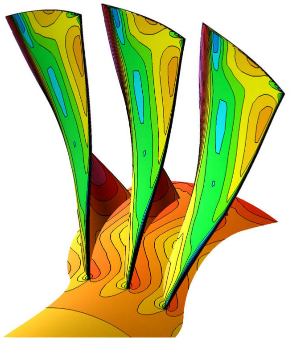
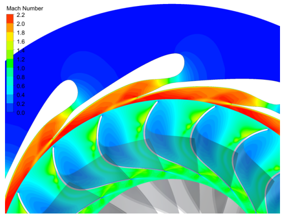
Recent Advances in Flow Analysis Capability and Adjoint-based Design for Turbomachinery with SU2



M. Pini, S. Vitale, A. Rubino, L. Azzini, N. Anand, P. Colonna

Propulsion and Power, Delft University of Technology

2nd Annual Developers Meeting, Stanford University



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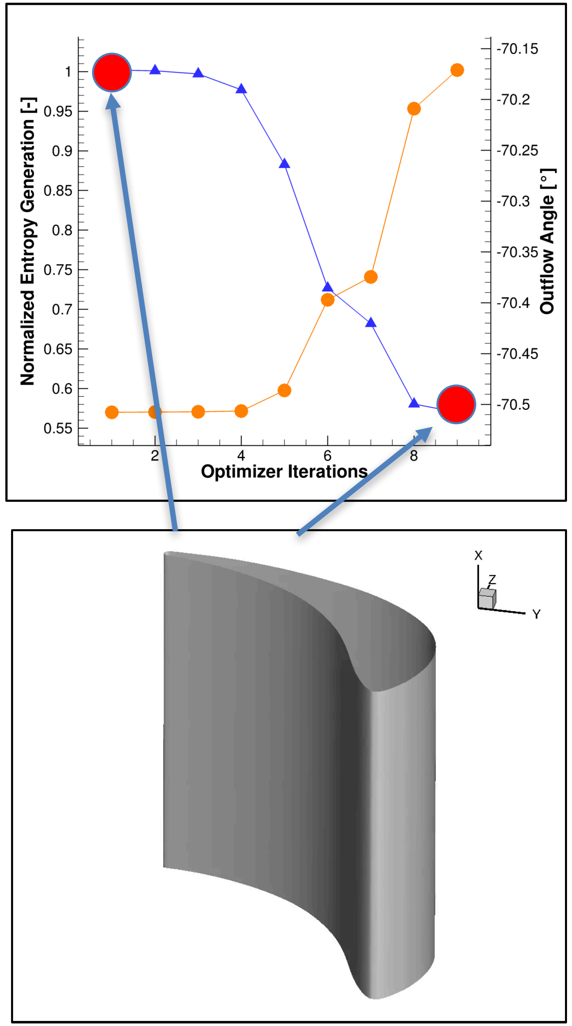
What Has Made It Possible?

Fluid: Air

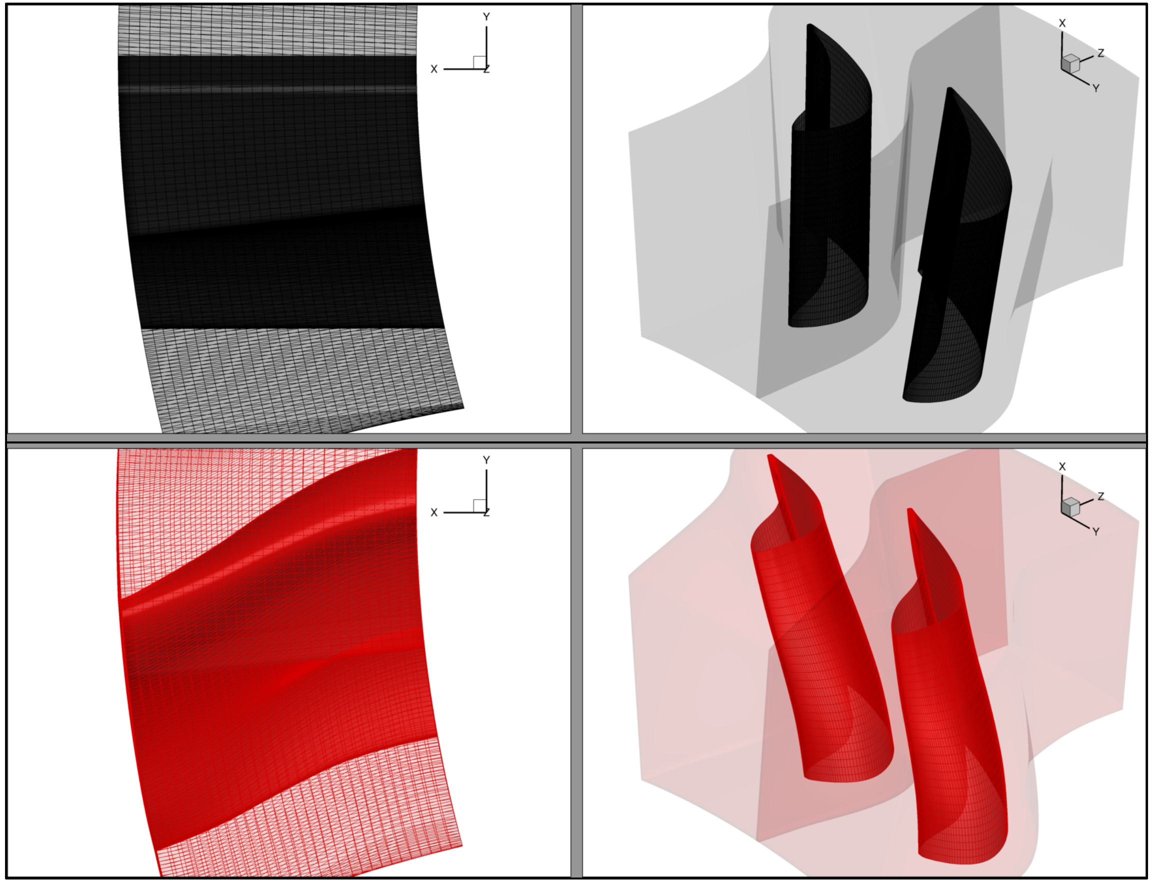
$$\begin{cases} \min S_{gen} \\ \alpha_{out} < -70.0 \end{cases}$$



500k nodes

27 DVs

12h on 20 cores



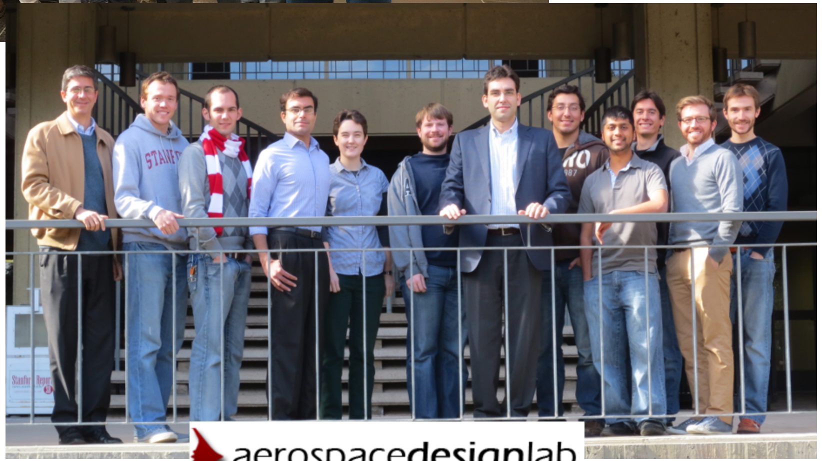
The Secret Recipe…

SU2

The Open-Source CFD Code

Scientific Computing

Technische Universität Kaiserslautern



aerospacedesignlab

Content

- SU2 for turbomachinery: What?
- (Some) Paradigmatic Examples
- Next steps

SU2 for Turbo: What…?

