Centrifugal pump design & optimization with optiSLang inside Workbench

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Overview

• Goal and motivation
• Parametric model and setup
• CFD Best Practice Study
• Sensitivity analysis
  – Best Practice for Meta-Model
    • 50, 100, 150 samples
• Optimization
  – Meta-Model Optimization
  – Direct Optimization
• Results
• Summary
• Outlook
Goal and Motivation

• Since 1st January 2013 EU Directive “Ökodesign-Richtlinie“
  – Directive for energy related products
  – Pumps has to achieve a certain energy efficiency index
  – Progressive efficiency increase until 2020

• Goal:
  – 23 TWh approximated energy saving in the EU in 2020

→ Equivalent to yearly energy consumption of 14 million EU citizens
Goal and Motivation

- Design & optimization platform
  - ANSYS Workbench
- Application area
  - Heating and water supply system
- Specifications
  - 70 m head
  - 80 l/s volume flow
- Dimensions
  - 300 kg weight with power unit
  - 1 m length
  - 40 cm diameter
  - 60 kW input power
Pre-Design – Specific speed $n_q$

$n_q = n \frac{\sqrt{Q}}{\sqrt[4]{H^3}}$

$n_q = 16.8$
Radial pump design

$n_q \sim 10$

$n_q \sim 25$

$n_q \sim 50$

$n_q \sim 100$

$n_q \sim 200$

Volume flow ($Q$)

Head ($H$)
Parametric model and setup – Workbench
Parametric model and setup – BladeEditor

- Create Blades in DesignModeler
  - BladeEditor
- Pre-Design based on nQ
- Blade parameterization
  - Blade angles
  - Blade thickness
  - Number of blades

- Input Parameter
  - 19 geometrical input parameter
Parametric model and setup – CFX setup

- **Steady State Simulation**
  - Physical Timescale
    - 1 [rad] / Ω = 6.63 x 10^{-3} s

- **Frame Change**
  - Frozen Rotor

- **SST turbulence model**

- **Advection scheme**
  - High Resolution

- **Boundary Conditions**
  - **Inlet:**
    - Mass Flow Rate:
      - Q = 11.4 kg s^{-1}
  - **Outlet:**
    - Average Static Pressure:
      - P_s = 1 bar
Parametric model and setup – CFD-Post

- **Output Parameter**
  - Convergence
    - Number of iterations
    - Residuals
    - Max. Grid angle
  - Geometrical
    - Key parameter
      - D1, D2, b2, b1
  - Pump performance
    - Efficiency
    - Head
    - Min. Pressure
CFD Best Practice Study

- Detailed quality assurance
  - Comparison of results on different grids
  - Select convergence criterion
    - Monotonic convergence
    - Convergence of global balances

- Plot target variables as Monitor Points
  - Efficiency
  - Torque
  - Head

Residuals with monotonic convergence
Convergence of global balances
Constant target variables
CFD Best Practice Study – Grid

Coarse Mesh

Medium Mesh

Fine Mesh
# CFD Best Practice Study – Target variables

<table>
<thead>
<tr>
<th>Target variable</th>
<th>Coarse Mesh</th>
<th>Medium Mesh</th>
<th>Fine Mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head, m</td>
<td>71.41</td>
<td>72.37</td>
<td>72.39</td>
</tr>
<tr>
<td>Power, kW</td>
<td>57.40</td>
<td>58.31</td>
<td>58.41</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.973</td>
<td>0.971</td>
<td>0.971</td>
</tr>
</tbody>
</table>

→ Medium Mesh chosen for further simulations
Optimization strategy

1. Sensitivity Analysis
   - Parameter identification
   - Reduce parameter space
   - Best Practice for Meta-Model
     • 50, 100, 150 samples

2. Optimization on Meta-Modell
   - Fast optimization on existing database
   - Indicates global optimum

3. Direct Optimization
   - Optimize within reduced parameter space
Sensitivity analysis – Efficiency

50 Samples

100 Samples

150 Samples

COP: 84%

COP: 89%

COP: 91%
Sensitivity analysis – Parameters

6 important parameters

- Outer radius
- Width outlet
- Control points shroud curve
- Width inlet
- Control points hub curve
Sensitivity analysis – Parameters

- Leading edge position
- Blade angle @ Trailing edge
- Blade angle @ Leading edge
Optimization – Meta-Model Optimization

• Optimize on existing Meta-Model
• Gradient optimization
  – NLPQL algorithm
• Goal
  – Maximize Efficiency for pump best point
• Constraints
  – Head
    • 70 m – 72 m
  – Normalized minimum Pressure
    • ≤ 1
## Results – Meta-Model Optimization

