SHAPE OPTIMIZATION OF AN ORC RADIAL TURBINE NOZZLE

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Outline

1. Introduction
   - ORC Turbine
   - Objectives
   - Tri-O-Gen Design
2. Methodology
   - Optimization Algorithm
3. Results
   - Optimization Strategies Comparison
   - Optimized Results

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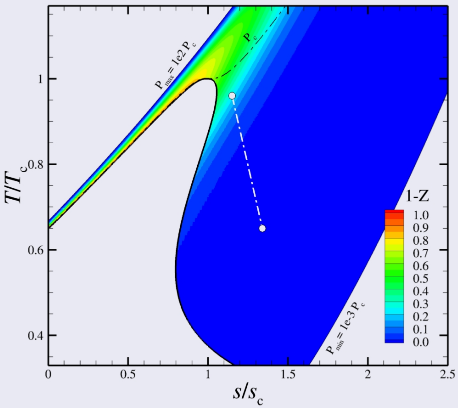
Outline

Small Power Output ORC Turbine ($< 500kW_e$)

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



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

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

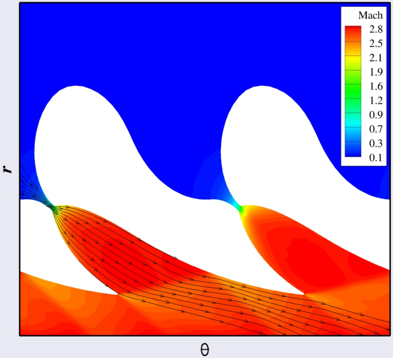
- improve the performance of the original Tri-O-Gen stator in terms of flow uniformity and shock losses

Tri-O-Gen Original Stator Design

Turbine Features

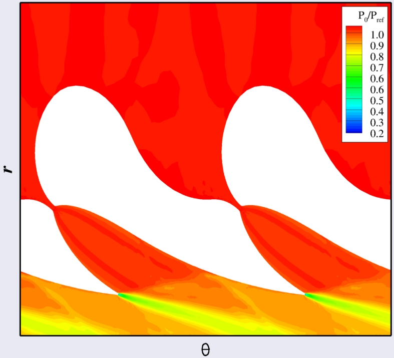
- one stage radial inflow turbine ($\simeq 150kW_e$)
- high expansion ratio $\beta \simeq 62$
- low degree of reaction

Mach number



- highly tangential flow
- high Mach number

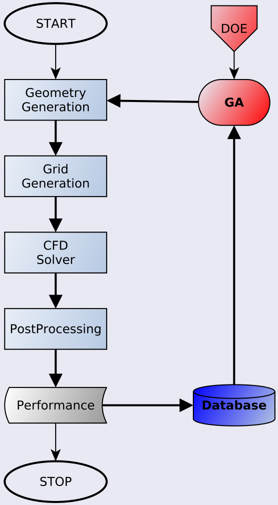
Total Pressure



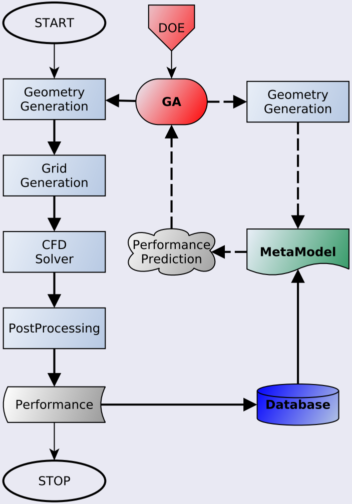
- strong shock wave
- flow dis-uniformity

Optimization Algorithm

Genetic Algorithm



Off-line trained Metamodel



Objective Function Definition

Minimization of **one** objective function

sum of three non-concurrent contributions:

$$\varphi = \varphi_M + \varphi_\alpha + \varphi_{P_{0_{\mathrm{loss}}}}$$

Mach number deviation

$$\varphi_M = \sqrt{\frac{\frac{1}{q}\sum_{j=1}^{q} c_j M_j \left[\frac{M_j - M_{\mathrm{mix}}}{M_{\mathrm{toll}}}\right]^2}{\frac{1}{q}\sum_{j=1}^{q} c_j M_j}}$$

