Probabilistic Structure-Mechanical Robustness Estimation of Rotor Discs Considering Geometry Variations

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6. Dresdner Probabilistic-Workshop, 10th-11th October, 2013
motivation – Monte Carlo method

probabilistic input variables

- deterministic model

scatter of output variables

➢ types of input parameters:
  - material
  - geometry
  - boundary conditions

\[ x_1, x_2, x_3, \ldots, x_n \]

\[ y_1, y_2, \ldots, y_m \]

\[ ProSi \quad - \quad PRE \quad - \quad EXE \quad - \quad POST \]

- sensitivity analysis
- system improvement and robustness estimation
- probability of occurrence

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Slide 3
**deterministic model**

- FE-model provide by MTU Aero Engine
- based on test rig - spin test disc
  - blisk construction
  - material Ti6246
  - integrate dummyblades
  - 39000 rpm

- MTU-internal FE-solver Calculix and life time prediction with MTULife
- elastic analysis, one cycle
- 18° - 3D sector model
- ~ 900 000 nodes
- boundary conditions:
  - axial, tangential fixed
  - loads: rotating speed, radial temperature distribution
probabilistic model

- input variables
  - 7 geometrical input parameters
  - uniformly distributed
  - given variation range:
    - manufacturing tolerance
    - range for design improvement

- result parameter
  - von-Mises stress

- Monte Carlo simulation
  - with optimized Latin Hypercube Sampling
  - 60 and 75 realizations

- using the probabilistic tool ProSi
automated process chain

parametrical geometry
Unigraphics NX

remeshing

FE - calculation

life time prediction

variation file

export

\[ a_1_{FT}=20 \]
\[ a_2_{BT}=19 \]
\[ a_3_{BD}=40 \]
\[ a_4_{RT}=30 \]
\[ a_5_{TK}=103 \]
\[ a_6_{O}=0.5 \]
\[ a_7_{WT}=6.4 \]
statistical evaluation

- result transfer of all MCS realizations on the evaluation mesh of a basic geometry

- Calculation of:
  - mean value
  - standard deviation
  - Spearman rank coefficient of correlation
  - relative frequency
  - response surface

- e.g. 50 Mises stress values per node
MCS manufacturing tolerances

<table>
<thead>
<tr>
<th>RT [mm]</th>
<th>29.85</th>
<th>30</th>
<th>30.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT [mm]</td>
<td>6.25</td>
<td>6.4</td>
<td>6.55</td>
</tr>
<tr>
<td>FT [mm]</td>
<td>19.85</td>
<td>20</td>
<td>20.15</td>
</tr>
<tr>
<td>RD [mm]</td>
<td>102.96</td>
<td>103</td>
<td>103.04</td>
</tr>
<tr>
<td>O [mm]</td>
<td>0.35</td>
<td>0.5</td>
<td>0.65</td>
</tr>
<tr>
<td>BT [mm]</td>
<td>18.85</td>
<td>19</td>
<td>19.15</td>
</tr>
<tr>
<td>BD [mm]</td>
<td>39.85</td>
<td>40</td>
<td>40.15</td>
</tr>
</tbody>
</table>

Relative frequency: von Mises > limit
• offset parameter large influence

manufacturing tolerances baseline

von Mises stress [MPa]

0.35  0.65

15

O [mm]
### Engineering Characteristic
- Exceed of limit values
- Occurrence of sudden changes in results variables
- Occurrence of system instabilities

### Statistic Characteristic
- Position of mean value
- Amount of the coefficient of variation in results variables

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**Diagram:**
- Left: von Mises stress (MPa) vs. O (mm)
- Right: Frequency distribution

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Slide 10
MCS with parameter range for design improvement

von Mises stress [MPa]
MCS with parameter range for design improvement

- MCS with variation range for system improvement

max von Mises stress [MPa]

max von Mises stress of all 4 nodes

MCS with parameter range for design improvement

- MCS with variation range for system improvement

![Diagram showing max von Mises stress of all 4 nodes against mass.](image)
MCS with parameter range for design improvement

