Robust Design: CAE Driven Design Development

Dr. Oleksiy Kurenkov
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- Examples 1: CAD + CFD + optimization
- Examples 2: System simulation + robustness analyses
- Summary
Company Profile

- global supplier for the automotive industry
- focus on engine components
- 1600 employees
- 8 locations in Europe, North America and Asia
Product Portfolio

Engine Applications
(Cam Phasers)

Transmission Applications
(Valves)
Quo vadis, simulation world?

- Ansys “Digital Twin” (simulation describes the current status of running parts using real-time sensor data)
- More and more complex multiphysics (example: ultrasonic sensor simulation: electric->structural->acoustics)
- Increasing part of system simulation and coupled simulations (1D->3D)
- CAE + optimization tools = Design optimization & Sensitivity & robustness analyses
When we need design optimization

- Every product development process is an iterative design optimization process
- Optimization tools improves design faster and better than simple "what-if" studies
- Numerical optimization is the next logical evolutional step in virtual prototyping
- Numerical optimization does not replace engineers -> it gives them more powerful tools!
Examples of numerical optimization

- DOE in experiment -> reduced overall time of experiment due to the optimal scheme of design parameter variation (lower number of physical samples & experiments)

- Design optimization of the fluid pump -> optimal design
When we need robustness analysis

- An ultimative „firefighting“ tool for solving quality issues in real production world
- Find out which design parameter is responsible for the failure and fix them
- Let perform quickly the quality improvement studies -> saves money!

- Helps to prevent quality issues by identifying safe limits for design parameters
Example 1: Jet pump
Parametric optimization

*O.Kurenkov, Ansys User Meeting, 2012
Example 1: CAD+CFX+Optislang
Example 2: System simulation + robustness analysis

- VSL hydraulic valve used in automatic gear systems
- Problem statement 1: to decrease the variation of the pressure switching points due to the process tolerances
- Problem statement 2: to decrease the valve wear
- Solution: system simulation + robustness analysis using the real tolerances data
Modeling methods

2D-Planar Mechanics + 1D/3D-Hydraulics + Valve Switching point setup = VSL AMESim modell

VSL AMESim model + optiSlang = Robustness analysis

ASCII-Interface
VSL system simulation model

- 1D System simulation with AMESim
- Contains 0D/1D hydraulics and 2D contact mechanics
- Key hydraulics is modeled in 3D CFD
- Model calibration is mandatory
Every model was calibrated in order to fit the pressure switching points of the valve to the production data.
Model calibration
static mechanics

Spring force
F=13.8N

- Simplified model
- Latching force validated
Madel validation latching force

<table>
<thead>
<tr>
<th>μ</th>
<th>Analytical solution, N</th>
<th>Amesim, N</th>
<th>Difference, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>28.91</td>
<td>28.87</td>
<td>0.1</td>
</tr>
<tr>
<td>0.08</td>
<td>33.86</td>
<td>33.75</td>
<td>0.3</td>
</tr>
<tr>
<td>0.15</td>
<td>39.73</td>
<td>39.50</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Analytical solution for the latching force**

\[ F_R = F_0 \frac{\sin(\delta + \arcsin \frac{s}{d}) - \mu_2 \cos(\delta + \arcsin \frac{s}{d})}{\sqrt{1 - \frac{s^2}{d^2} - \mu_1 \frac{s}{d}}} [\sin \delta - \mu_2 \cos \delta] \]
Model validation in the dynamics

2D MBD with contact
Contact Modeling
Planar Mechanics Library

\[ F_C = K_e p - H_c V_c (1 - e^{-p/dp}) \]

\[ K_e = (K_c^{-1} + K_{max}^{-1})^{-1} \]

Two contact parameters to calibrate:

- \( H_c \) – damping coefficient
- \( dp \) – limit of penetration for full damping

Figure 11: contact force model
Model validation dynamics

3D explicit Amesim

Optimal contact setup:
-limit penetration for full damping = 0.001mm
-damping rate contacts = 10

Contact force, N

Time, s

~7%

~20%
Animation of valve reaction on pressure drop
Hydraulik part: 3D CFD Modeling

Important leakages were modeled in 3D CFD and stored as p-Q tables.
Flow/Force data for system simulation model

Future steps:
Generate a metamodel -> export to Amesim
Squeeze oil simulation

Oil trapped in a small volume has damping influence on valve dynamics
Squeeze oil simulation 2

