Optimization and design of turbo machines using ANSYS optiSLang and CFturbo

Marius Korfanty, CFturbo GmbH
Markus Wagner, Dynardo GmbH
Outline

• Introduction into optiSLang and CFturbo

• I : Optimization of an axial pump (M. Korfanty, CFturbo GmbH)
  • Aim of analysis
  • CAE Workflow
  • Sensitivity analysis
  • Optimization
  • Summary

• II : Performance map analysis of a radial compressor (M. Wagner, Dynardo GmbH)
  • Aim of analysis
  • CAE Workflow
  • Sensitivity analysis
  • Optimization on MOP
  • Summary
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Dynardo

• Founded: 2001
• More than 60 employees, offices at Weimar and Vienna
• Leading technology companies Daimler, Bosch, ZF/TRW, Siemens are supported

Software Development

Dynardo is engineering specialist for CAE-based sensitivity analysis, optimization, robustness evaluation and robust design optimization

CAE-Consulting

• Mechanical engineering
• Civil engineering & Geomechanics
• Automotive industry
• Consumer goods industry
• Power generation
optiSLang

- is a **general purpose tool** for variation analysis

using CAE-based design sets (and/or data sets) for the purpose of

- sensitivity analysis
- design/data exploration
- calibration of virtual models to tests
- optimization of product performance
- quantification of product robustness and product reliability
- Robust Design Optimization (RDO) and Design for Six Sigma (DFSS)

serves arbitrary CAX tools with support of process integration

- process automation
- workflow generation
Webinar: Optimization and design of turbomachines using ANSYS optiSLang and CFturbo
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Model Calibration
Identify important model parameters for the best fit between simulation and measurement

Design Understanding
Investigate parameter sensitivities, reduce complexity and generate best possible meta models

Design Improvement
Optimize design performance

Design Quality
Ensure design robustness and reliability

Robust Design

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CAE - Data

Measurement Data
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Design Software

- **CFturbo®** is a modern, powerful and user-friendly software for **Conceptual Turbomachinery Design**
- 160 active clients globally
- **CFturbo®** modules to design
  - Pumps
  - Blowers
  - Compressors
  - Turbines
  - Stators and diffusers
  - Voluttes

- **Industries**: Aerospace, Automotive, Consumer Products, Energy, Oil & Gas, Marine, Mechanical & Process Engineering, Semiconductor,
Company structure

CFturbo® GmbH

1. CFturbo® Software
   - Conceptual Design Software
   - Custom development
   - Training

2. CAE Consulting
   - Turbomachinery Design
   - Flow & strength simulation (CFD, FEA)

3. Workflows
   - Automated CAE workflows
   - DOE
   - Optimization
I Aim of analysis

Design point
- Flow rate $Q = 1.476 \text{ m}^3/\text{s}$
- Total pressure difference $\Delta p_t = 0.466 \text{ bar} (H = 4.755 \text{ m})$
- Rotational speed = 780 rpm
- Water, no pre-swirl

Objective
- Max. hydraulic efficiency $\eta$

Constraints
- $\beta_{B2} < 90^\circ$
- Total pressure difference $\Delta p_t \pm 10\%$
I CAE Workflow – CFturbo

→ Fully parametric geometry model of machines
→ Each parameter can be used for optimization
I CAE Workflow – PumpLinx

CFD system with high solver speed, especially for fluid systems with rotating/sliding components

Geometry model with

Mesh density:
292,000 nodes
200,000 cells
I CAE Workflow – Optimization parameters

<table>
<thead>
<tr>
<th>#</th>
<th>Parameter</th>
<th>Reference</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(d_{H1} = d_{H2})</td>
<td>176 mm</td>
<td>140 mm</td>
<td>210 mm</td>
</tr>
<tr>
<td>2</td>
<td>(d_{S1} = d_{S2})</td>
<td>584 mm</td>
<td>467 mm</td>
<td>700 mm</td>
</tr>
<tr>
<td>2</td>
<td>(v = d_{H1}/d_{S1})</td>
<td>0.30</td>
<td>0.20</td>
<td>0.45</td>
</tr>
<tr>
<td>3</td>
<td>(\Delta z)</td>
<td>204 mm</td>
<td>160 mm</td>
<td>320 mm</td>
</tr>
<tr>
<td>4</td>
<td>(z_{LE,H}^*)</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>(z_{LE,S}^*)</td>
<td>0.2</td>
<td>0.02</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td>(z_{TE,H}^*)</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>(z_{TE,S}^*)</td>
<td>0.9</td>
<td>0.6</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Simplifications:
- Hub and Shroud (Tip) axis-parallel
- Straight meridional leading and trailing edge
### I CAE Workflow – Optimization parameters