SU2 for Turbo: What…Direction?

Provide Industrial-Strength Design Methods for NextGen Turbomachines…of any kind!

- ✓ Simulation of complex flows
  (NICFD: pure fluids + mixtures, two-phase, unsteady, ROMs)
- ✓ Efficient automated design based on discrete adjoint
- ✓ Multi-physics analysis and design (FSI, topology)

ROMs = reduced order models, e.g. harmonic balance

SU2 for Turbo: What…is in it?

- NICFD → complex TMD models (hard-coded, FluidProp, look-up tables)
- Method of Moments for non-equilibrium condensation
- Turbo features → NRBC, MP, SLI for even pitches, HB
- Discrete turbo adjoint solver: steady/unsteady

For single and multi-row

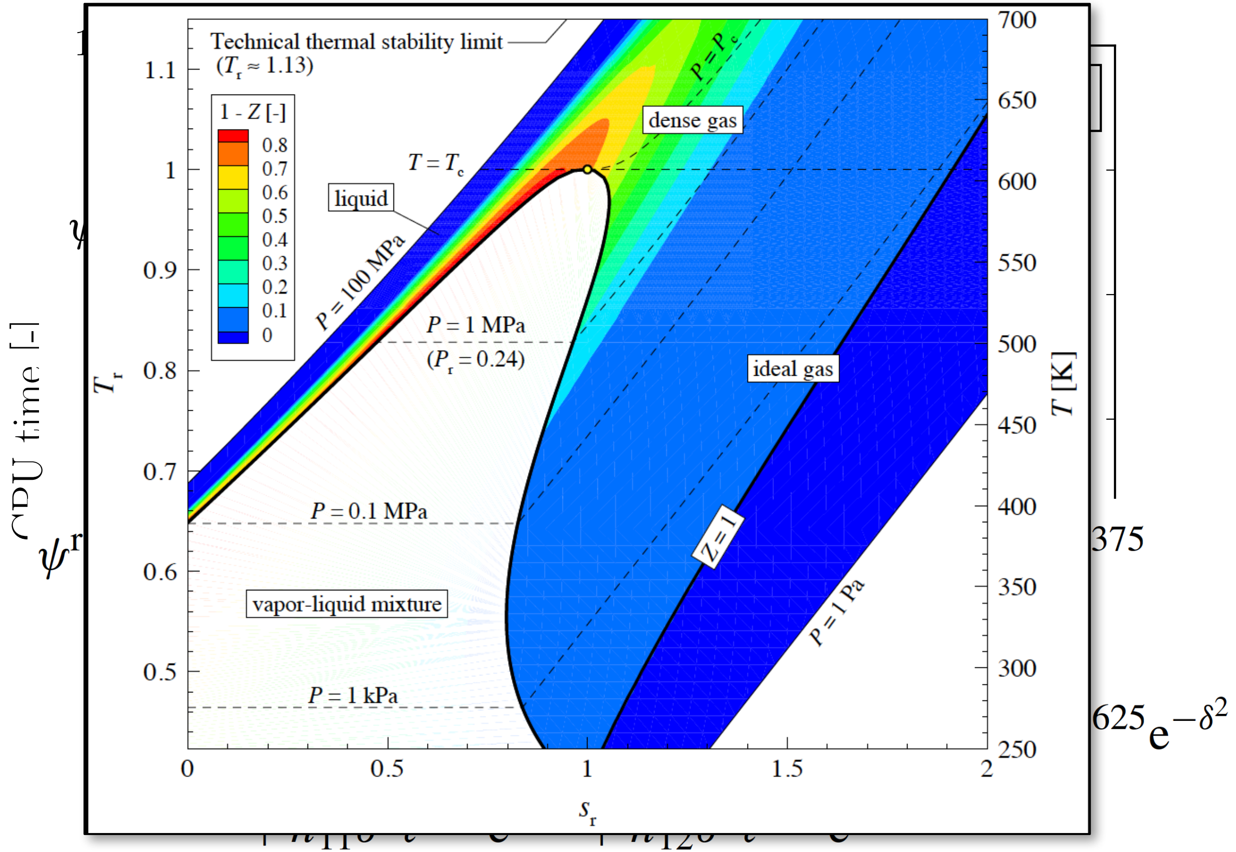
Emphasis (for now) is on compressible flows!

NRBC = Non-reflecting Boundary Conditions
MP = Mixing Plane
SLI = Sliding Interface

Look-up Tables → "Ideal" Cost

$$Pv = RT$$

$$\frac{\Psi(T,\rho)}{RT} = \psi^0(\tau,\delta) + \psi^r(\tau,\delta)$$



- Explicit vs. Implicit
- Secondary thermodynamic properties

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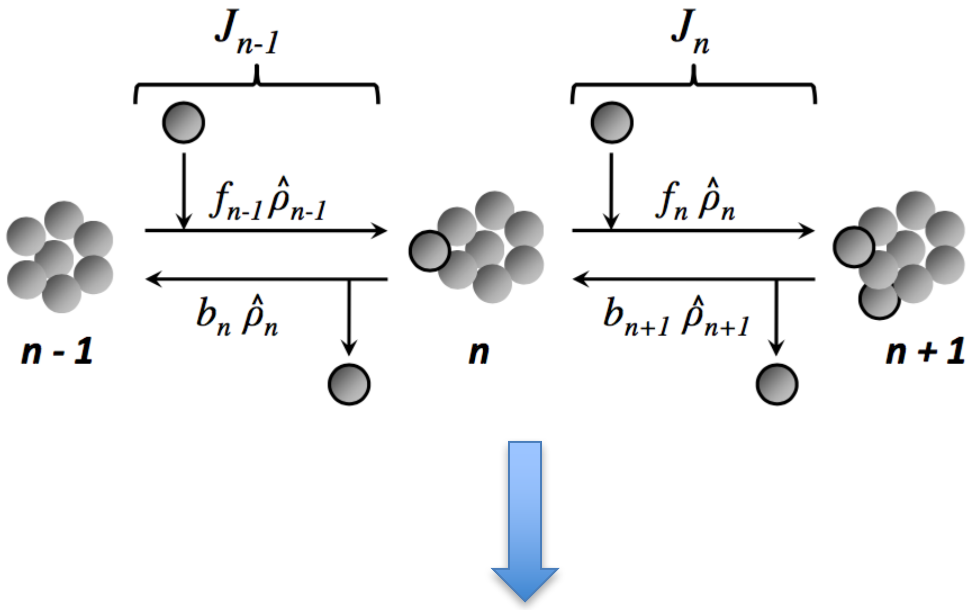
ROM for Dispersed Liquid Flows

- Method of Moments → 4 Transport Equations

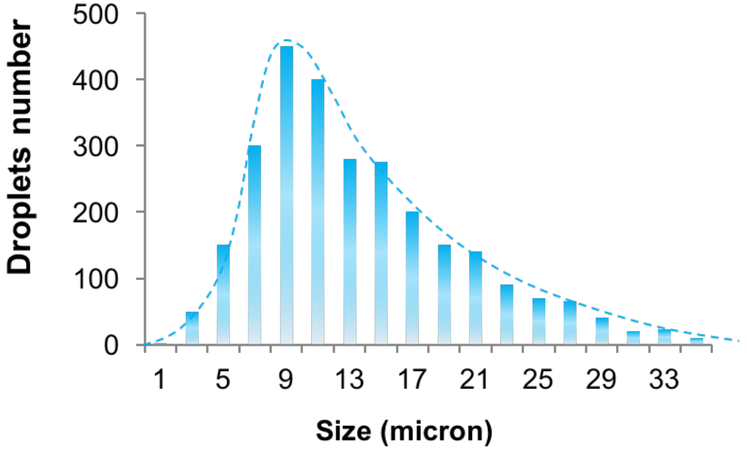


$$\mu_0 = N_{tot} \quad \mu_1 = N_{tot}R \quad \mu_2 = N_{tot}R^2 \quad \mu_3 = N_{tot}R^3$$

