Multibody Model for Planetary Gearbox of 500 kW Wind Turbine

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DTU Mechanical Engineering
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.

[Diagram of wind turbine components: Rotor, Gearbox, Generator, Power electronics, Transformer, Grid, with DTU (Risø/Lyngby) and AAU connections.]
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

(a) Illustration of rotor, nacelle, main shaft, gearbox (planetary + 2 parallel stages), brake, 500 kW generator, 3 yaw motors etc.

DTU Mechanical Engineering – p.4
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)

   \[ C_i = \frac{L}{\frac{1}{2} \rho V^2 c} \quad C_d = \frac{D}{\frac{1}{2} \rho V^2 c} \]

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

FLEX5 Input

FLEX5 Output

Wind speed (m/s)

Power (kW)

Main shaft torque (kNm)
4. Multibody model – bodies and constraints

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

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

\[
\Phi = 0
\]  \hspace{1cm} (9.51)

the velocity and acceleration equations are

\[
\Phi_q \dot{q} = 0
\]  \hspace{1cm} (9.52)

and

\[
\Phi_q \ddot{q} - \gamma = 0
\]  \hspace{1cm} (9.53)

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

\[
M \ddot{q} - \Phi_q^T \lambda = g
\]  \hspace{1cm} (9.54)

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

\[
\begin{bmatrix}
M & \Phi_q^T \\
\Phi_q & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{q} \\
-\lambda
\end{bmatrix}
=
\begin{bmatrix}
g \\
\gamma
\end{bmatrix}
\]  \hspace{1cm} (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

\[
\Phi : (A_{70} \cdot v_r)^T \left( \begin{cases} \dot{x}_1 \\ \dot{y}_1 \end{cases} \right) + r_{p1}(\omega_1 \hat{v}_r) - (A_{70} \cdot v_r)^T \left( \begin{cases} \dot{x}_2 \\ \dot{y}_2 \end{cases} \right) - r_{p2}(\omega_2 \hat{v}_r) = 0
\]

\[
\ddot{\Phi} : (A_{70} \cdot v_r)^T (\ddot{r}_1 + r_{p1} \omega_1 \dot{\hat{v}}_r) + (A_{70} \cdot v_r)^T (\dddot{r}_1 + r_{p1} \omega_1 \dot{\hat{v}}_r + r_{p1} \omega_1 \ddot{\hat{v}}_r)
- (A_{70} \cdot v_r)^T (\dddot{r}_2 - r_{p2} \omega_2 \dot{\hat{v}}_r) - (A_{70} \cdot v_r)^T (\dddot{r}_2 - r_{p2} \omega_2 \dot{\hat{v}}_r + r_{p2} \omega_2 \ddot{\hat{v}}_r) = 0
\]

20 deg. pressure angle

2D gear constraint equation
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):

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

Used for calculating bearing and gear tooth reaction forces and moments
5. Results (gear tooth normal forces)

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

[Graph showing tooth normal forces over time]
Example: Mean sun/planet gear tooth stresses:

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>6</th>
<th>10</th>
<th>14</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed  (m/s)</td>
<td>8</td>
<td>12</td>
<td>18</td>
<td>20</td>
</tr>
</tbody>
</table>

DTU Mechanical Engineering – p.12
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