Simulation of gears with complex geometries in SIMPACK using reduced elastic models

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why elastic gears?

modeling of gears with reduced EMBS

implementation and usage of GTM

applications

summary
Classical Approaches

- simple, very fast, robust
- simple collision detection
- choice of stiffness?
- parameter identification by heuristic means
- model lacks elastic deformations
- often unrealistic results → heuristics

- one rigid body per gear
- spring-damper combination
  - Hertzian contact
  - elasticity of teeth and gear body
  - material damping and possibly oil film
- different implementations in commercial gear modules exist (ADAMS, Recurdyn, SIMPACK, ...)

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Classical Approaches

**rigid body model**

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**elastic approach: finite element method**

- elastic deformations
- collision detection based on geometry
- precise results
- large computational effort
- very slow computation
Impact Investigations

- real technical gear pairing
- investigation of several impacts
- detailed FE-Model
- rigid body model with $c=5.72$ N/μm/mm (static FEA)
- FEM is reference

Graphs showing contact force in kN over time in ms.
Outline

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Elastic Multibody Model

**simulation of gears**

- A simulation of a complete gear system in a global system using FE is practically impossible.
- Precise simulations of gears require an elastic approach.
- Appropriately discretized gears are large systems.

**Elastic Multibody System**

- Reduction necessary.
- Coarse collision detection on a geometrical basis.
- Contact calculation on nodal basis.
- Explicit integration scheme.

\[
\begin{bmatrix}
M_{tt} & M_{tr} & M_{te} \\
M_{tr} & M_{rr} & M_{re} \\
\text{sym} & M_{re} & M_{ee}
\end{bmatrix}
\begin{bmatrix}
\dot{v} \\
\dot{\phi} \\
\dot{\ddot{q}}
\end{bmatrix}
= \begin{bmatrix}
h_{\omega t} \\
h_{\omega r} \\
h_{\omega e}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
h_e
\end{bmatrix}
+ \begin{bmatrix}
h_{dt} \\
h_{dr} \\
h_{de}
\end{bmatrix}
\]
Two Step Collision Detection

- only check a subset of possible contact pairs
- necessary transformation data is dynamically loaded on demand
- all necessary data is combined into one small transformation matrix
- pure node-to-segment contact
- contact surface is parameterized according to the element displacement shape function
- solve set of nonlinear equations iteratively in every integration step
- penalty formulation
Comparison EMBS vs FEM

- almost no heuristics
- no parameter identification
- very precise
- fast
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- implementation as Simpack user-force routine
- code is written in C/C++
- coupling with Simpack using Co-Simulation

### User Force Routine
- control of Co-Simulation
- parametrization
- applicable in Simpack

### Gear Train Module GTM
- integration of elastic bodies
- contact calculation
- data interfaces (preprocessor, postprocessor)

### Code Files
- uforce21.c
- gtm_interface.cpp
Interfaces

gtm_globals();
gtm_geardata();

Parameters, Markers, Kinematics

gtm_init();
gtm_InitialTime();
gtm_InitialShaftKinematics();

gtm_integrator();
gtm_GearKinematics();

gtm_interactiondata();

gtm_finish();
- models are calculated alternately
- Simpack integrates first, calculation of hub-forces using quadratic extrapolation of GTM

- GTM integrates last and receives the linearly interpolated hub-forces from Simpack using a callback-routine
Practical Usage of GTM

FE-model

- preprocessing
- model setup + simulation
- postprocessing

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starting: FE-model

- setup using graphical user-interface of Ansys or Abaqus
- reading of input-file

requirements

- one gear per input file
- z-axis is rotation axis of gear
- linear elastic, homogeneous material
- units: m, kg, s
- only hexahedron-elements
- one nodeset per flank „flank_1l“ and bore-set „bore“
- origin is coupling position
- structured mesh on flanks
Pass 1: Geometry Analysis

- parsing input file
- read contact nodes
- identify contact faces
- read node-set „bore“
- user selected number of modes
- write input-file for modal analysis

Solve: Abaqus or Ansys

Pass 2: Process modal data

- read system matrices
- read modal data
- calculate transformation data
- calculate standard data
- write index-file
- arbitrary EMBS
- axle, bearings
- position of gears (marker)
- linkage of GTM
- fill GTM-mask
- evtl. set graphical primitives (independent from Simpack-GTM)

<table>
<thead>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Name: F_gtm</td>
<td></td>
</tr>
<tr>
<td>From Marker: M_10y</td>
<td></td>
</tr>
<tr>
<td>To Marker: M_10y</td>
<td></td>
</tr>
<tr>
<td>Type: 21 GTM: Elastic Gears</td>
<td></td>
</tr>
<tr>
<td>Communication step size:</td>
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<td>GTM integration time step size:</td>
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<td>rtsel_index.dat</td>
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<td>RAYLEIGH damping Wheel 1:</td>
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<tr>
<td>Bushing 1 rad stiff:</td>
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<tr>
<td>Bushing 1 rad damping:</td>
<td>2000000</td>
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<tr>
<td>Bushing 1 ax stiff:</td>
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<tr>
<td>Bushing 1 rad rot stiff:</td>
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<td>Bushing 1 rad rot damping:</td>
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<tr>
<td>Bushing 1 ax rot stiff:</td>
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<tr>
<td>Bushing 1 ax rot damping:</td>
<td>0</td>
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<tr>
<td>Marker Wheel 2:</td>
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<td>Interaction Type 1:</td>
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</tr>
<tr>
<td>Marker Gear Wheel 2 int 1:</td>
<td>M_10y_gear2</td>
</tr>
</tbody>
</table>
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- pinion and large gear
- visualization with primitives
- pinion has initial velocity
teeth hammering observable
• tooth bounces within the backlash
Skew Gear: Misalignment

- rotating pinion about y-axis
- contact gets softer
- less vibrations
- GTM can monitor small differences precisely
### Beveloid Gears

- non-standard tooth profile
- non-parallel axis
- corrected and uncorrected gear pair

<table>
<thead>
<tr>
<th>Property</th>
<th>gear 1</th>
<th>gear 2</th>
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<tbody>
<tr>
<td>number of teeth $z$ [-]</td>
<td>35</td>
<td>39</td>
</tr>
<tr>
<td>profile shift angle $\theta$ [°]</td>
<td>5</td>
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<tr>
<td>head conical angle $\theta_a$ [°]</td>
<td>4.729</td>
<td>5.271</td>
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<tr>
<td>distance to intersected point [mm]</td>
<td>1401.489</td>
<td>1400.33</td>
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<tr>
<td>helical angle $\beta$ [°]</td>
<td>-6</td>
<td>6</td>
</tr>
<tr>
<td>flank direction [-]</td>
<td>Left</td>
<td>right</td>
</tr>
<tr>
<td>face width $b$ [mm]</td>
<td>91</td>
<td>85</td>
</tr>
<tr>
<td>normal module $m$ [mm]</td>
<td>6.5</td>
<td>6.5</td>
</tr>
</tbody>
</table>
Corrected tooth profile for steady transmission

Transmission error $\epsilon = \frac{\omega_1}{\omega_2} - 1$
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- GTM models elastic gears with nodal contact, implemented as u-force for Simpack
- funded by FVA/FVV and licensed from FVA
- preprocessor prepares standard data for elastic gears and transformation data for nodal contact calculation
- 3D – contact calculations are possible with arbitrary tooth shapes, arbitrary orientation of rotation axis
- contact routine is based on FE-mesh and allows detection of small differences of the gear system
- already applied to complete gear trains, marine systems, tooth corrections, automotive

thank you for your attention!