Flow angle deviation

$$\varphi_\alpha = \sqrt{\frac{\frac{1}{q}\sum_{j=1}^{q} c_j M_j \left[\frac{\alpha_j - \alpha_{\mathrm{trg}}}{\alpha_{\mathrm{toll}}}\right]^2}{\frac{1}{q}\sum_{j=1}^{q} c_j M_j}}$$

Total pressure losses

$$\varphi_{P_{0_{\mathrm{loss}}}} = \frac{1 - P_{0_{\mathrm{mix}}}}{P_{0_{\mathrm{toll}}}}$$

where:

$$M_{\mathrm{toll}} = 0.025 \qquad \alpha_{\mathrm{trg}} = 106[^\circ] \qquad P_{0_{\mathrm{toll}}} = 0.05$$

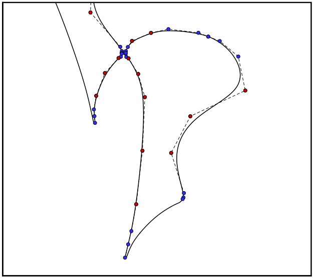
$$\alpha_{\mathrm{toll}} = 1[^\circ]$$

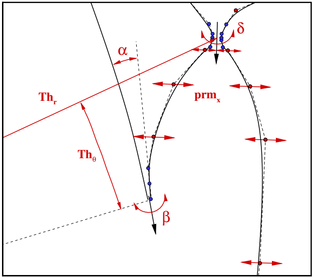
and q is the number of grid nodes at the outlet bound

Original TriOgen Design Performance

$$\varphi_{\mathrm{des}} = 2.035 + 1.761 + 3.533 = 7.329$$

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

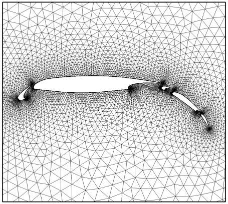
Design Variables

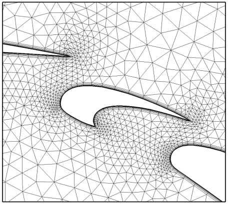
- throat angle and position (δ, Th_r, Th_θ)
- trailing edge aperture angle (α)
- trailing edge discharge angle (β)
- 1 d.o.f. for each *free* control point (prm_x) of 2 curves (diverging part)

Grid generation and CFD solver

adMesh

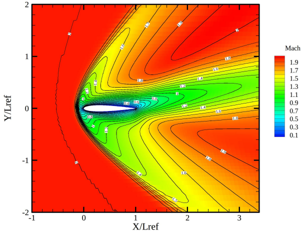
- fully automated 2D unstructured mesh generator
- hybrid anysotropic elements
- based on the advancing-Delaunnay algorithm





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



CFD Solution
an Example

Grids

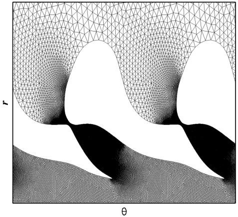
- 2D unstructured grid with local refinements
- three different spacing:
  - very coarse ($\simeq$ 2000 cells)
  - coarse ($\simeq$ 5000 cells)
  - fine ($\simeq$ 35000 cells)

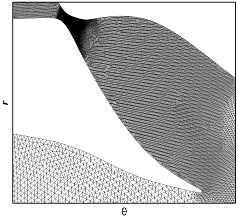
Flow Solver

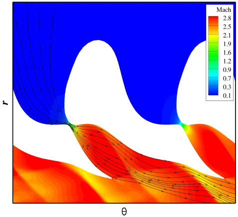
- inviscid flow (2D Euler equations)
- accurate toluene thermodynamic properties (Lemmon - Span EOS)

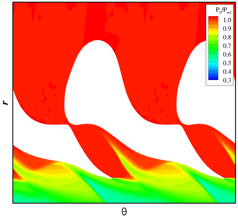
Bounday Conditions:

- total inlet pressure and temperature
- static backpressure ($\beta \simeq 58$)