<table>
<thead>
<tr>
<th>#</th>
<th>Parameter</th>
<th>Reference</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>( n_{Bl} )</td>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>( t_{LE,S} )</td>
<td>0°</td>
<td>-25°</td>
<td>25°</td>
</tr>
<tr>
<td>10</td>
<td>( t_{TE,S} )</td>
<td>80.3°</td>
<td>64.25°</td>
<td>96.37°</td>
</tr>
<tr>
<td>11</td>
<td>( t_{TE,H} )</td>
<td>80.3°</td>
<td>64.25°</td>
<td>96.37°</td>
</tr>
<tr>
<td>12</td>
<td>( m_{\beta B1,H} )</td>
<td>0.333</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>13</td>
<td>( m_{\beta B1,S} )</td>
<td>0.166</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>14</td>
<td>( m_{\beta B2,H} )</td>
<td>0.718</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>15</td>
<td>( m_{\beta B2,S} )</td>
<td>0.773</td>
<td>0.6</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**15 parameters for optimization**

**Simplifications:**

- Free vortex velocity distribution
- Automatic calculation of blade angles \( \beta_{B1} \) (shock-less inflow), \( \beta_{B2} \) (Euler equation)
I CAE Workflow – Optimization Cycle

Variation of geometry parameters

Geometry update & export (*.spro, *.stl)

Check log for warnings and errors

PumpLinx

Meshing, simulation, convergence check, interpretation

Data evaluation

\[ \beta_{B2} < 90^\circ \]
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- **Design Understanding**: Investigate parameter sensitivities, reduce complexity and generate best possible meta models.
- **Model Calibration**: Identify important model parameters for the best fit between simulation and measurement.
- **Design Improvement**: Optimize design performance.
- **Design Quality**: Ensure design robustness and reliability.
- **Robust Design**:
I Sensitivity analysis

Advanced Latin Hypercube Sampling

<table>
<thead>
<tr>
<th></th>
<th>Samples</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td>Failed</td>
<td>CFt turbo</td>
<td>15</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>PumpLinx</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Valid</td>
<td>samples</td>
<td>84</td>
<td>165</td>
</tr>
<tr>
<td>Reduced</td>
<td>samples</td>
<td>74</td>
<td>139</td>
</tr>
</tbody>
</table>

| CoP  | Q      | 83.6% | 86.6% | 89.1% |
|      | Δp_t   | 85.8% | 90.6% | 88.4% |
|      | P      | 91.5% | 92.9% | 94.0% |
|      | η      | 57.4% | 66.5% | 73.6% |
I Sensitivity analysis

η  hydraulic efficiency (objective)

\[ \eta = \frac{Q \cdot \Delta p_t}{P} \]

Q  Flow rate
\( \Delta p_t \)  Total pressure difference
P  Power consumption

Reduced to 7 parameters

\( \Delta p_t: \text{CoP}=88\% \)

\( P: \text{CoP}=94\% \)

\( \eta: \text{CoP}=74\% \)
I Sensitivity analysis

Kriging of $D_{pt}$
Coefficient of Prognosis = 88%

Response surface for
$\Delta p_t = f(d_{S1}, \Delta z)$

$\Delta p_t$: CoP=88%
I Sensitivity analysis – Geometry examples
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## I Optimization

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Samples</th>
<th>Simulation Time</th>
<th>Simulation time/ sample</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA Evolutionary Algorithm</td>
<td>330</td>
<td>72.2 h (3.0 d)</td>
<td>13.1 min</td>
<td>69.9% + 5.0%</td>
</tr>
<tr>
<td>ARSM Adaptive Response Surface Method</td>
<td>540</td>
<td>126.3 h (5.3 d)</td>
<td>14.0 min</td>
<td>69.3% + 4.4%</td>
</tr>
</tbody>
</table>

Desktop PC
- 2 x Intel Xeon 3.07 GHz, 6 cores
- 64 GB RAM
- Max. 2 parallel simulation jobs
I Optimization

Initial ARSM

Initial EA

ARSM EA
Summary

- Workflow CFTurbo + PumpLinx + optiSLang successful set up and >80% successful designs in sensitivity analysis
- CFTurbo initial design can be used as very reasonable starting point ("pre-optimized") to save computation time
- CFTurbo provides a well parametrized geometry that enables to work in a wide parameter range
- PumpLinx solver speed is beneficial for optimization and enables optimization on desktop PCs
- Threw the sensitivity analyses the imported parameters could be identified
- Number of parameters could be reduced to ~ 50% by sensitivity analysis for the direct optimization
- Efficiency could be improved by 5% compared to the reference design by using direct optimization
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II Aim of analysis

Performance indicators for characterizing turbochargers:

- Pressure ratio \( \pi_{tt} = \frac{p_{t2}}{p_{t1}} \)

- Isentropic efficiency
  \[
  \eta_s = \frac{\left(\frac{p_{t2}}{p_{t1}}\right)^{\frac{\kappa - 1}{\kappa}} - 1}{\frac{T_{t2}}{T_{t1}} - 1}
  \]