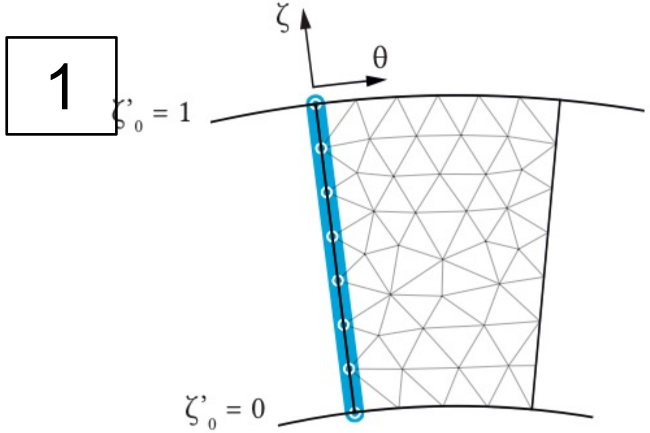
✓ Upwind flux, 1st – 2nd order

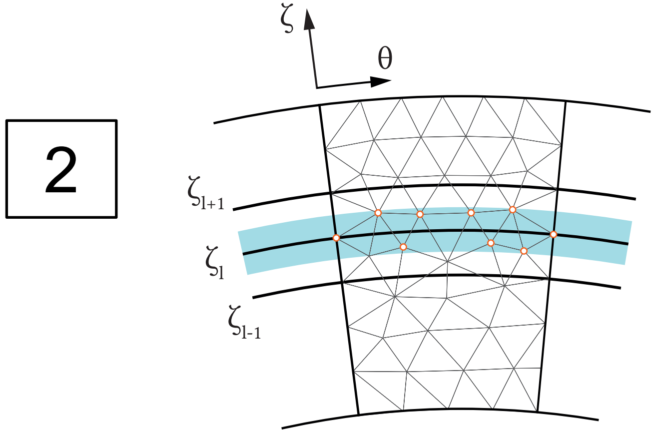
✓ Implicit time integration

✓ Segregated approach

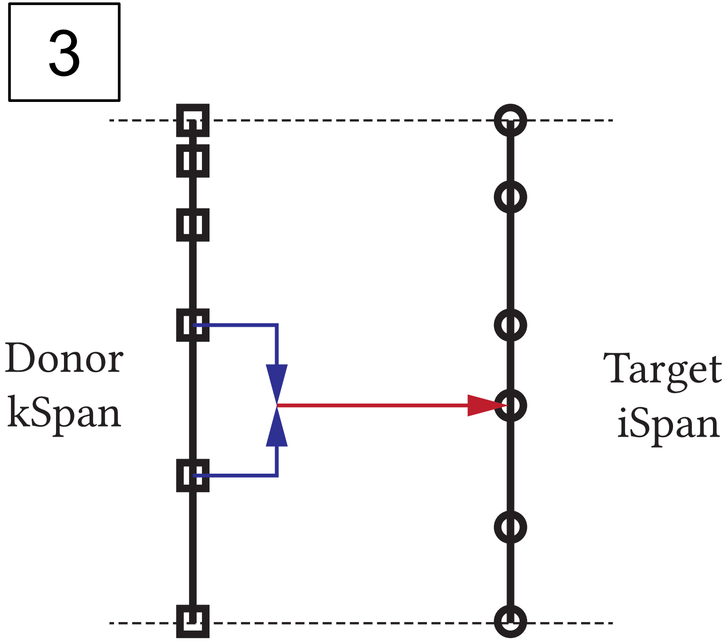


Fluid-Fluid Interface for Generic Grids

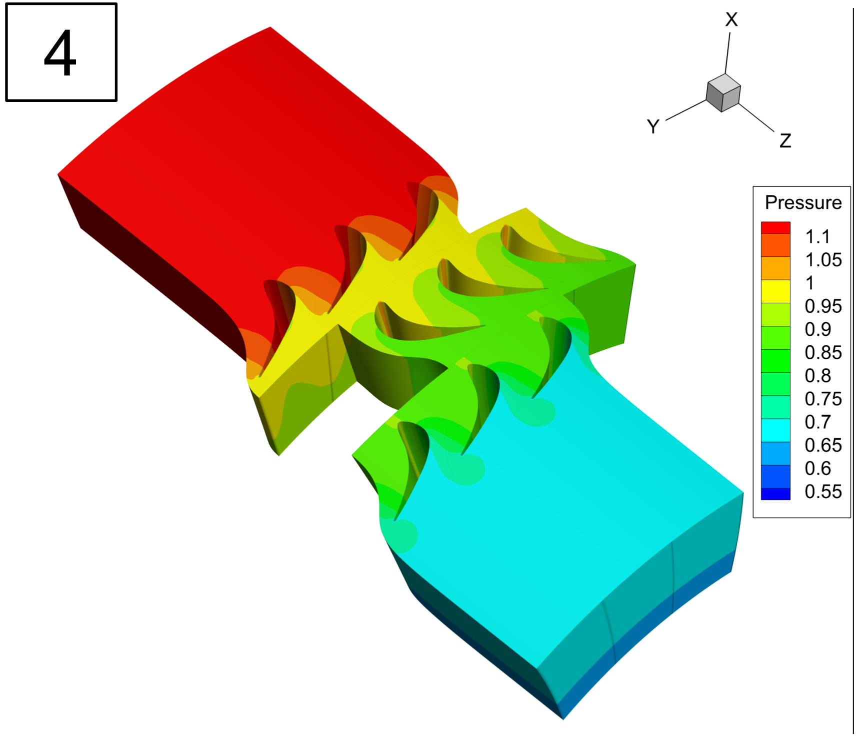




1,2: vertex ordering algorithm



interpolation



simulation

Turbo vertex: same data structure for MP and SLI

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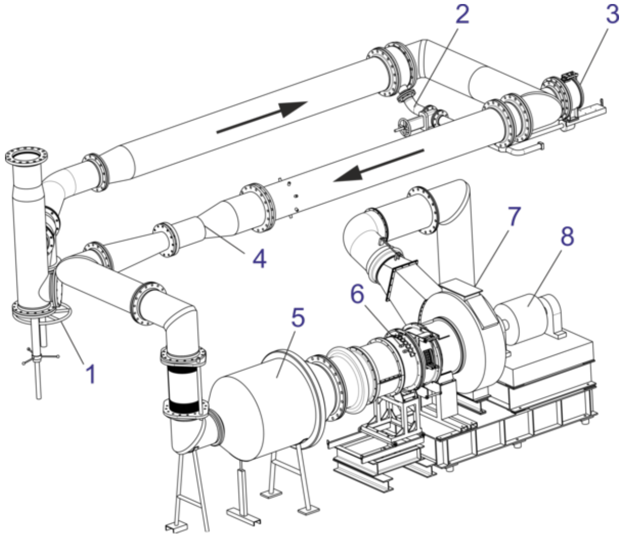
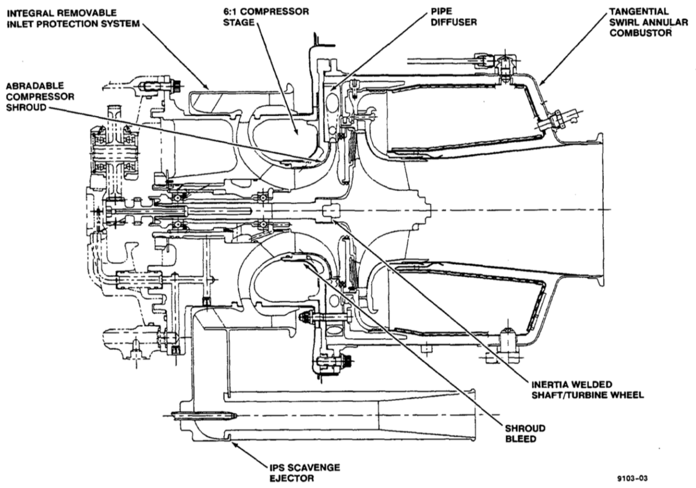
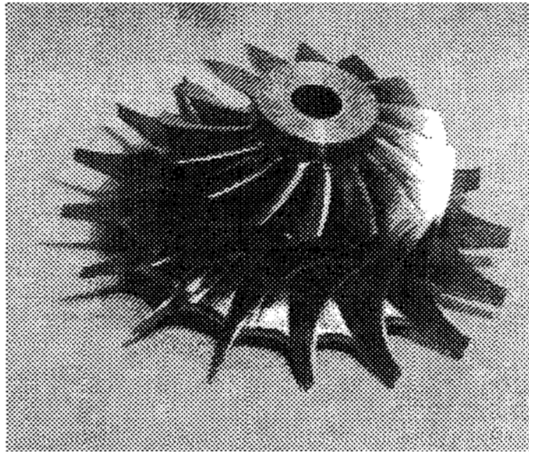
SU2 for Turbo: What…Accuracy?



