Design optimization of a radial compressor impeller

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Agenda

1. Introduction
2. CAE-model and workflow
3. Sensitivity analysis
4. Optimization
5. Robustness evaluation
6. Result validation & conclusion
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KSPG’s contribution to CO2 reduction

Optimized transmissions
Transmission plain bearings, electric oil pumps

Downsizing
Divert-air valves, wastegate actuators, pressure-control valves for exhaust turbochargers

On-demand ancillary parts
Variable oil, coolant and vacuum pumps

Dethrottling
Univalve, Flexvalve, throttle bodies

Optimized combustion
EGR systems, air path valves and flaps, exhaust flaps

Friction reduction
Pistons, piston coatings, rings, steel pistons, plain bearings and bearing coatings, cylinder coatings

Lightweight components
Structural parts in aluminum, engine blocks and cylinder heads in aluminum
Design optimization of a radial compressor impeller / Introduction

**Electrical Air Compressor (eAC)**

![Diagram of AFU, CAC, eAC, and engine connected by tubing]

- **AFU**
- **CAC**
- **eAC**
- **engine**

Graph showing:
- **eAC speed**
- **Brake mean effective pressure [bar]**
  - Full load of supercharged engine
  - Full load of naturally aspirated engine
  - Load step

Comparison between:
- **without eAC**
- **with eAC**

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Design optimization of a radial compressor impeller / CAE-model and workflow

CAE-process for optimization

Input parameters

Responses

Convergence history

KSPG Excel Tool

optiSLang

ANSYS Workbench
CAE-process for optimization

KSPG Excel-tool
- In total 79 parameters are available
- 49 parameters used for optimization
- Parameters are:
  - General dimensions
  - Control points of Bezier-splines to describe:
    - Meridional contour
    - Blade angle distribution
    - ...
  - Exported ASCII-files contain point based geometry description
CAE-process for optimization

Input parameters → optiSLang → Responses

KSPG Excel Tool

Convergence history

ANSYS Workbench model
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Optimization workflow

1. Design of Experiment (DoE)

2. Sensitivity analysis (SA)

3. Creation of Metamodel of optimal Prognosis (MoP)

4. Global optimization on MoP

5. Local optimization with most important parameters

6. Robustness evaluation of best design
Sensitivity analysis - objectives

- Identification of sensitive parameters and their influence on the various outputs, objectives of optimization and constraints
- Reduction of the parameter space for the optimization
- Analysis of correlations between input parameters and output parameters
- Estimation of the most important variables for the metamodels
- Determination of the prognosis quality of the metamodels (Coefficient of Prognosis CoP)
Sensitivity Analysis – Design of Experiment (DoE)

- DoE with Latin Hypercube Sampling (LHS)
- 130 Design calculations.
- Iterations of design improvements regarding regeneration stability.

- Reasons for failed designs were:
  - The geometry could not be regenerated.
  - Mesh in mechanical-, modal-, CFD- analysis could not be regenerated.
  - Solver failed in mechanical- or CFD- analysis.

- 17 Designs failed
Sensitivity Analysis – Plausibility check

a) Convergence CFD-analysis
   (Efficiency & Pressure ratio)
   Coefficient of Variation:
   \[ \text{CoV} = \frac{\text{Standard deviation}}{\text{mean value}} \leq 0.3\% \]

b) Check of design output range and plausibility
   (Anthill plots)

→ 12 Designs excluded
→ 101 valid Designs < 23% failed
Sensitivity analysis - Metamodel of optimal Prognosis (MoP)

### Output Parameter | CoP | Annotation
--- | --- | ---
N1: Efficiency_LC1_Norm | 0.73 | Total isentropic efficiency of load case 1 normalized on the reference design
N2: Stat_pressure_ratio_LC1_Norm | 0.50 | Static pressure ratio of load case 1 normalized on the reference design
N3: Efficiency_LC2_Norm | 0.90 | Total isentropic efficiency of load case 2 normalized on the reference design
N4: Stat_pressure_ratio_LC2_Norm | 0.75 | Static pressure ratio of load case 2 normalized on the reference design
N5: Bending_moment_Norm | 0.95 | The bending moment of the eAC-impeller normalized on the reference design
N6: Moment_of_inertia_Norm | 0.98 | The moment of inertia of the eAC-impeller normalized on the reference design

- All CoPs except the CoP of Stat_pressure_ratio_LC1_norm are very good (CoP > 90%) or acceptable (90% < CoP < 70%).
- Reasons for bad CoPs could be:
  - Discontinues behaviour of result values.
  - Missing parameters for the physical interpretation.
  - Insufficient design sampling.
Sensitivity analysis – Most important parameters

The parameter space could be reduced to only 6 most important parameters for all objectives and constraints.

local optimization
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Optimization – Objectives/Constraints

Objectives

For CFD:
\[
\max(O_1) = \left( 0.4 \times (0.7 \times N1 + 0.3 \times N2) + 0.6 \times (0.3 \times N3 + 0.7 \times N4) \right)
\]

For mechanic:
\[
\min(O_2) = (0.7 \times N5 + 0.3 \times N6)
\]

Overall optimization objective:
\[
\min(O_3) = (-0.7 \times O_1 + 0.3 \times O_2)
\]

Constraints

- Global stress maximum of all defined stress outputs should be lower than the maximal allowed stress value.
- Minimal pressure ratio should be higher as a specified value.
- Maximal deformation should be smaller than a specified value.
- First eigenfrequency should avoid a critical range which corresponds to the machine frequency.
- Minimal impeller diameter should be higher than a specific value.
- Diffuser diameter should also be higher than a specific value.