- Pressure
  - Default Domain Default
  - 100463
  - 82865
  - 65266
  - 47668
  - 30069
  - 12471
  - -5128

- Velocity
  - Sym2
  - 7.4
  - 6.4
  - 5.5
  - 4.6
  - 3.7
  - 2.8
  - 1.8
  - 0.9
  - 0.0
  - [m s\(^{-1}\)]

Graphs showing:
- Pressure versus flow rate (L/min)
- Pressure versus force on the disc (N)

Legend:
- gap 0.05mm
- gap 0.1mm
- gap 0.15mm
- gap 0.2 mm
- gap 0.5mm

21.06.2018
15th Optimization and Stochastic Days 2018
Weimar, Germany
Robustness study: input parameters

<table>
<thead>
<tr>
<th>Parameter of grate</th>
<th>Picture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle fillet height</td>
<td><img src="image1.png" alt="Picture" /></td>
</tr>
<tr>
<td>Middle fillet width</td>
<td><img src="image2.png" alt="Picture" /></td>
</tr>
<tr>
<td>Notch width</td>
<td><img src="image3.png" alt="Picture" /></td>
</tr>
<tr>
<td>Fillet height left/right</td>
<td><img src="image4.png" alt="Picture" /></td>
</tr>
</tbody>
</table>

l6: distance sphere centrum to cone
l7: distance contact point cone/sphere to fase of cone
Robustness study: distribution of input parameters

<table>
<thead>
<tr>
<th>Nr.</th>
<th>parameter</th>
<th>name in the model</th>
<th>PDF</th>
<th>Averaged value</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Preload force of large spring</td>
<td>l_spring_f0</td>
<td>Normal</td>
<td>215</td>
<td>0.66</td>
</tr>
<tr>
<td>2</td>
<td>Friction force of large spring</td>
<td>l_spring_fr_force</td>
<td>Normal</td>
<td>12.75</td>
<td>1.5833</td>
</tr>
<tr>
<td>3</td>
<td>Stiffness of large spring</td>
<td>l_spring_rate</td>
<td>Exponent.</td>
<td>8.814</td>
<td>1.128</td>
</tr>
<tr>
<td>4</td>
<td>Stiffness of small spring</td>
<td>sm_spring_rate</td>
<td>Lognormal</td>
<td>3.26</td>
<td>0.03789</td>
</tr>
<tr>
<td>5</td>
<td>µ contacts (grating)</td>
<td>fmu_contacts</td>
<td>Normal</td>
<td>0.11</td>
<td>0.00367</td>
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<tr>
<td>6</td>
<td>Toler. of the middle fillet heights</td>
<td>middle_part_height</td>
<td>Normal</td>
<td>-0.005</td>
<td>0.00065</td>
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<tr>
<td>7</td>
<td>Toler. of the middle fillet heights</td>
<td>middle_part_width</td>
<td>Normal</td>
<td>0</td>
<td>0.01667</td>
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<tr>
<td>8</td>
<td>Toler. notch width left</td>
<td>notch_width_left</td>
<td>Normal</td>
<td>-0.0013</td>
<td>0.0057</td>
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<tr>
<td>9</td>
<td>Toler. notch width right</td>
<td>notch_width_right</td>
<td>Normal</td>
<td>-0.0013</td>
<td>0.0057</td>
</tr>
<tr>
<td>10</td>
<td>Toler. of left fillet height</td>
<td>outer_part_height_left</td>
<td>Normal</td>
<td>0</td>
<td>0.001375</td>
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<td>11</td>
<td>Toler. of left fillet height</td>
<td>outer_part_height_right</td>
<td>Normal</td>
<td>0</td>
<td>0.001375</td>
</tr>
<tr>
<td>12</td>
<td>Clearance sphere/piston</td>
<td>clearance_piston_ball</td>
<td>Normal</td>
<td>0</td>
<td>0.005</td>
</tr>
</tbody>
</table>
### Robustness study: distribution of input parameters (ext.)