Aachen turbine

NASA rotor 37





APU turbine

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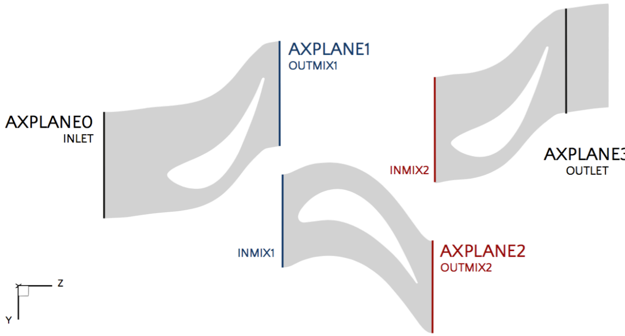
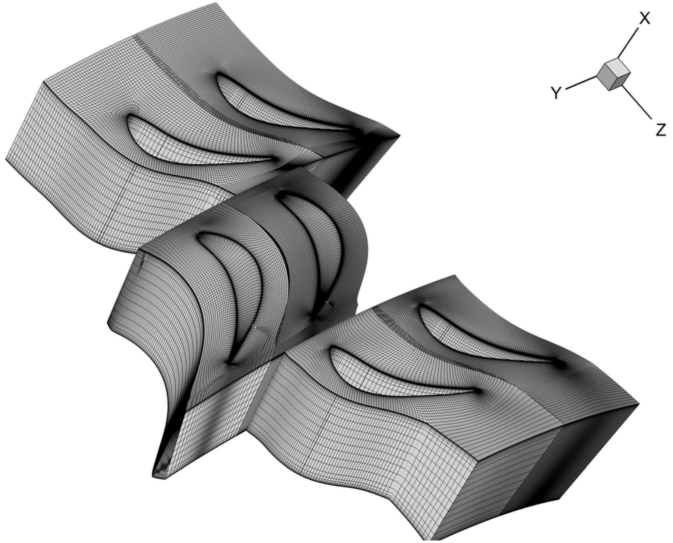
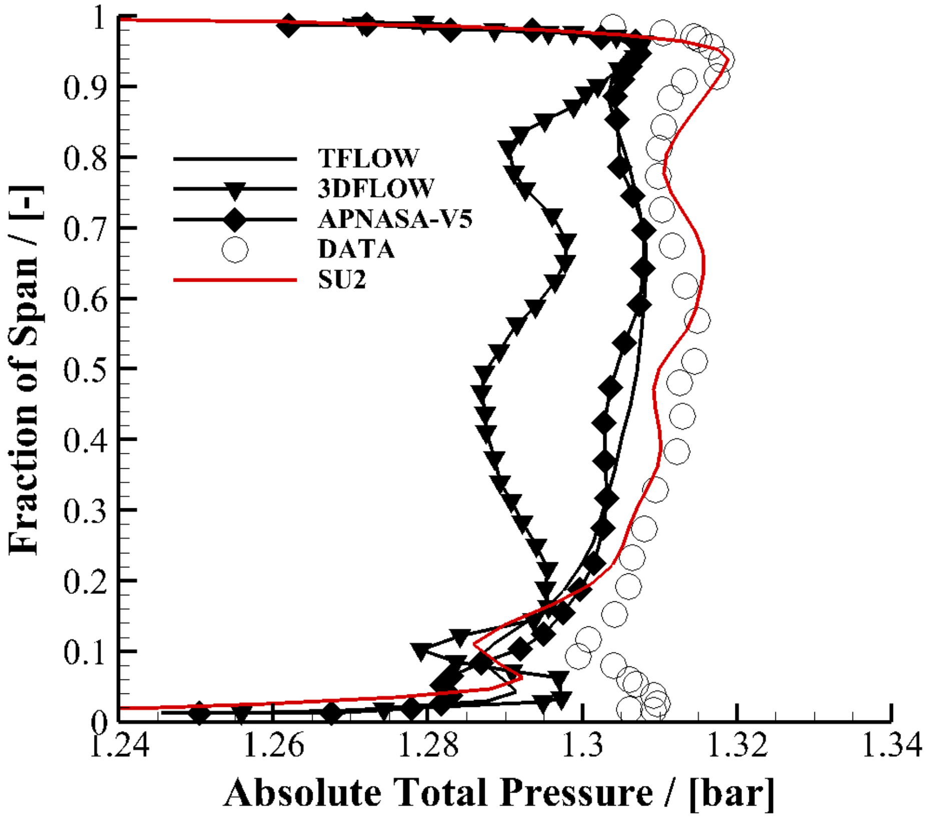
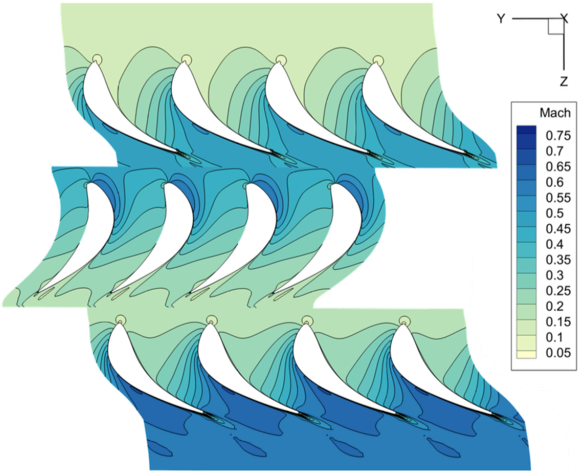
Axial Turbine