Output Parameter

<table>
<thead>
<tr>
<th>N1: Efficiency_LC1_Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2: Stat_pressure_ratio_LC1_Norm</td>
</tr>
<tr>
<td>N3: Efficiency_LC2_Norm</td>
</tr>
<tr>
<td>N4: Stat_pressure_ratio_LC2_Norm</td>
</tr>
<tr>
<td>N5: Bending_moment_Norm</td>
</tr>
<tr>
<td>N6: Moment_of_inertia_Norm</td>
</tr>
</tbody>
</table>
Global preoptimization on metamodel

- Evolutionary Algorithm (EA) using the best design and 11 other interesting designs from the DoE as start designs.
- In total 4000 designs have been evaluated until assumed convergence of the optimization

<table>
<thead>
<tr>
<th>Output / Objective (term)</th>
<th>Reference</th>
<th>Design 3943 MoP/Calculated</th>
<th>Difference to reference in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1 Efficiency_LC1_Norm</td>
<td>1.00</td>
<td>1.02 / 1.00</td>
<td>+0.1</td>
</tr>
<tr>
<td>N2 Stat_Pressure_ratio_LC1_Norm</td>
<td>1.00</td>
<td>1.02 / 0.98</td>
<td>-1.6</td>
</tr>
<tr>
<td>N3 Efficiency_LC2_Norm</td>
<td>1.00</td>
<td>1.04 / 1.03</td>
<td>+2.7</td>
</tr>
<tr>
<td>N4 Stat_Pressure_ratio_LC2_Norm</td>
<td>1.00</td>
<td>1.01 / 1.01</td>
<td>+1.2</td>
</tr>
<tr>
<td>N5 Bending_moment_Norm</td>
<td>1.00</td>
<td>0.53 / 0.50</td>
<td>-50.2</td>
</tr>
<tr>
<td>N6 Moment_of_inertia_Norm</td>
<td>1.00</td>
<td>0.54 / 0.58</td>
<td>-42.1</td>
</tr>
<tr>
<td>O1 CFD</td>
<td>1.00</td>
<td>1.02 / 1.01</td>
<td>+0.8</td>
</tr>
<tr>
<td>O2 Mechanic</td>
<td>1.00</td>
<td>0.54 / 0.55</td>
<td>-44.7</td>
</tr>
<tr>
<td>O3 Overall</td>
<td>1.00</td>
<td>-0.55 / -0.54</td>
<td>-46.1</td>
</tr>
</tbody>
</table>
Local optimization best parameter subspace

- Adaptive Response Surface Method (ARSM)
- 6 most important parameters (of SA)
- Start design 3943 of preoptimization

**Output / Objective (term)**

<table>
<thead>
<tr>
<th>Output</th>
<th>Design 144</th>
<th>Difference to reference in %</th>
<th>Difference to preoptimization in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency_LC1_Norm</td>
<td>1.00</td>
<td>+0.3</td>
<td>+0.2</td>
</tr>
<tr>
<td>Stat_Pressure_ratio_LC1_Norm</td>
<td>0.98</td>
<td>-2.5</td>
<td>-0.9</td>
</tr>
<tr>
<td>Efficiency_LC2_Norm</td>
<td>1.03</td>
<td>+2.5</td>
<td>-0.2</td>
</tr>
<tr>
<td>Stat_Pressure_ratio_LC2_Norm</td>
<td>1.01</td>
<td>+1.3</td>
<td>+0.0</td>
</tr>
<tr>
<td>Bending_moment_Norm</td>
<td>0.48</td>
<td>-51.8</td>
<td>-3.3</td>
</tr>
<tr>
<td>Moment_of_inertia_Norm</td>
<td>0.57</td>
<td>-43.0</td>
<td>-1.5</td>
</tr>
<tr>
<td>O1 CFD</td>
<td>1.01</td>
<td>0.7</td>
<td>0.1</td>
</tr>
<tr>
<td>O2 Mechanic</td>
<td>0.54</td>
<td>-45.6</td>
<td>-1.6</td>
</tr>
<tr>
<td>O3 Overall</td>
<td>-0.54</td>
<td>-45.8</td>
<td>-0.6</td>
</tr>
</tbody>
</table>
Optimization – Results

- In summary the optimization resulted in an significant improvement especially in the mechanical objective (-45.6%) and a slight improvement in the CFD objective (-0.7%) while maintaining efficiency level.

