hz</td>
</tr>
<tr>
<td>18</td>
<td>1527,82 Hz</td>
<td>1513,66 Hz</td>
</tr>
<tr>
<td>19</td>
<td>1975,95 Hz</td>
<td>2039,40 Hz</td>
</tr>
<tr>
<td>20</td>
<td>2422,31 Hz</td>
<td>2412,34 Hz</td>
</tr>
</tbody>
</table>

Remark: This table shows very clear the advantages of a full Multi-Body-System-Simulation compared to a Torsional-Simulation.
Results of the Simulation

Natural modes and frequencies of the linearized model:

259.11 Hz: Translatorical
Results of the Simulation - Campbell Diagram

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Technische Universität Dresden
Institut für Maschinenelemente und Maschinenkonstruktion
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Results of the Simulation

Torques in kNm

Mx

My

Mz

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Results of the Simulation

Forces in kN

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Results of the Simulation - Normal Operation

Input Torque Rotor [Nm]

Axial Force Bearing Shaft 2 [N]
Load Case - Braking
Results of the Simulation - Braking

Braking Torque [Nm]

Axial Force Bearing Shaft 2 [N]
## Comparison Torsional vibration model versus Multibody model

<table>
<thead>
<tr>
<th></th>
<th>Torsional vibration model</th>
<th>Multibody model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Positions</strong></td>
<td>1 rotation</td>
<td>3 rotation axes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 linear displacements</td>
</tr>
<tr>
<td><strong>Speeds</strong></td>
<td>1 rotation</td>
<td>3 translational</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 rotational</td>
</tr>
<tr>
<td><strong>Accelerations</strong></td>
<td>1 rotation</td>
<td>3 translational</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3 rotational</td>
</tr>
<tr>
<td><strong>Internal forces</strong></td>
<td>-</td>
<td>3 directions</td>
</tr>
<tr>
<td><strong>Internal moments</strong></td>
<td>1 rotation axis</td>
<td>3 rotation axes</td>
</tr>
<tr>
<td><strong>Bearing forces</strong></td>
<td>-</td>
<td>tangential, radial, axial</td>
</tr>
<tr>
<td><strong>Gearing forces</strong></td>
<td>Tangential</td>
<td>tangential, radial, axial</td>
</tr>
</tbody>
</table>

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Summary and Outlook

• The manufacturer of wind turbines and their subsupplier have a great interest in the determination of dynamic loads in drive trains for all operational situations (especially for the planned Offshore applications).

• Therefore we suggested to do a Multi-Body-System Simulation of the complete Drive Train to calculate the internal torques and forces in the gear box as a function of the acting wind loads.

• A comparison with measured data was not possible up to now but we have the feed-back of the manufacturer that we are on the right way.
Summary and Outlook

Existing problems:

- Data mining to get all the necessary input data of the subsuppliers (e.g. bearing stiffnesses) is very boring
- Availability of measured data for direct comparison

Prospects:

- Comparison will be possible in the near future
- Extension of the model to planetary gear boxes
- Complete Model for Electrical and Control System
- Direct connection between wind-load simulation and drive train simulation
Model Extension to complete Wind Turbine
Simulation of Drive Trains with Planetary Gears

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Planetary Gear Box
with Parameter Excitation by the Tooth Contact
Force Element for the Tooth Contact

General Force Equation:
\[ K \cdot s(t) + D \cdot s(t) = F(t) \]

Momentum of Force Element:
\[ s_{\text{res}}(t) = s_t(t) \cdot \cos(\beta) + s_a(t) \cdot \sin(\beta) \]
\[ s_{\text{res}}(t) = (d_1 \cdot \dot{\phi}_1(t) + d_2 \cdot \dot{\phi}_2(t)) \cdot \cos(\beta) + (s_1(t) - s_2(t)) \cdot \sin(\beta) \]
\[ s_{\text{res}}(t) = s_t(t) \cdot \cos(\beta) + s_a(t) \cdot \sin(\beta) \]
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Tooth Force:
\[ F_n(t) = c_{\text{Zahnpaar}} \cdot s_{\text{res}}(t) + d_{\text{Zahnpaar}} \cdot \dot{s}_{\text{res}}(t) \]
\[ F_a(t) = F_n(t) \cdot \sin(\beta) \]
\[ F_t(t) = F_n(t) \cdot \cos(\beta) \]
Gear Set
with Parameter Excitation by the Tooth Contact

Problem of Parameter Excitation

Because of the changing Stiffness of Toothing there is an Parameter Excitation in the Gear Set. The influence of the natural frequencies of the gear is unknown up to date. The analysis will shown the effect of the Parameter Excitation.

Characteristics of Stiffness

\[ k \quad \text{... Resulting Stiffness of Toothing} \]
\[ k_z \quad \text{... Stiffness of Tooth} \]
\[ p_e \quad \text{... Circular Pitch} \]
Gear Set
with Parameter Excitation by the Tooth Contact
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Thank you for your Attention