V&V Aachen 1.5 Stage Axial Turbine



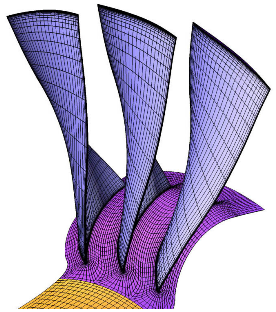


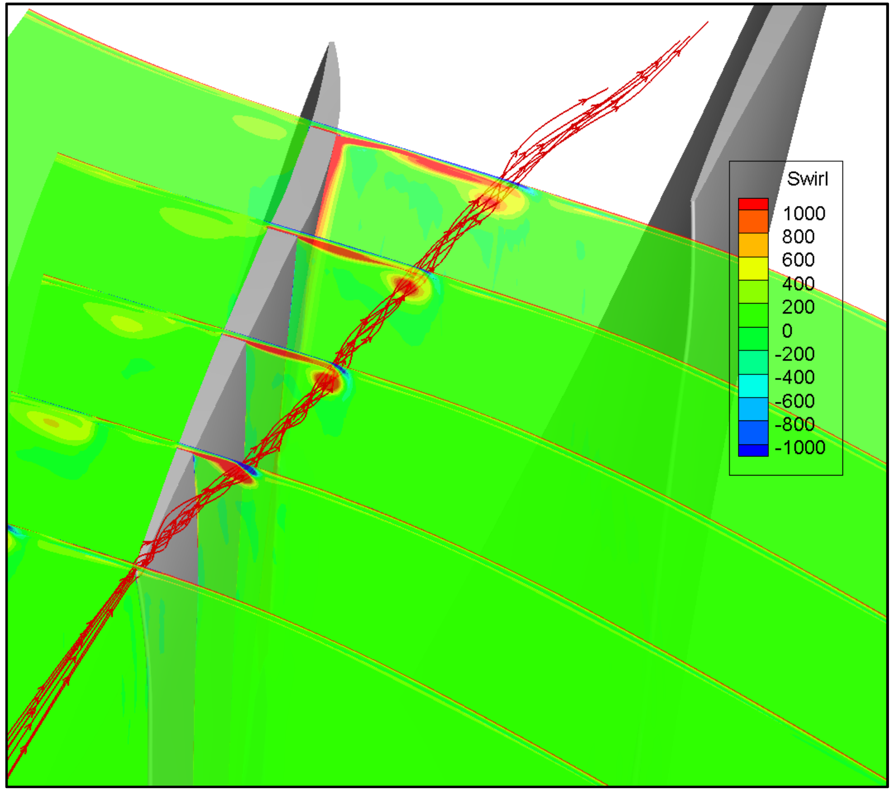


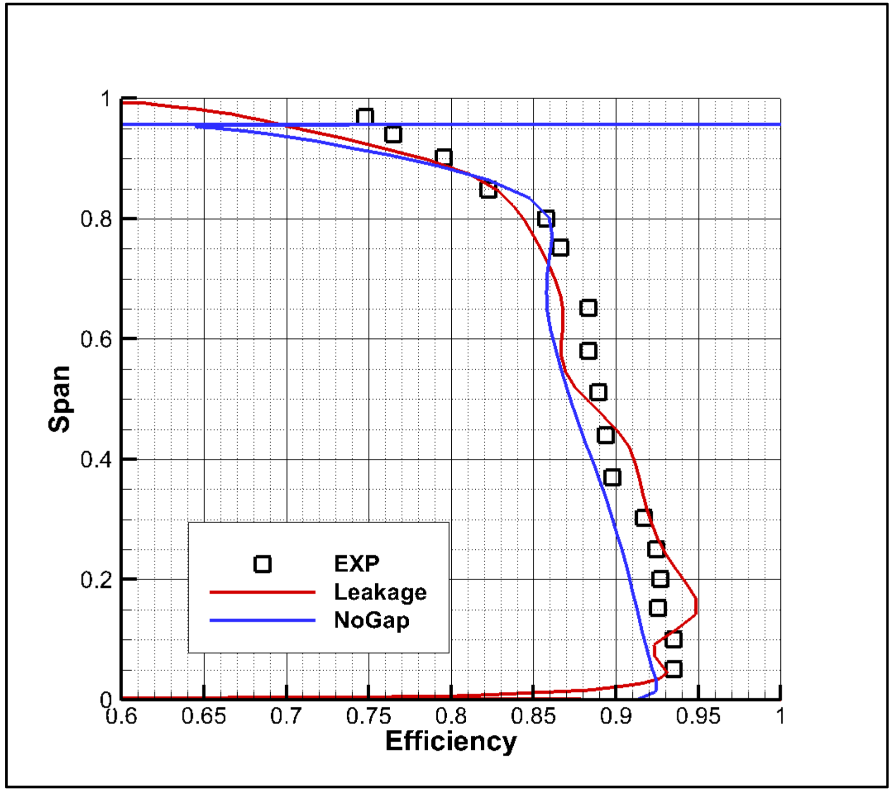


Transonic Compressor

Nasa Rotor 37 - Comparison with Experiments

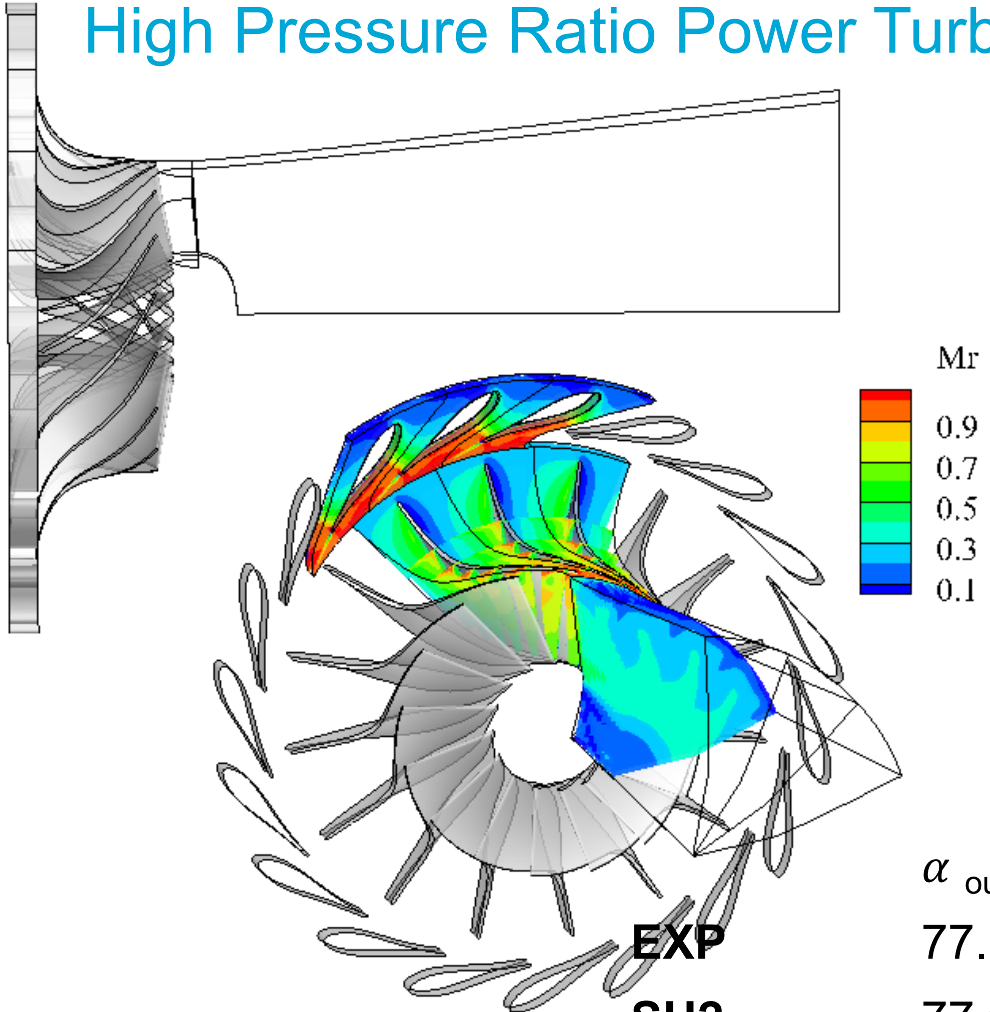


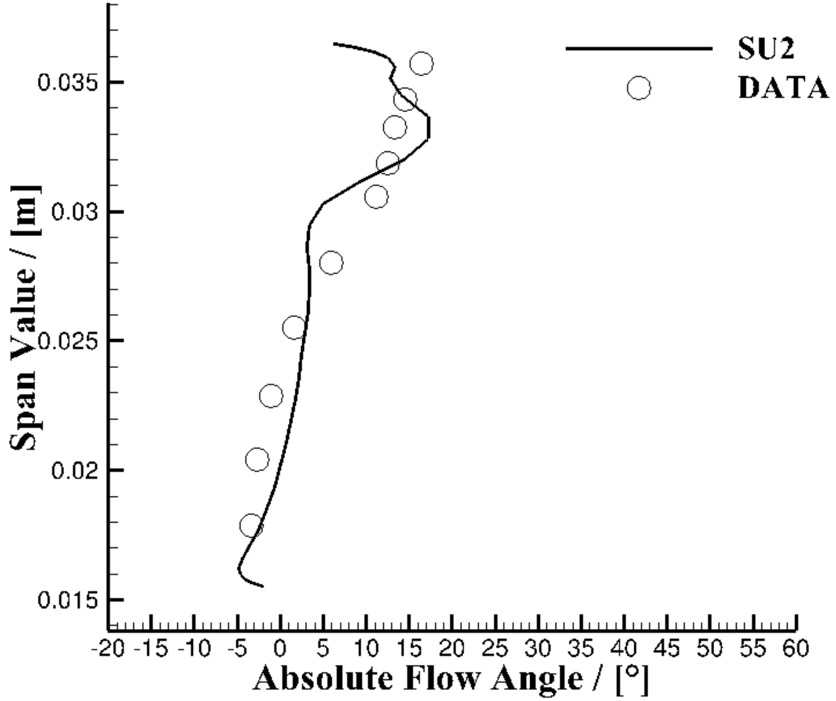




APU Turbine

