Design and Optimization of Turbo Charger Turbine Maps by Meta-Model of optimal Prognosis

Johannes Einzinger
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Turbo Charger, Basics
Turbo Charger, Thermodynamics

Compressor: \( P_V = \frac{1}{\eta_V} \cdot m_V \cdot \Delta h_{is} \)

Turbine: \( P_T = \eta_T \cdot m_T \cdot \Delta h_{is} \)

\[
\Rightarrow \left( \frac{p_2}{p_1} \right) \frac{K_V^{-1}}{K_V} = 1 + \frac{m_T}{m_V} \cdot \frac{c_{p3}T_3}{c_{p1}T_1} \cdot \eta_V \cdot \eta_T \cdot \left[ 1 - \left( \frac{p_4}{p_3} \right) \frac{K_T^{-1}}{K_T} \right]
\]
Turbo Charger, Matching

\[
\left( \frac{p_2}{p_1} \right)^{\frac{K_v - 1}{K_v}} = 1 + \frac{m_T}{m_v} \cdot \frac{c_{p_3} T_3}{c_{p_1} T_1} \cdot \eta_v \cdot \eta_T \cdot \left[ 1 - \left( \frac{p_4}{p_3} \right)^{\frac{K_v - 1}{K_v}} \right]
\]

- Compressor Map must fit Engine Characteristic
  \( \rightarrow m_v, \eta_v, n, \Pi_v \)
- Matching \( \rightarrow \Pi_T \) wrt \( C \)
- Turbine Map \( \rightarrow m_T, \eta_T \)
- Check / Iterate \( C \)
- Does Mass Flow match?
Matching by Turbine Meta-Model

\[
\left( \frac{p_2}{p_1} \right)^{\frac{\kappa_v - 1}{\kappa_v}} = 1 + \frac{m_T}{m_v} \cdot \frac{c_{p_3} T_3}{c_{p_1} T_1} \cdot \eta_v \cdot \eta_T \cdot \left[ 1 - \left( \frac{p_4}{p_3} \right)^{\frac{\kappa_r - 1}{\kappa_r}} \right]
\]

- Compressor Map must fit Engine Characteristic
  \[m_V, \eta_V, n_V, \Pi_V\]
- Turbine Map as MoP
- Required \[m_T, \eta_T\]
- Matching \[\Pi_T\] wrt C
- \(\rightarrow\) Optimal Turbine Map
• PRIMARY DESIGN
• GEOMETRY
• CFD-SIMULATION
• META-MODEL
PRIMARY DESIGN
GEOMETRY
CFD-SIMULATION
META-MODEL
Turbine Design

\[ d_s = d \cdot \frac{Q^{0.5}}{\Delta h_{is}^{0.75}} \]

\[ n_s = n \cdot \frac{Q^{0.5}}{\Delta h_{is}^{0.75}} \]

Considered Region

\[ c_u \]

\[ c_m \]

\[ u \]

\[ n_s = 0.5 \]

\[ n_s = 0.7 \]

\[ n_s = 0.9 \]
Meridian Plane

Defined Parameters:

Rotational Speed: \( \Omega \)

Pressure Ratio: \( \frac{p_{t3}}{p_4} \rightarrow \Delta h_{is} \rightarrow c_{is} \)

Velocity Ratio: \( \frac{u_3}{c_{is}} \rightarrow u_3 \rightarrow r_3 \)

Velocity Ratio: \( \frac{c_{m4}}{u_3} \rightarrow c_{m4} \)

Specific Speed: \( n_s = n \cdot \frac{Q^{0.5}}{\Delta h_{is}^{0.75}} \rightarrow r_{4s} \rightarrow \dot{m} \)

Radius Ratio: \( \frac{r_{4h}}{r_{4s}} \rightarrow r_{4h} \cdot u_{4h} \cdot u_{4s} \)

Loss Coefficient: \( \Delta h_{V} = 0.5 \cdot \zeta \cdot c_{m4}^2 \)

Height: \( \dot{m} = 2 \cdot \pi \cdot r \cdot b \cdot \rho \cdot c_{m3} \)

Entropy Gain: \( \Delta s = c_p \cdot \ln \left( \frac{T_4}{T_3} \right) - R \cdot \ln \left( \frac{p_4}{p_3} \right) \)
Blade to Blade

Absolute Velocity $c$ ↓

Relative Velocity $w$ ↑

$\beta_B = f(m)$

Euler Equation

$\Delta h_t = \Delta (u \cdot c_u)$

Total Enthalpy stn Frame

$h_t = h + 0.5 \cdot c^2$

Total Enthalpy rel Frame

$h'_t = h + 0.5 \cdot w^2$

Inlet:

$\alpha_3, u_3, \beta_3 \approx \beta_{B3} \rightarrow c_3, w_3$

Outlet:

$\alpha_4 = 0, c_{m4}, u_4 \rightarrow c_4, w_4, \beta_4$
### Design Parameters

#### Output Parameter

Output Parameter will be compared with CFD Result → Correlation

#### Input Parameter

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<thead>
<tr>
<th>#</th>
<th>Name</th>
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<th>Ref. Value</th>
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#### Constants

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• PRIMARY DESIGN
• GEOMETRY
• CFD-SIMULATION
• META-MODEL
BladeModeler

- Mean Line Design tool
  - Preliminary blade design
- Generation of 3D CAD
- Auto creation of
  - One or all blades
  - Hub & shroud solid
  - Fillets, …
  - Periodic fluid volumes for CFD analysis
  - Named selections
- Parametric CAD modifications
Meridian Plane

