Response surface based robust design optimization on the example of a high pressure turbine blade

Frank Wagner, Arnold Kühhorn
Department of Structural Mechanics and Vehicle Vibrational Technology

BTU Cottbus-Senftenberg
Motivation / Task

- Manufacturing uncertainties influence component properties, which can result in invalid components
- Robust design addresses this problem in an early design stage
- Challenge: new methods and strong increase in the number of simulations

Focus of this work:

- Go through a robust design workflow for a real world turbine blade
- To ensure the physical integrity a deep look into the methods and an extensive validation are necessary
Motivation / Task

Toolbox: Procedure, methods and validation

Case of HP turbine blade

Results

Conclusions
Motivation / Task

Toolbox: Procedure, methods and validation

Case of HP turbine blade

Results

Conclusions
Toolbox: basic functionality

- Sample point generation
  - monte-carlo-simulation
  - latin hypercube sampling
  - optimal latin hypercube sampling
- Calculation of "real" values
- Generation of response surface
  - linear regression (LR)
  - radial basis functions (RBF)
  - combination of LR und RBF
  - kriging method
- Optimization
  - Simplex
  - CMA-ES
  - NSGA-II

Usage of typical test functions for optimization problems
Later: real world problem of HP turbine blade
Toolbox: validation – sample point generation

Sample point generation → calculation of "real" values → generation of response surface → optimization

Validation of sample point methods

$\rho_{X,Y} \quad \frac{\min(\min(r_{ij}))}{\min(d_{min})}$

Graph showing the relationship between the number of sample points and distance, with different methods represented by lines.

- MCS
- LHS
- IHS
- oLHS

Branding and logos for BTU, University Technology Centre (UTC), and Rolls-Royce.
Toolbox: validation – generation of response surface

- sample point generation
- calculation of “real” values
- generation of response surface
- optimization

RMS for equidistant grid

Validation of response surface:
- $R^2_{adj}$
- LOOCV
- splitting

Graph showing RMS value vs. number of sample points for different models:
- LIN
- RBF
- LIN+RBF
- KRINGING
Motivation / Task

Toolbox: Procedure, methods and validation

Case of HP turbine blade

Results

Conclusions
Case: input and output parameters

Geometry $\rightarrow$ 16 Parameters
  • Lean, skew and axial shift for 5 sections
  • Lean, skew and axial shift for platform
  • Scaling factor for wall thickness of PS and SS

Boundary conditions $\rightarrow$ 1 Parameter
  • Scaling factor for temperature field

Material $\rightarrow$ 1 Parameter
  • Crystal angle

$\Rightarrow$ uncorrelated 18 dimensional normal distribution

Main objective
  • external combined life of LCF and Creep on the aerofoil

Further objectives
  • internal combined life (core)
  • mass of the blade
  • aero efficiency
Execution:

- Generate 2 sets of sample points: 300 with oLHS- and 130 with MCS-sampling
- Distributed calculation (~3-4h per sample point) over different workstations
- Create response surface for every output parameter
- Run various optimizations
Motivation / Task

Toolbox: Procedure, methods and validation

Case of HP turbine blade

Results

Conclusions
Results: generation and validation of response surfaces

<table>
<thead>
<tr>
<th></th>
<th>mass</th>
<th>external</th>
<th>internal</th>
<th>efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>LR</td>
<td>0.749</td>
<td>0.749</td>
<td>0.348</td>
<td>0.988</td>
</tr>
<tr>
<td>RBF</td>
<td>0.931</td>
<td>0.896</td>
<td>0.216</td>
<td>0.991</td>
</tr>
<tr>
<td>Kriging</td>
<td>0.976</td>
<td>0.965</td>
<td>0.715</td>
<td>0.999</td>
</tr>
</tbody>
</table>

LOOCV with correlation coefficient after Pearson
Results: robust design optimization for external life

**Optimizer**
- NSGA-II
- 80 individuals
- 100 generations
- 500 evaluations
Results: multi objective and robust design optimization

- **Reference**
- $\min \mu$ mass
- $\min \sigma$ mass
- $\max \mu$ life
- $\min \sigma$ life
- $\max \mu$ eff
- $\min \sigma$ eff

<table>
<thead>
<tr>
<th>Optimizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>- NSGA-II</td>
</tr>
<tr>
<td>- 150 individuals</td>
</tr>
<tr>
<td>- 300 generations</td>
</tr>
<tr>
<td>- 500 evaluations</td>
</tr>
</tbody>
</table>

$\Rightarrow 22.5$ million evaluations
Motivation / Task

Toolbox: Procedure, methods and validation

Case of HP turbine blade

Results

Conclusions
Achievements

• Created a toolbox containing most important methods for sample point and response surface generation, a lot of generic test function and various optimization algorithms

• First demonstration of a full multi-objective and robust design optimization for a real world turbine blade with the help of response surfaces at RRD

Research outlook

• Use correlated set of input parameter with more realistic distributions for the robust statement and reduce the number of evaluations for robustness with more advanced methods
Thank you for your attention!

Frank Wagner

Contact BTU Cottbus-Senftenberg:
Mail: wagnerf@b-tu.de
Phone: +49-355-69-5138

Contact RRD:
Mail: frank.wagner@rolls-royce.com
Phone: +49-33708-6-2635

Acknowledgement
The authors gratefully acknowledge Rolls-Royce Deutschland for granting permission for this publication. Especially Dr. Roland Parchem and Dr. Ulf Gerstberger for the support of the work.
References

[1] – BR715 → engine and high pressure turbine blade, Rolls-Royce Deutschland