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Parameter</th>
<th>name in the model</th>
<th>PDF</th>
<th>Averaged value</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Tol. of cone angle</td>
<td>cone_angle_tol</td>
<td>Normal</td>
<td>0.55</td>
<td>0.04561</td>
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<td>14</td>
<td>Clearance piston/sleeve</td>
<td>gap_piston_housing</td>
<td>Normal</td>
<td>5.375e-6</td>
<td>9.583e-7</td>
</tr>
<tr>
<td>15</td>
<td>Notch width</td>
<td>s</td>
<td>Normal</td>
<td>1.5987</td>
<td>0.0057</td>
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<tr>
<td>16</td>
<td>Sphere diameter</td>
<td>d</td>
<td>Uniform</td>
<td>2.997</td>
<td>0.00086</td>
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<tr>
<td>17</td>
<td>Inner radius of grating</td>
<td>Rrast</td>
<td>Normal</td>
<td>4.5786</td>
<td>0.001375</td>
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<tr>
<td>18</td>
<td>Fase on cone</td>
<td>Rkkegel</td>
<td>Gumbel</td>
<td>2.241</td>
<td>0.003506</td>
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<tr>
<td>19</td>
<td>Free Length of small spring</td>
<td>l0</td>
<td>Lognormal</td>
<td>23.698</td>
<td>0.13738</td>
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<tr>
<td>20</td>
<td>l1 small spring</td>
<td>l1</td>
<td>Uniform</td>
<td>21.0</td>
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<td>21</td>
<td>l2 small spring</td>
<td>l2</td>
<td>Weibull</td>
<td>2.037</td>
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<tr>
<td>22</td>
<td>l3 small spring</td>
<td>l3</td>
<td>Trunc. Normal</td>
<td>5.054</td>
<td>0.01041</td>
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<tr>
<td>23</td>
<td>l4 small spring</td>
<td>l4</td>
<td>Lognormal</td>
<td>1.5105</td>
<td>0.0081</td>
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<tr>
<td>24</td>
<td>l8 small spring</td>
<td>l8</td>
<td>Lognormal</td>
<td>7.714</td>
<td>0.03123</td>
</tr>
</tbody>
</table>
Results robustness analysis

Largest influence: stiffness of large spring
Statistical distribution of the pressure spread

- Pressure spread (difference top switching point – bottom switching point) is a result of tolerances variation
- The distribution can even give directly the estimation of the failure rate
- Corrective actions and economic decisions can be made using the computed failure rate
Corrective action: sorting out of „bad“ large springs

standard

Large spring $C_r > 9 \text{ N/mm}$ sorted out 31.2%
Effect of outsorting of the large springs

No outsorting

With outsorting

INPUT: \( I_2 \) 0 %
INPUT: \( I_1 \) 1 %
INPUT: clearance_piston_ball 1 %
INPUT: \( I_8 \) 1 %
INPUT: gap_piston_housing 1 %
INPUT: sm_spring_rate 5 %
INPUT: fmu_contacts 8 %
INPUT: l_spring_rate 32 %
INPUT: l_spring_fr_force 10 %
INPUT: \( I_0 \) 39 %

INPUT: \( I_2 \) 1 %
INPUT: clearance_piston_ball 1 %
INPUT: \( I_1 \) 1 %
INPUT: gap_piston_housing 3 %
INPUT: \( I_8 \) 3 %
INPUT: l_spring_rate 4 %
INPUT: sm_spring_rate 7 %
INPUT: fmu_contacts 13 %
INPUT: l_spring_rate 16 %
INPUT: l_spring_fr_force 50 %
Quality improvement studies

*possible further improvement: Optimization over robustness studies

Valve switching points spread, bar

- Standard
- gr. Feder aussortiert
- kleine UND große Feder aussortiert
- große UND kleine Feder eng sortiert

PDF

0,0 0,2 0,4 0,6 0,8 1,0 1,2 1,4 1,6

3,5 4 4,5 5 5,5 6 6,5
Improvement of tolerance studies (Dynardo idea)

- **How to:** Create an optimization process over the number of robustness systems
- **Variate the design parameters** limits *(sorting out process)* or design parameters distributions *(manufacturing process)*
- **Goal function:** fulfill some design requirements *(i.e. switching points spread)*
- **Find out the allowed tolerance ranges**
Summary

- Coupling of CAE tools with optimization/sensitivity/robustness studies is one of the next evolitional steps in the CAE driven product development process.

- It can be used for any CAE tool and even for experimental DOE.

- DESIGN FOR A DESIRED QUALITY is possible!
Thank you very much for your kind attention!