Optimization Strategy

Off-Line Trained Metamodel

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

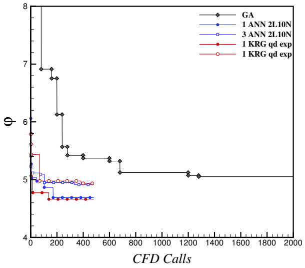
- one and two layers
- five to twenty neurons
- early-stopping technique

Optimization Strategies Comparison

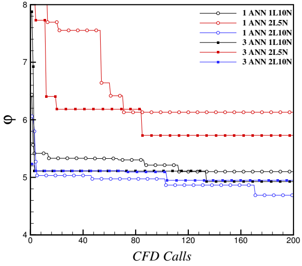
Test Case

- coarse grid
- 10 design variables (throat with 2 d.o.f)
- 1 Metamodel (φ) or 3 Metamodels (φ_M, φ_α, $\varphi_{P_{0_{\text{loss}}}}$)

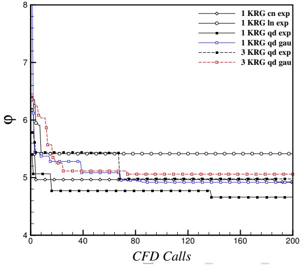
GA vs MetaModels



ANN



KRIGING

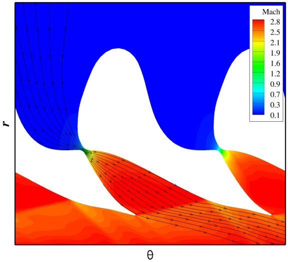


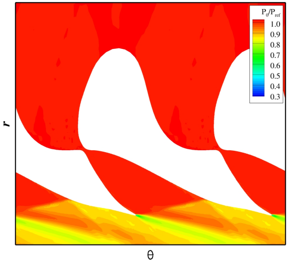
Optimized Results: Fixed Throat

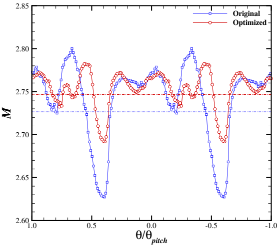
8 design variables

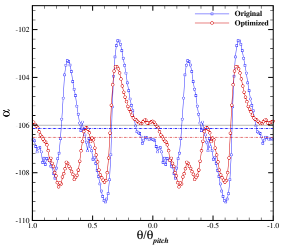
found after 102 CFD simulations

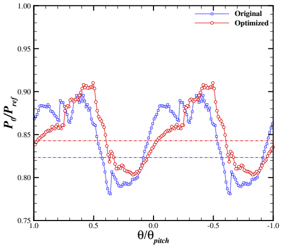
$$\varphi = 0.912 + 1.476 + 3.143 = 5.531$$









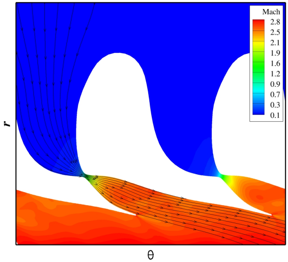


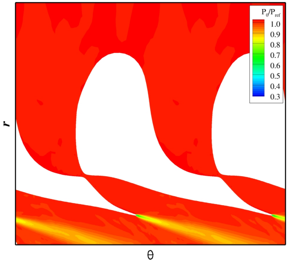
Optimized Results: Throat with 1 d.o.f. (r)

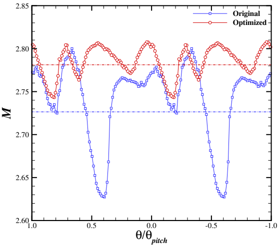
9 design variables

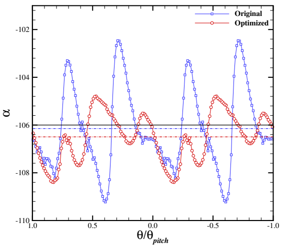
found after 125 CFD simulations

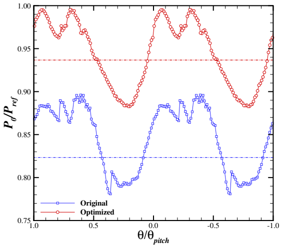
$$\varphi = 0.947 + 1.196 + 1.266$$
$$= 3.409$$









