SHAPE OPTIMIZATION OF AN ORC RADIAL TURBINE NOZZLE

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Delft - September 22th – 23th, 2010
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   - Optimized Results
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Small Power Output ORC Turbine ($< 500 kW_e$)

**Introduction**

- Objectives
- Tri-O-Gen Design
- ORC Turbine

**Methodology**

- High molecular-weight fluids (e.g. Toluene)

**Results**

- Expansion:
  - real gas effects
  - high pressure ratio
  - high volume ratio
  - low specific enthalpy drop

- Challenging Design:
  - small-size turbomachinery
  - moderate/high rotational speed
  - few stages

**Intensive** use of CFD to design high-efficiency and optimized turbines

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Shape Optimization of an ORC Radial Turbine Nozzle
Objectives

General Geometry Parameterization

- development of a generic blade shape parameterization suitable for radial and axial supersonic geometries

General Optimization Procedure

- development of an efficient, effective and fully automated optimization procedure
- comparison of different optimization strategies in terms of convergence rate

Test Case

- improve the performance of the original Tri-O-Gen stator in terms of flow uniformity and shock losses
Tri-O-Gen Original Stator Design

Turbine Features

- one stage radial inflow turbine ($\approx 150kW_e$)
- high expansion ratio $\beta \approx 62$
- low degree of reaction

Mach number

- highly tangential flow
- high Mach number

Total Pressure

- strong shock wave
- flow dis-uniformity

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Shape Optimization of an ORC Radial Turbine Nozzle
Optimization Algorithm

Genetic Algorithm

START

DOE

Geometry Generation

Grid Generation

CFD Solver

PostProcessing

Performance

STOP

Database

Off-line trained Metamodel

START

DOE

Geometry Generation

Grid Generation

CFD Solver

PostProcessing

Performance

STOP

Database

MetaModel

Performance Prediction

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Shape Optimization of an ORC Radial Turbine Nozzle
Objective Function Definition

Minimization of one objective function

sum of three non-concurrent contributions:

\[ \varphi = \varphi_M + \varphi_\alpha + \varphi_{P_0\text{loss}} \]

\( \varphi_M = \sqrt{\frac{1}{q} \sum_{j=1}^{q} c_j M_j \left( \frac{M_j - M_{\text{mix}}}{M_{\text{toll}}} \right)^2} \)

\( \varphi_\alpha = \sqrt{\frac{1}{q} \sum_{j=1}^{q} c_j M_j \left( \frac{\alpha_j - \alpha_{\text{trg}}}{\alpha_{\text{toll}}} \right)^2} \)

\( \varphi_{P_0\text{loss}} = \frac{1 - P_{0\text{mix}}}{P_{0\text{toll}}} \)

where:

\( M_{\text{toll}} = 0.025 \)

\( \alpha_{\text{trg}} = 106[^\circ] \)

\( \alpha_{\text{toll}} = 1[^\circ] \)

\( P_{0\text{toll}} = 0.05 \)

and \( q \) is the number of grid nodes at the outlet bound

Original TriOgen Design Performance

\[ \varphi_{\text{des}} = 2.035 + 1.761 + 3.533 = 7.329 \]
**Introduction**

**Methodology**

**Results**

**Optimization Algorithm**

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**Geometry Generation**

**B-Spline Curves**

\[ \mathbf{B}(u) = \sum_{i=1}^{n} N_i(u) \mathbf{P}_i \]

- cubic curves
- \( C^2 \) continuous at the junctions
- chordal parametrization

**Design Variables**

- throat angle and position \((\delta, Th_r, Th_\theta)\)
- trailing edge aperture angle \((\alpha)\)
- trailing edge discharge angle \((\beta)\)
- 1 d.o.f. for each free control point \((prm_x)\) of 2 curves (diverging part)
Grid generation and CFD solver

**adMesh**
- fully automated 2D unstructured mesh generator
- hybrid anisotropic elements
- based on the advancing-Delaunay algorithm

**zFlow**
- hybrid Finite Element (FE)/Finite Volume (FV) RANS solver
- linked to FluidProp, a fluid library for thermodynamic and transport properties calculation using state of the art physical models
**Grids**

- 2D unstructured grid with local refinements
- three different spacing:
  - very coarse ($\approx 2000$ cells)
  - coarse ($\approx 5000$ cells)
  - fine ($\approx 35000$ cells)

**Flow Solver**

- inviscid flow (2D Euler equations)
- accurate toluene thermodynamic properties (Lemmon - Span EOS)

**Boundary Conditions:**

- total inlet pressure and temperature
- static backpressure ($\beta \approx 58$)
Optimization Strategy

Off-Line Trained Metamodell

Nexus

- commercial multi-disciplinary and multi-objective optimisation framework
- several gradient-based and evolutionary algorithms available
- several metamodels available
- GUI and batch-mode

Design Of Experiment

- Latin HyperCube allocation
- correlation based on entropy formulation

Kriging

- constant, linear and quadratic base functions
- Gaussian and exponential interpolating functions