High Pressure Ratio Power Turbine - Comparison with Experiments

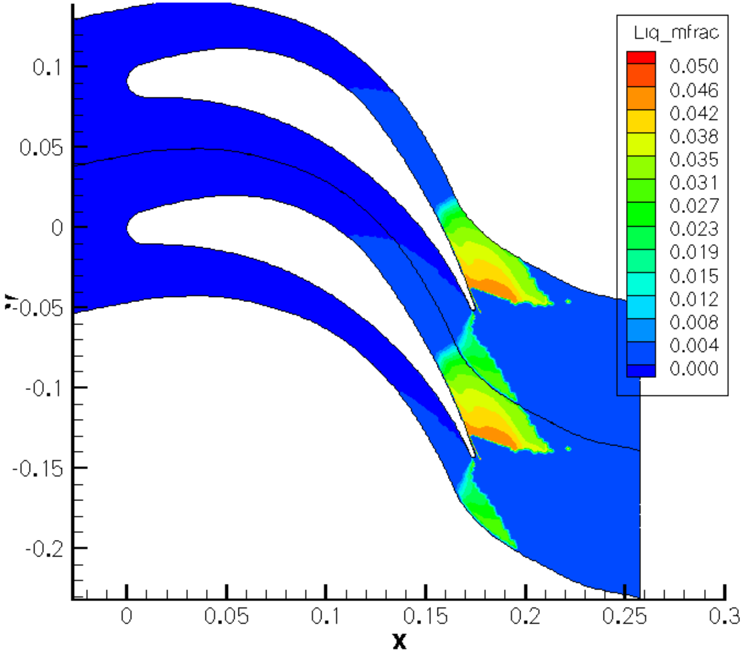




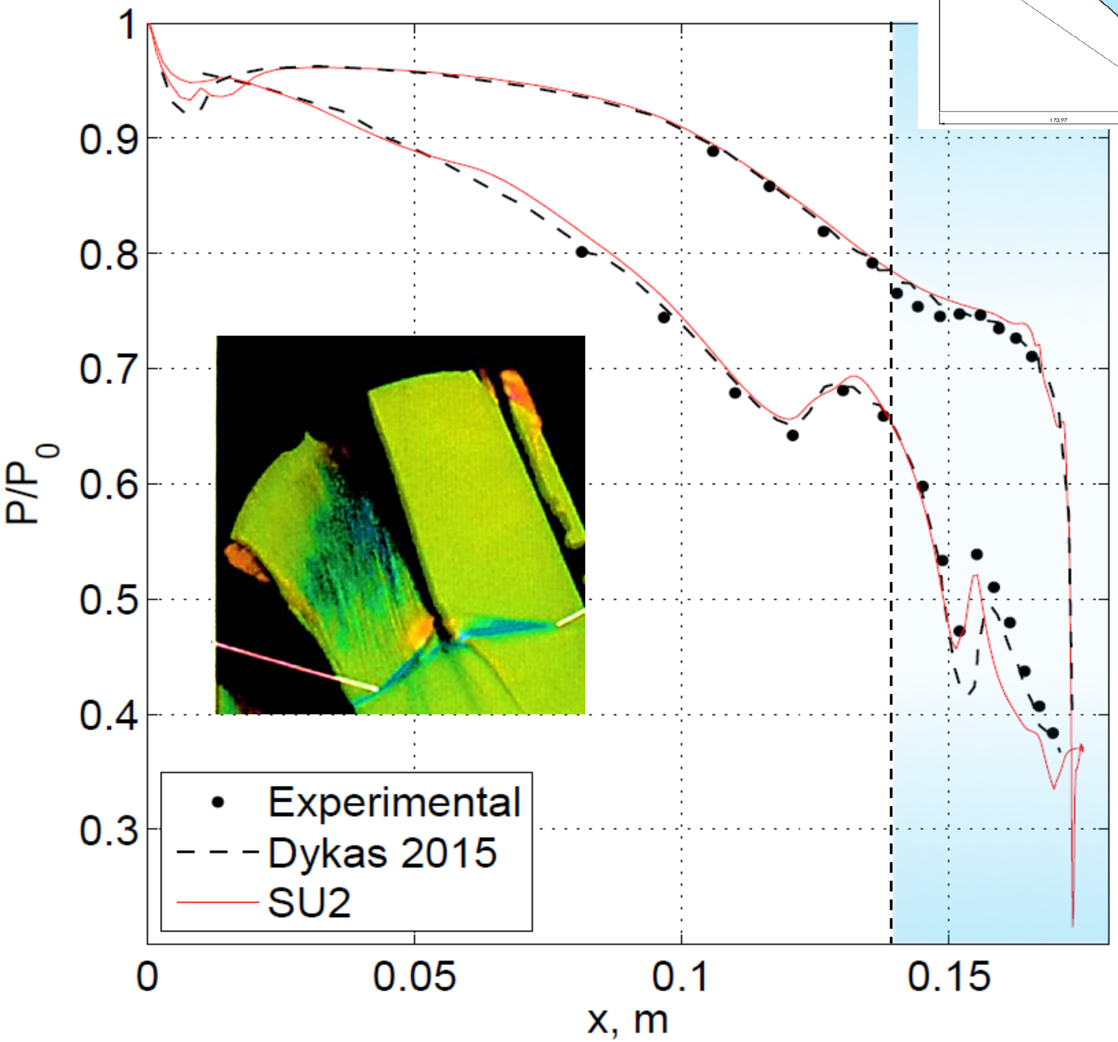
	$\alpha_{out,stator}$ [°]	$M_{out,stator}$ [-]	$\beta_{out,rotor}$ [°]	$M_{out,rotor}$ [-]
EXP	77.7	0.985	56.1	0.710
SU2	77.9	0.982	56.8	0.720
Diff. [%]	0.02	0.3	1.2	1.4