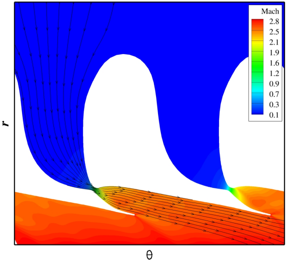


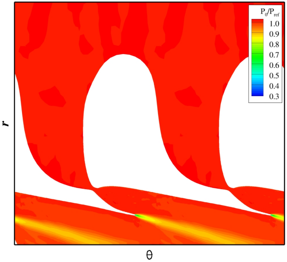
Optimized Results: Throat with 2 d.o.f. (r, θ)

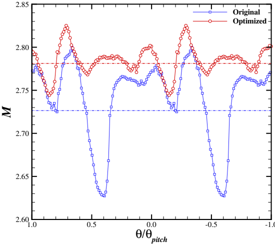
10 design variables

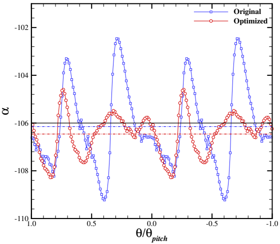
found after 278 CFD simulations

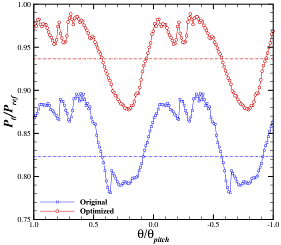
$$\varphi = 0.944 + 1.043 + 1.271$$
$$= 3.258$$









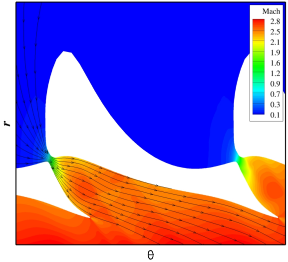


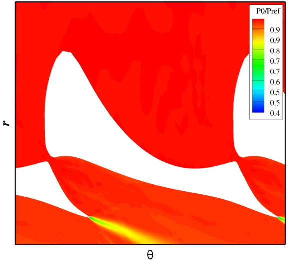
Preliminary Results: Half Number of Blades

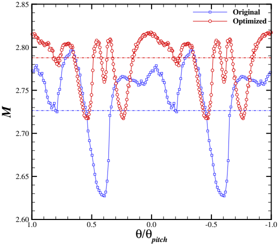
10 design variables

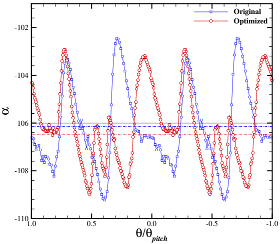
found after 205 CFD simulations

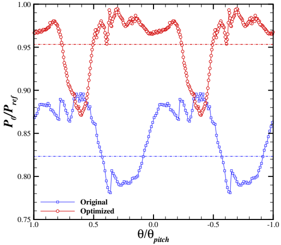
$$\varphi = 0.961 + 1.217 + 0.934$$
$$= 3.112$$











Optimized Results: Summary

Objective Function

Design	φ_M	%	φ_α	%	$\varphi_{P_{0_{\mathrm{loss}}}}$	%	φ	%
Original	2.035		1.761		3.533		7.329	
Th_{fix}	0.912	−55.2	1.476	−16.2	3.143	−11.0	5.531	−24.5
Th_{1dof}	0.947	−53.5	1.196	−32.1	1.266	−64.2	3.409	−53.5
Th_{2dof}	0.944	−53.6	1.043	−40.8	1.271	−64.0	3.258	−55.5
$Th_{\mathrm{2dof},\,\frac{Z}{2}}$	0.961	−52.8	1.217	−30.9	0.934	−73.6	3.112	−57.5

Downstream Mixed Flow Parameters

Design	M	%	α [°]	%	P_0	%
Original	2.726		−106.15		0.8234	
Th_{fix}	2.747	+0.77	−106.50	−0.33	0.8429	+2.37
Th_{1dof}	2.781	+2.02	−106.50	−0.33	0.9369	+13.78
Th_{2dof}	2.781	+2.02	−106.46	−0.29	0.9365	+13.74
$Th_{\mathrm{2dof},\,\frac{Z}{2}}$	2.788	+2.27	−106.47	−0.30	0.9532	+15.76

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!