- MCS with variation range for system improvement

max von Mises stress of all 4 nodes vs. mass
approximation by metamodel

- for each node and rotor disc mass, one metamodel
- first order, linear behaviour

<table>
<thead>
<tr>
<th>node</th>
<th>delta stress [MPa]</th>
<th>max error [MPa]</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>169</td>
<td>10</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>208</td>
<td>23</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>118</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>165</td>
<td>15</td>
<td>0.99</td>
</tr>
<tr>
<td>mass</td>
<td>0.0234</td>
<td>2 %</td>
<td>1</td>
</tr>
</tbody>
</table>
• 50000 shots MCS with variation range for system improvement
• 50000 shots MCS with variation range for system improvement
### Input values for design improvement

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Improved design by MCS Metamodell</th>
<th>Improved design consider sensitivities</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT [mm]</td>
<td>30</td>
<td>30.1044</td>
<td>29.85</td>
</tr>
<tr>
<td>WT [mm]</td>
<td>6.4</td>
<td>5.42313</td>
<td>5.4</td>
</tr>
<tr>
<td>FT [mm]</td>
<td>20</td>
<td>21.606</td>
<td>22</td>
</tr>
<tr>
<td>RD [mm]</td>
<td>103</td>
<td>101.737</td>
<td>103</td>
</tr>
<tr>
<td>O [mm]</td>
<td>0.5</td>
<td>0.539213</td>
<td>0</td>
</tr>
<tr>
<td>BT [mm]</td>
<td>19</td>
<td>20.8614</td>
<td>21</td>
</tr>
<tr>
<td>BD [mm]</td>
<td>40</td>
<td>35.067</td>
<td>35</td>
</tr>
<tr>
<td>mass</td>
<td>1</td>
<td>0.9908</td>
<td>0.99167</td>
</tr>
<tr>
<td>Mises stress</td>
<td>1</td>
<td>0.8870</td>
<td>0.88468</td>
</tr>
</tbody>
</table>

**RT** [mm]: 29.85, 30, 31  
**WT** [mm]: 5.4, 6.4, 7.4  
**FT** [mm]: 18, 20, 22  
**RD** [mm]: 101, 103, 105  
**O** [mm]: 0, 0.5, 1  
**BT** [mm]: 19, 21  
**BD** [mm]: 35, 40, 45
MCS manufacturing tolerances on improved design

![Graph showing von Mises stress vs. O [mm]]

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<thead>
<tr>
<th>RT [mm]</th>
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<th>FT [mm]</th>
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<th>O [mm]</th>
<th>BT [mm]</th>
<th>BD [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.85</td>
<td>5.4</td>
<td>21.7</td>
<td>102.96</td>
<td>0</td>
<td>20.7</td>
<td>35</td>
</tr>
<tr>
<td>30</td>
<td>5.55</td>
<td>21.85</td>
<td>103</td>
<td>0.15</td>
<td>20.85</td>
<td>35.15</td>
</tr>
<tr>
<td>30.15</td>
<td>5.7</td>
<td>22</td>
<td>103.04</td>
<td>0.3</td>
<td>21</td>
<td>35.3</td>
</tr>
</tbody>
</table>

Max von Mises $\sigma_{\text{Mises}}$ [MPa]: 796
Min Cycles: 11950

Max von Mises stress range: 709 - 796 MPa

Design according to Max von Mises criterion $\sigma_{\text{Mises}}$.

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MCS manufacturing tolerances on improved design

Baseline

Improved design

21.35 MPa  5.19 MPa

6.7 MPa  31.03 MPa

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• implementation of a deterministic automated process chain

• demonstrate a system improvement with all important steps

  • analyse maximum von Mises stress of a base geometry regarding mean value and scatter

  • perform MCS with improvement parameter range

  • improvement of the base geometry with a metamodel

  • Checking the new improved geometry with manufacturing tolerances
Thank you for your attention!