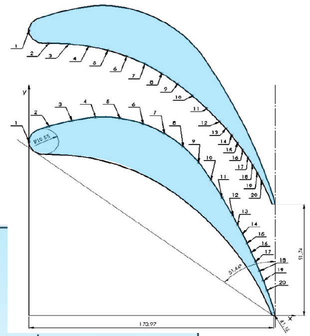
Steam Turbine Cascade

Prediction of metastable condensation



Liquid mass fraction



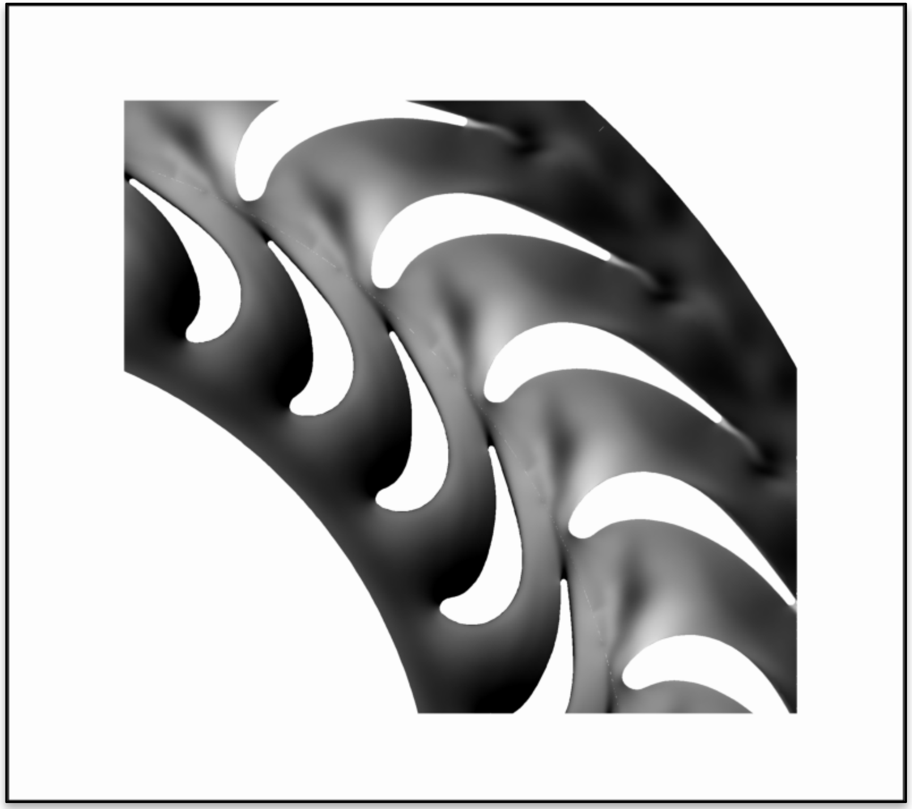


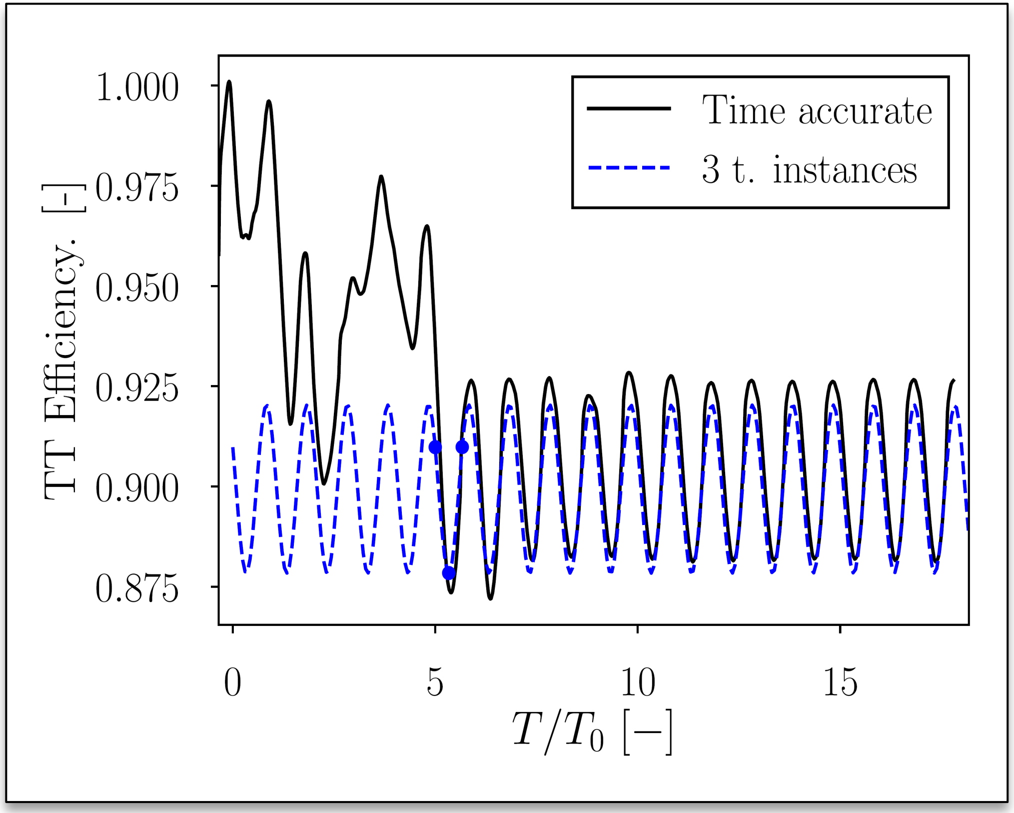
(Some) Paradigmatic Examples

Stator-Rotor Interaction with HB

Radial Outflow ORC Turbine Stage

$$\frac{time_{\mathrm{UNST}}}{time_{\mathrm{HB}}} \cong 5$$