- Polytropic efficiency
  \[
  \eta_p = \frac{\frac{\kappa - 1}{\kappa} \ln\left(\frac{p_{t2}}{p_{t1}}\right)}{\ln\left(\frac{T_{t2}}{T_{t1}}\right)}
  \]
II Aim of analyzes

- Fixed reference points (choke, optimum, surge) will not be conserved with parameter changes!
- How to analyze and compare maps?
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Design Understanding
- Investigate parameter sensitivities, reduce complexity and generate best possible meta models

Model Calibration
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Design Improvement
- Optimize design performance

Design Quality
- Ensure design robustness and reliability

CAE - Measurement Data

Robust Design

© Dynardo GmbH
II CAE Workflow

Workflow:
- Driven by optiSLang
- Geometry and the 1D flow computation (CFturbo)
- Meshing (TurboGrid)
- 3D CFD of performance map (CFX)
II CAE Workflow

- Geometry parameters are determined to generate a 3D geometry
- CFturbo allows geometry variations in a large design space
II CAE Workflow

- 3D Geometry (right)
- Meshing of periodic segment with TurboGrid (left)
II CAE Workflow

1. Calculate “choke point” → choke mass flow (Dimensional analyses)
2. Reduce mass flow → “operating points”
3. Stop at estimated surge (user defined limit)
**Model Calibration**
Identify important model parameters for the best fit between simulation and measurement

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II Sensitivity analysis Parametrization

Parameters that have been used:

- global parameters: \( d_{2G} = \text{konst.}, b_2, d_S \)
- leading edge of main and splitter blade
- blade angle \( \beta_1, \beta_2 \) (\( \beta_2 \): hub dep. on shroud)
- Bezier curves hub and shroud
- number of Blades
- blade mean lines
- wrap angle

Total 31 free Parameter

e.g. Position of leading edge at splitter
II Sensitivity analysis Methodology

Sensitivity analysis scans the design space and evaluates the variance of the inputs- (e.g. Geometry) output parameters (e.g. pressure ratio)

1) Design of experiments within the design space of the sensitivity analysis and calculate the Designs,

2) Usage of regression methods for setting Meta-Models e.g. pressure ratio and

3) Evaluate important parameters

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One Design represents one performance map

MOP for one operating point
II Sensitivity analyzes Results overview

sensitivity study of performance maps
• 88% successful design points
  • 1% no geometry generation
  • 5% failed meshing
  • 6% problems with CFD Solver

Generation of response surfaces
• Approximation accuracy is good for choke and $\pi_{tt\ max} n_1$
• Dissatisfying quality e.g. for $\eta_p\ max$
• Increase number of Designs/speed line for better COP!

Number of speed lines: 2
Max. number of operating points/speed line: 6

<table>
<thead>
<tr>
<th>Meta-modell</th>
<th>$n_1 = 120000 \ [1/min]$</th>
<th>$n_2 = 150000 \ [1/min]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi_{tt\ max}$</td>
<td>$\eta_p\ max$</td>
<td>choke massflow</td>
</tr>
<tr>
<td>CoP [%]</td>
<td>83</td>
<td>45</td>
</tr>
</tbody>
</table>
II Sensitivity analysis
Meta-Model, Results for \( n_1 = 120000 \) [1/min]
Model Calibration
Identify important model parameters for the best fit between simulation and measurement

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II Optimization on MOP Methodology

• Objective function includes 6 values for each performance map, optimization on 6 Response Surfaces (MOP)
• Algorithm used: global evolutionary algorithm
• Validating best design with real solver call

\[
ZF = \frac{1}{3n} \sum_{i=1}^{n} \left( \frac{m_{sperr, i}}{m_{ref, i}} + \frac{\eta_p \text{ max}_i}{\eta_p \text{ max ref}_i} + \frac{\pi_{tt \text{ max}_i}}{\pi_{tt \text{ max ref}_i}} \right)
\]
II Optimization on MOP
Result comparison

<table>
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<tr>
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<th>$n_1 = 120000$ [1/min]</th>
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<tbody>
<tr>
<td>$\pi_{tt \ max}$</td>
<td>$\eta_p \ max$</td>
<td>$\text{choke massflow}$</td>
</tr>
<tr>
<td>ref</td>
<td>2,44</td>
<td>0,897</td>
</tr>
<tr>
<td>opt</td>
<td>2,52</td>
<td>0,885</td>
</tr>
</tbody>
</table>
II Optimization on MOP
Result comparison

<table>
<thead>
<tr>
<th></th>
<th>Reference Design</th>
<th>Optimization on MOP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><img src="image1.png" alt="Reference Design" /></td>
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</table>

### Optimization on MOP

**Result comparison**

<table>
<thead>
<tr>
<th></th>
<th>$n_1 = 120000$ [1/min]</th>
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</table>
II Summary

Methodology of adaptive analysis of performance maps:
✓ Automation of an adaptive workflow
✓ In Sensitivity successful applied for ~90% of the designs
✓ Optimization on MOP successful applied
  • Improves method for performance maps in 3D-CFD

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