<table>
<thead>
<tr>
<th></th>
<th>NLPQL 50 DOEs MOP</th>
<th>CFD</th>
<th>NLPQL 100 DOEs MOP</th>
<th>CFD</th>
<th>NLPQL 150 DOEs MOP</th>
<th>CFD</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head, m</strong></td>
<td>71.9</td>
<td>71.8</td>
<td>71.4</td>
<td>70.6</td>
<td>72</td>
<td>70.7</td>
</tr>
<tr>
<td></td>
<td>- 0.14 %</td>
<td></td>
<td>- 1.12 %</td>
<td></td>
<td>- 1.8 %</td>
<td></td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>0.974</td>
<td>0.974</td>
<td>0.973</td>
<td>0.973</td>
<td>0.974</td>
<td>0.974</td>
</tr>
<tr>
<td></td>
<td>0 %</td>
<td></td>
<td>0 %</td>
<td></td>
<td>0 %</td>
<td></td>
</tr>
<tr>
<td><strong>Norm. min. Pressure</strong></td>
<td>0.867</td>
<td>0.889</td>
<td>0.859</td>
<td>0.889</td>
<td>0.847</td>
<td>0.887</td>
</tr>
<tr>
<td></td>
<td>+ 2.47 %</td>
<td></td>
<td>+ 3.37 %</td>
<td></td>
<td>+ 4.5 %</td>
<td></td>
</tr>
<tr>
<td><strong>COP</strong></td>
<td>64 %</td>
<td></td>
<td>90 %</td>
<td></td>
<td>91 %</td>
<td></td>
</tr>
</tbody>
</table>
Results – Meta-Model Optimization

- Compare relative size to parameter limits
- Best design at parameter limit
- Parameter range
  - 6 x increase parameter range
  - 2 x decrease parameter range

Best design
Blade angle @ Trailing edge
Outlet width
Head
## Results – Meta-Model Optimization

<table>
<thead>
<tr>
<th></th>
<th>NLPQL 50 DOEs</th>
<th>NLPQL 100 DOEs</th>
<th>NLPQL 150 DOEs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head, m</strong></td>
<td>69.99</td>
<td>70</td>
<td>69.99</td>
</tr>
<tr>
<td></td>
<td>69.31</td>
<td>69.33</td>
<td>69.47</td>
</tr>
<tr>
<td>Change</td>
<td>- 0.97 %</td>
<td>- 0.95 %</td>
<td>- 0.74 %</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>0.973</td>
<td>0.974</td>
<td>0.973</td>
</tr>
<tr>
<td></td>
<td>0.970</td>
<td>0.972</td>
<td>0.972</td>
</tr>
<tr>
<td>Change</td>
<td>- 0.3 %</td>
<td>- 0.2 %</td>
<td>- 0.1 %</td>
</tr>
<tr>
<td><strong>Norm. min. Pressure</strong></td>
<td>0.868</td>
<td>0.860</td>
<td>0.852</td>
</tr>
<tr>
<td></td>
<td>0.856</td>
<td>0.871</td>
<td>0.859</td>
</tr>
<tr>
<td>Change</td>
<td>- 1.38 %</td>
<td>+ 1.26 %</td>
<td>+ 0.81 %</td>
</tr>
<tr>
<td><strong>COP</strong></td>
<td>64 %</td>
<td>90 %</td>
<td>91 %</td>
</tr>
<tr>
<td><strong>COP</strong></td>
<td>84 %</td>
<td>89 %</td>
<td>91 %</td>
</tr>
<tr>
<td><strong>COP</strong></td>
<td>82 %</td>
<td>92 %</td>
<td>96 %</td>
</tr>
</tbody>
</table>

*Head: 68-70 m
Best design not @ parameter limit*
Optimization – Direct Optimization

- Adaptive Response Surface Method (ARSM)
  - Improve the approximation quality around the optimum
  - Increased parameter range
    1. Previous best point used as start design
    2. Initial sample new Approximated Response Surface → New best point
    3. New sample with smaller range → New best point
    4. ..

→ Find global optimum
# Results – NLPQL vs. ARSM

<table>
<thead>
<tr>
<th></th>
<th>Start-Design</th>
<th>NLPQL (150 DOEs)</th>
<th>ARSM (80 DPs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power, kW</td>
<td>58.44</td>
<td>56.83</td>
<td>56.65</td>
</tr>
<tr>
<td>Head, m</td>
<td>72.3</td>
<td>70.7</td>
<td>70.9</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.967</td>
<td>0.974</td>
<td>0.98</td>
</tr>
<tr>
<td>Norm. min. Pressure</td>
<td>1</td>
<td>0.887</td>
<td>0.856</td>
</tr>
</tbody>
</table>

- **Power**: - 2.8 %
- **Efficiency**: + 0.72 %
- **Norm. min. Pressure**: - 11.3 %
- **Increased parameter range**: - 3 %
  + 1.32 %
  - 14.4 %
Results – Blade design

Start-Design vs. NLPQL (150 DOEs)

Start-Design vs. ARSM (80 DPs)

Start-Design: Red
Optimized design: Green
Summary

• Parametric pump design
• CFD Best Practice Study
• Sensitivity Analysis
  – Best Practice for Meta-Model with 50, 100, 150 samples
  – COP increases with sample size
  – Important parameter identified with 50 samples
  – More samples necessary for low influence parameters
• Meta-Model Optimization
  – 0.72 % Efficiency improvement
  – 11 % Normalized minimum pressure improvement
• Direct Optimization with increased parameter range
  – 1.32 % Efficiency improvement
  – 14 % Normalized minimum pressure improvement
Outlook – Pump characteristic & spiral casing

- Optimization on pump characteristic
- Volute

\[ H \]
\[ Q \]
\[ n_1 \]
\[ n_2 \]
\[ n_3 \]
\[ \eta_H = 0.98 \]
Outlook – Robust design optimization

• Investigate the effect by scattering input parameters