Artificial Neural Network

- one and two layers
- five to twenty neurons
- early-stopping technique
Optimization Strategies Comparison

Test Case

- coarse grid
- 10 design variables (throat with 2 d.o.f)
- 1 Metamodel ($\varphi$) or 3 Metamodels ($\varphi_M$, $\varphi_\alpha$, $\varphi_{P_0\text{loss}}$

GA vs MetaModels

ANN

KRGING

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Shape Optimization of an ORC Radial Turbine Nozzle
Optimized Results: Fixed Throat

8 design variables
found after 102 CFD simulations

\[ \varphi = 0.912 + 1.476 + 3.143 = 5.531 \]
9 design variables

found after 125 CFD simulations

\[ \varphi = 0.947 + 1.196 + 1.266 = 3.409 \]
Optimized Results: Throat with 2 d.o.f. \((r, \theta)\)

10 design variables found after 278 CFD simulations

\[ \varphi = 0.944 + 1.043 + 1.271 = 3.258 \]
Preliminary Results: Half Number of Blades

10 design variables
found after 205 CFD simulations

\[ \varphi = 0.961 + 1.217 + 0.934 = 3.112 \]
# Optimal Results: Summary

**Objective Function**

<table>
<thead>
<tr>
<th>Design</th>
<th>$\varphi_M$</th>
<th>%</th>
<th>$\varphi_\alpha$</th>
<th>%</th>
<th>$\varphi_{P_0\text{loss}}$</th>
<th>%</th>
<th>$\varphi$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original</strong></td>
<td>2.035</td>
<td></td>
<td>1.761</td>
<td></td>
<td>3.533</td>
<td></td>
<td>7.329</td>
<td></td>
</tr>
<tr>
<td>$Th_{\text{fix}}$</td>
<td>0.912</td>
<td>$-55.2$</td>
<td>1.476</td>
<td>$-16.2$</td>
<td>3.143</td>
<td>$-11.0$</td>
<td>5.531</td>
<td>$-24.5$</td>
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<tr>
<td>$Th_{\text{1dof}}$</td>
<td>0.947</td>
<td>$-53.5$</td>
<td>1.196</td>
<td>$-32.1$</td>
<td>1.266</td>
<td>$-64.2$</td>
<td>3.409</td>
<td>$-53.5$</td>
</tr>
<tr>
<td>$Th_{\text{2dof}}$</td>
<td>0.944</td>
<td>$-53.6$</td>
<td>1.043</td>
<td>$-40.8$</td>
<td>1.271</td>
<td>$-64.0$</td>
<td>3.258</td>
<td>$-55.5$</td>
</tr>
<tr>
<td>$Th_{\text{2dof}, \frac{Z}{2}}$</td>
<td>0.961</td>
<td>$-52.8$</td>
<td>1.217</td>
<td>$-30.9$</td>
<td>0.934</td>
<td>$-73.6$</td>
<td>3.112</td>
<td>$-57.5$</td>
</tr>
</tbody>
</table>

**Downstream Mixed Flow Parameters**

<table>
<thead>
<tr>
<th>Design</th>
<th>$M$</th>
<th>%</th>
<th>$\alpha$ [°]</th>
<th>%</th>
<th>$P_0$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original</strong></td>
<td>2.726</td>
<td></td>
<td>$-106.15$</td>
<td></td>
<td>0.8234</td>
<td></td>
</tr>
<tr>
<td>$Th_{\text{fix}}$</td>
<td>2.747</td>
<td>$+0.77$</td>
<td>$-106.50$</td>
<td>$-0.33$</td>
<td>0.8429</td>
<td>$+2.37$</td>
</tr>
<tr>
<td>$Th_{\text{1dof}}$</td>
<td>2.781</td>
<td>$+2.02$</td>
<td>$-106.50$</td>
<td>$-0.33$</td>
<td>0.9369</td>
<td>$+13.78$</td>
</tr>
<tr>
<td>$Th_{\text{2dof}}$</td>
<td>2.781</td>
<td>$+2.02$</td>
<td>$-106.46$</td>
<td>$-0.29$</td>
<td>0.9365</td>
<td>$+13.74$</td>
</tr>
<tr>
<td>$Th_{\text{2dof}, \frac{Z}{2}}$</td>
<td>2.788</td>
<td>$+2.27$</td>
<td>$-106.47$</td>
<td>$-0.30$</td>
<td>0.9532</td>
<td>$+15.76$</td>
</tr>
</tbody>
</table>
Conclusions

Achieved so far

- general blade parameterization based on B-Spline curves
- comparison of a standard Genetic Algorithm optimization with respect to off-line trained Metamodels
- real turbine nozzle shape optimization based on Euler equations and real gas equation of state
- comparison of selected geometries with respect to the original design

Future development

- extension to turbulent flows
- extension to Multi-Objective Optimization
- extension to three-dimensional geometries
- further investigation for more efficient optimization algorithm (e.g. Hierarchical, Metamodel-Assisted Evolutionary Algorithms)
THANK YOU ALL!