**Hub/Shroud Spline with 5 Control-Points, Dimensions relative to first and last**

Length Scale:

\[ r_0 = \frac{\sqrt{\kappa \cdot R \cdot T_{t3}}}{\Omega} \]
Blade design on 2 layers, Hub and Shroud
Bezier curve with 4 Control Points
# Design Parameters

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TurboGrid

- Automated mesh generation for bladed turbo machinery components
- High quality hexahedral grids
- Repeatable
  - Minimize mesh influence in design comparison
- Scalable
  - Maintain quality with mesh refinement
CFX

- Fast & scalable solver
- Low speed to supersonic
- Steady/transient
- Turbulence & heat transfer

- Multiple Frame of Reference
- Multi-phase flow
- Real fluids
- Fluid/structure interaction
Set-Up & Boundary Conditions

- **Fluid ideal Gas**
- **Turbulence Model SST**
- **Total Pressure and Temperature @ Inlet**
- **Static Pressure @ Outlet**
- **Relative Frame of Reference**
Solver Run

RMS-Residuals
Mass Conservation
Momentum
Energy

Imbalances
Mass Conservation
Momentum
Energy

Monitor Points
Efficiency
Variable Ratios
Pressure, Temperature…

Monotonic Convergence
Limit 10^{-5}
Iteration 82

+2%
Imbalance ~0%
Limit 0.1%

-2%
Constant Values
Iteration 40
CFX-Post / Turbo-Post

- Turbo post-processing
  - Turbo plots
    - Blade-to-blade
    - Meridional
  - Turbo charts
    - Blade loading
    - Hub to shroud
  - Turbo report templates
    - 1 component → multi-stage
• PRIMARY DESIGN
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Design of Experiments
Licensing, HPC & Parametric Packs

- A lot of calculations!
- How can these calculations be done in a quick way?

![Diagram showing series of design points and solver keys with and without HPC packs.]

- 94% reduced time to innovation

![Diagram with x-axis: Simultaneous Design Points, Y-axis: Time, Z-axis: Parallel Solve, showing 3 sets of solver keys with and without HPC packs.]

+ 1 HPC Pack
Meta-Model of Optimal Prognosis

Correlation Filter
Importance Filter
Test-Point & Data Split
Response Surface
Coefficient of Prognosis

![Diagram showing basic points, test points, linear, quadratic regression, moving least square, and variation of filter limits.]

\[ CoP = \left( \frac{E(Y \cdot \hat{Y})}{\sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2 = \left( \frac{\sum_{k=1}^{N} (y^{(k)} - \mu_y) \cdot (\hat{y}^{(k)} - \mu_{\hat{Y}})}{(N - 1) \cdot \sigma_Y \cdot \sigma_{\hat{Y}}} \right)^2 \]
Best Practice CoP

- CoP is increasing with Number of Samples: 100% or to a Limit → ”Noise”
- The higher the Dimension of MoP the more Samples are required
- The more non-linear MoP is, the more Samples are required
- MoP wrt to Lower/Upper Limit of Parameters
Trouble Shooting for small CoP

- Number of Evaluated Designs?
  - Check CoP(80)~CoP(150)
- Numerical Error?
  - Best-Practice!
- Model Error?
  - Turbulence Model
  - Steady vs. transient
  - Hot vs. cold Geometry
  - ...
- Multiple-Mechanisms
  - Use alternative Output
Characteristic Data: Mass Flow Rate

1. High CoP 93%
2. Important Parameters
3. Plausible MoP

\[ n_s = \text{const} \Rightarrow m = f(p_{\text{out}}) \]
Characteristic Data: Efficiency

Medium CoP 61% / 66%

Full Data Set

Reduced, no Outliners
Alternative for Efficiency

• Definition of Efficiency:
  – CoP=66%
  \[
  \eta_{pl} = \frac{\kappa}{\kappa - 1} \cdot \frac{\ln(T_{t4}/T_{t3})}{\ln(p_{4}/p_{t3})}
  \]

• Entropy
  – CoP=89%
  \[
  \Delta s = c_p \cdot \ln \left( \frac{T_4}{T_3} \right) - R \cdot \ln \left( \frac{p_4}{p_3} \right)
  \]

• Total Temperature
  – CoP=93%
Correlation: Mass Flow Rate

- Real Mass Flow Rate is smaller than predicted due to blockage
- MoP can be used for blockage correlation
- Mass Flow Rate depends on
  - Specific Speed
  - Outlet Pressure
  - Blade Inlet Angle
Correlation: Efficiency

Efficiency prediction due to dynamic loss is not sufficient

\[ \Delta h_v = 0.5 \cdot \zeta \cdot c_m^2 \]

MoP for Entropy Gain can be used as prediction for Design Procedure
Summary & Outlook

- **Summary**
  - Turbine Map as Meta-Model $m, \eta = f(p, \text{Geometry})$
  - Design Correlations can be derived from Meta-Model
  - Primary Design by Meta-Model $\rightarrow$ turboSLang

- **Outlook**
  - Quality might be improved by
    - Finer Mesh to reduce numerical noise
    - More Design Points in Meta-Model
    - Better Lower/Upper Bounds for Parameter
  - Turbine Map as Meta-Model $m, \eta = f(p, \Omega, \text{Geometry})$
  - Compressor Map as Meta-Model