Multibody Model for Planetary Gearbox of 500 kW Wind Turbine

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Overview / topics

1. Introduction
2. Aeroelastic model (FLEX 5)
3. Experiments vs. simulations
4. Multibody model - description
5. Results
6. Conclusions
1. Introduction

**Objective:**
To create a multibody program for modelling drivetrain loads, forces etc on main components such as bearings and all stages in the gearbox.

**Method:**
Matlab code with input for generator and rotor loads from FLEX5, using a complete structural model of the wind turbine.
1. Introduction

“Multibody drivetrain model of a 500 kW wind turbine for predicting gear tooth stresses in a planetary gearbox” – methods:

Shown on the next 3 slides
2. Aeroelastic model (FLEX 5)

a) **Input:**
   a) “Real” atmospheric turbulent wind speed.
   - Wind field (based on TI+mean wind sp)
   - Blade aerodynamic data: Lift+ Drag coefficients, radial stations
   - Elastic properties, mass, structural damping, (bending) stiffness, distances, generator data (mass, moment of inertia, slip, loss/efficiency)

\[
C_i = \frac{L}{\frac{1}{2} \rho V \alpha^2 c}
\]

\[
C_d = \frac{D}{\frac{1}{2} \rho V \alpha^2 c}
\]

\[
M \ddot{x} + C \dot{x} + K x = F_g
\]

b) **Output:**
   Main shaft/generator torque, rotor/blade forces, displacements etc.
2. Aeroelastic model (+ validation: winddata.com)

- Wind speed (m/s)
- Power (kW)
- Main shaft torque (kNm)
4. Multibody model – bodies and constraints

- B1: Main shaft + pl. carrier
- B2: Ring
- B3+B5+B6: Planets
- B4: Sun etc (blue)
- B7: Lower gearparts
- B8: Gear, shaft and generator
4. Multibody model – bodies and constraints

For a constrained mechanical system with \( m \) independent constraints

\[
\Phi = 0
\]  \quad (9.51)

the velocity and acceleration equations are

\[
\Phi_q \dot{q} = 0
\]  \quad (9.52)

and

\[
\Phi_q \ddot{q} - \gamma = 0
\]  \quad (9.53)

The equations of motion for this constrained system are as given in Eq. 9.6:

\[
M\ddot{q} - \Phi_q^T \lambda = g
\]  \quad (9.54)

Equation 9.53 can be appended to Eq. 9.54 and the result can be written as

\[
\begin{bmatrix}
M & \Phi_q^T \\
\Phi_q & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{q} \\
-\lambda
\end{bmatrix}
= 
\begin{bmatrix}
g \\
\gamma
\end{bmatrix}
\]  \quad (9.55)

Convert 2\textsuperscript{nd} order Initial Value Problem \(\rightarrow\) Two 1\textsuperscript{st} order ODEs:

ODE45 in Matlab to integrate and get velocities and positions
4. Multibody model – bodies and constraints

\[ \Phi : (A_{70} \cdot v_r)^T \left( \begin{pmatrix} x_1' \\ y_1' \end{pmatrix} + r_{p1}(\omega_{1} \hat{v}_r) \right) - (A_{70} \cdot v_r)^T \left( \begin{pmatrix} x_2' \\ y_2' \end{pmatrix} - r_{p2}(\omega_{2} \hat{v}_r) \right) = 0 \]

20 deg. pressure angle

2D gear constraint equation

\[ \Phi : (A_{70} \cdot v_r)^T (\ddot{r}_1 + r_{p1}\omega_{1} \hat{v}_r) + (A_{70} \cdot v_r)^T (\ddot{r}_1 + r_{p1}\omega_{1} \hat{v}_r) \\
- (A_{70} \cdot v_r)^T (\ddot{r}_2 - r_{p2}\omega_{2} \hat{v}_r) - (A_{70} \cdot v_r)^T (\ddot{r}_2 - r_{p2}\omega_{2} \hat{v}_r) = 0 \]
4. Multibody model – equations of motion

\[
\begin{bmatrix}
M & \Phi_q^T \\
\Phi_q & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{q} \\
-\lambda
\end{bmatrix}
= 
\begin{bmatrix}
g \\
\gamma
\end{bmatrix}
\]

Reaction forces (in bearings/gear tooth forces etc):

\[M\ddot{q} = \sum F \quad \text{or:} \quad M\ddot{q} = \sum F_{ext} + \sum F_{react} \Rightarrow M\ddot{q} - \Phi_q^T \lambda = F_{ext}\]

Used for calculating bearing and gear tooth reaction forces and moments.

DTU Mechanical Engineering – p.10
5. Results (gear tooth normal forces)

![Graph showing gear tooth normal forces](image)

- **Sun/planet** ≈ 236 kN
- **Planet/ring** ≈ −236 kN
- **Par.gear 1** ≈ −83 kN
- **Par.gear 2** ≈ 30 kN

**Time [sec]**

**Tooth normal force [kN]**
5. Results

Example: Mean sun/planet gear tooth stresses:

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>10</td>
<td><img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>14</td>
<td><img src="image3" alt="Image" /></td>
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<tr>
<td>18</td>
<td><img src="image7" alt="Image" /></td>
</tr>
<tr>
<td>20</td>
<td><img src="image8" alt="Image" /></td>
</tr>
</tbody>
</table>
5. Results

Rigid gearbox animation

Flexible gearbox animation (work in progress)
Step: 2072

Simulation time: 8.85

Time elapsed: 130.875

FPS = 16

Speed: 0
6. Conclusions

- Realistic dimensions and input parameters have been used for modelling a real 500 kw wind turbine and gearbox.
- Input to multibody code from Flex 5 has successfully been validated using real data (wind speed + strain gauge torque + electrical power).
- A realistic drive-train multibody model has been made.
- The multibody program makes it possible to extract e.g. bearing and gear tooth forces and moments (information which cannot be found with Flex 5 without modifications).
- Results from the program can easily be extracted for further analysis using FEM or other tool (e.g. FEM-model of gear tooth stresses made in Comsol Multiphysics).
Thank you for your time