- The local optimization in the sensitive subspace showed only minor changes compared to the preoptimization (overall objective -0.55%).

- The moment of inertia of the impeller could be reduced significantly to -43% compared to the reference design.

- Most important parameters mainly define the meridional contour. That means fundamental design is most important.
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Robustness evaluation

- Feasibility study (no information available for input parameters distribution type or tolerances).
- Robustness evaluation of optimal Design 144.
- Scattering parameters out of geometry, material and loads (total 15 parameters).
- Latin Hypercube Sampling 130 Designs (26 failed).
- The results of the robustness analysis are analogous to the initial sensitivity analysis:
  - Which scattering parameters have the most influence on a specific constraint (e.g. safety factor of total stress)?
  - Are there correlations of scattering parameters?
  - Determination of statistical data (e.g. min / max value).
- Necessary Inputs:
  - Distribution type/Min/Max/CoV for all scattering parameters.
  - Limits of Constraints (e.g. max stresses)
Robustness evaluation – Assumptions / Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distribution type</th>
<th>CoV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of elasticity</td>
<td>Normal</td>
<td>0.05</td>
</tr>
<tr>
<td>Density</td>
<td>Normal</td>
<td>0.05</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>Normal</td>
<td>0.10</td>
</tr>
<tr>
<td>Massflow_LC1</td>
<td>Normal</td>
<td>0.05</td>
</tr>
<tr>
<td>Massflow_LC2</td>
<td>Normal</td>
<td>0.05</td>
</tr>
<tr>
<td>Geometry parameters</td>
<td>Normal</td>
<td>0.02</td>
</tr>
</tbody>
</table>

(Reference: green, Design144: blue, designs of robustness evaluation: grey)
Robustness evaluation – Overview statistical results

- All outputs showed nearly normal distribution type like the input distribution.
- Mean values of the output correspond to the design values of the optimized design 144.
- The CoVs of all outputs are max. 10% like the max. CoVs for the input parameters.
- The CoVs of the checked convergence history are <0.3%.
- Design 144 showed a robust behaviour against the scattering parameters of geometry / material / loads (under the made assumptions).

<table>
<thead>
<tr>
<th>Output</th>
<th>CoV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent_vonMises_Stress_1</td>
<td>0.07</td>
</tr>
<tr>
<td>Equivalent_vonMises_Stress_2</td>
<td>0.06</td>
</tr>
<tr>
<td>Equivalent_vonMises_Stress_3</td>
<td>0.07</td>
</tr>
<tr>
<td>Equivalent_vonMises_Stress_4</td>
<td>0.06</td>
</tr>
<tr>
<td>Equivalent_vonMises_Stress_5</td>
<td>0.07</td>
</tr>
<tr>
<td>Equivalent_vonMises_Stress_6</td>
<td>0.06</td>
</tr>
<tr>
<td>Equivalent_vonMises_Stress_7</td>
<td>0.11</td>
</tr>
<tr>
<td>Equivalent_vonMises_Stress_8</td>
<td>0.10</td>
</tr>
<tr>
<td>Equivalent_vonMises_Stress_9</td>
<td>0.05</td>
</tr>
<tr>
<td>Mode_1_Reported_Frequency</td>
<td>0.06</td>
</tr>
<tr>
<td>p2tot_to_p1tot_LC1</td>
<td>0.01</td>
</tr>
<tr>
<td>Efficiency_LC1_Norm</td>
<td>0.01</td>
</tr>
<tr>
<td>Stat_pressure_ratio_LC1_Norm</td>
<td>0.01</td>
</tr>
<tr>
<td>Efficiency_LC2_Norm</td>
<td>0.01</td>
</tr>
<tr>
<td>Stat_pressure_ratio_LC2_Norm</td>
<td>0.01</td>
</tr>
<tr>
<td>Bending_moment_Norm</td>
<td>0.06</td>
</tr>
<tr>
<td>Moment_of_inertia_Norm</td>
<td>0.08</td>
</tr>
</tbody>
</table>
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Result validation

Design optimization of a radial compressor impeller / Result validation & conclusion

![Diagram of engine and components]

- AFU
- CAC
- TC
- eAC
- Engine

---

- eAC speed
- Brake mean effective pressure [bar]

Graph showing:
- Full load of naturally aspirated engine
- Full load of supercharged engine
- Load step

Lines representing:
- Without eAC
- With eAC
- With eAC (Design 144)
Conclusion

- Fluid mechanical and structural properties of a radial compressor impeller were optimized
  - Mass and moment of inertia of the impeller were reduced by approx. 45%.
  - Aerodynamic performance near surge line was improved
- Stability of the KSPG Excel-tool and connected CAE-process was improved
- Six parameters with the biggest influence on performance of the eAC were identified
- An approach to evaluate the robustness of the optimized design against scattering inputs was shown
- Comparative engine process simulations show an improved acceleration behaviour and a reduced time to torque of the combustion engine
OUR HEART BEATS FOR YOUR ENGINE.
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