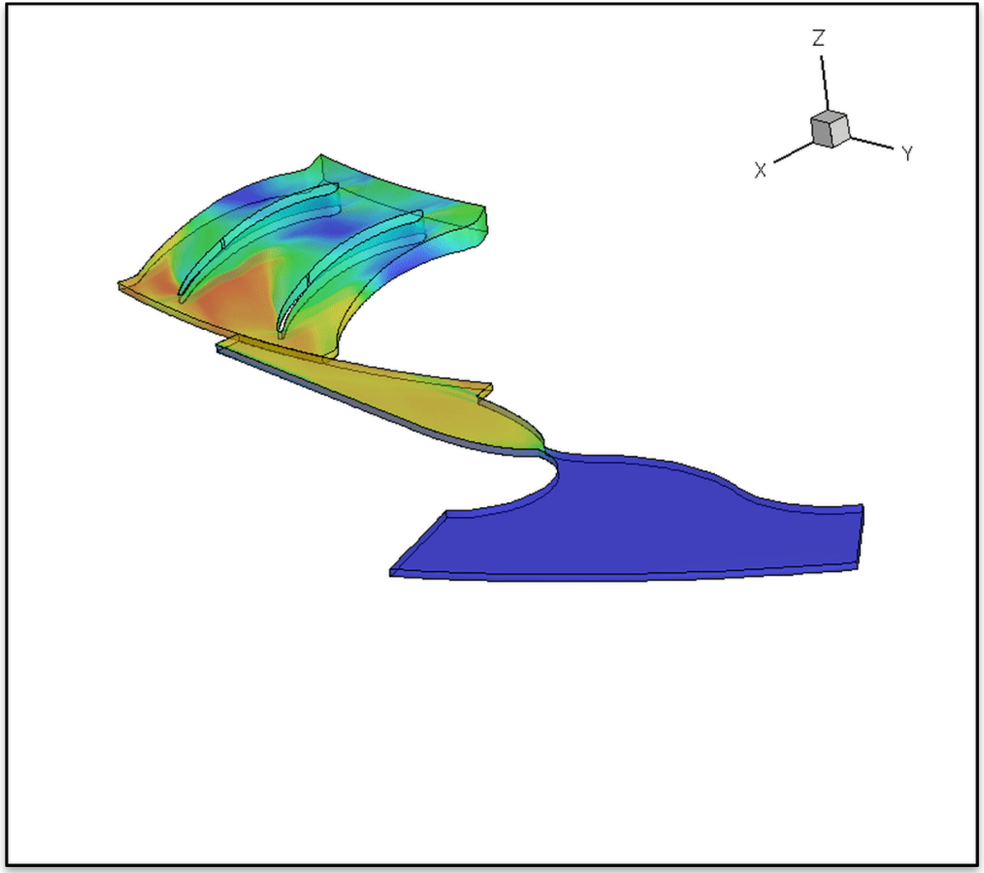


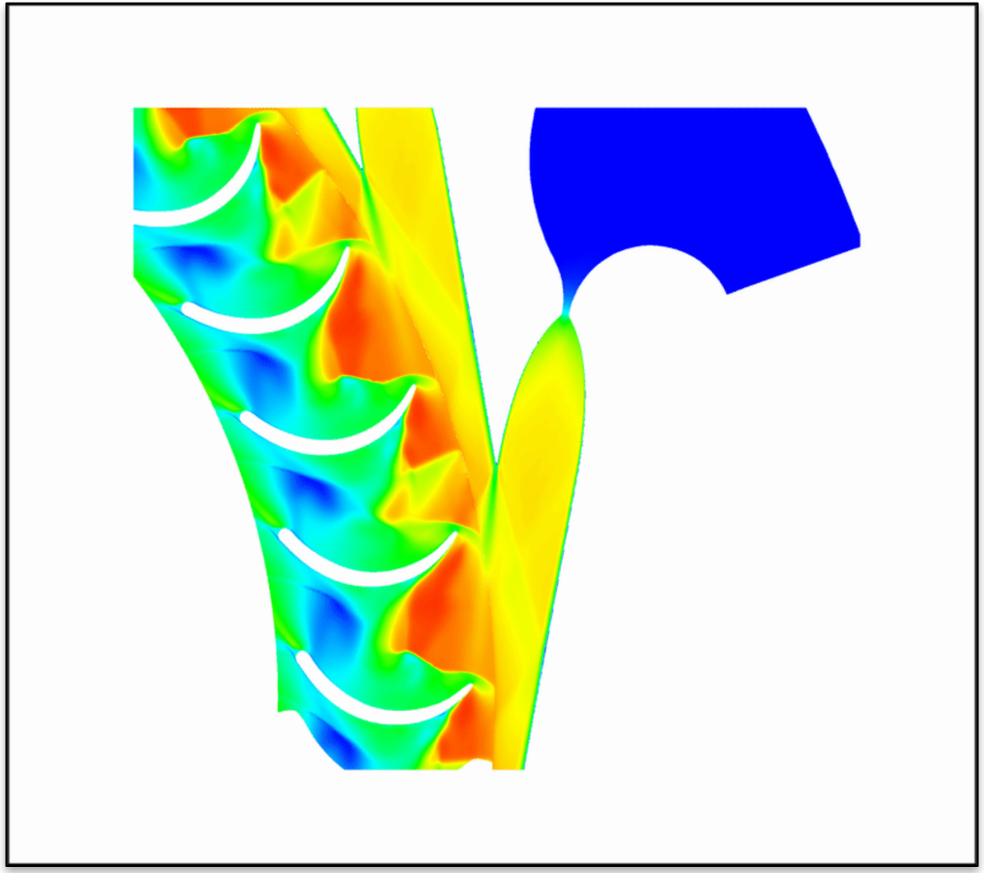


Stator-Rotor Interaction with HB

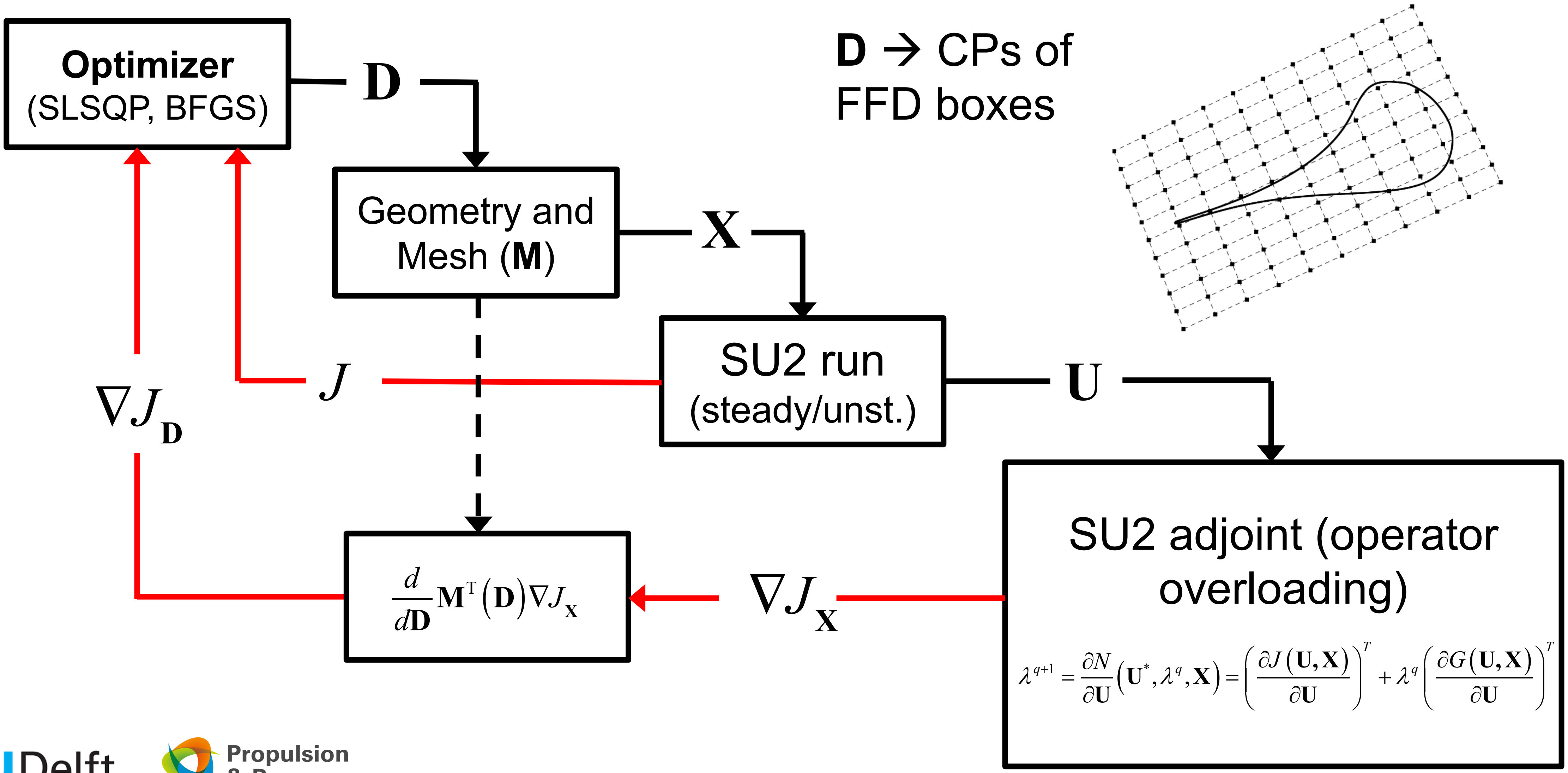
Supersonic ORC Radial-Inflow Turbine, Q3D

$$\frac{time_{\mathrm{UNST}}}{time_{\mathrm{HB}}} \cong 6$$





How We Solve the Turbo Design Problem



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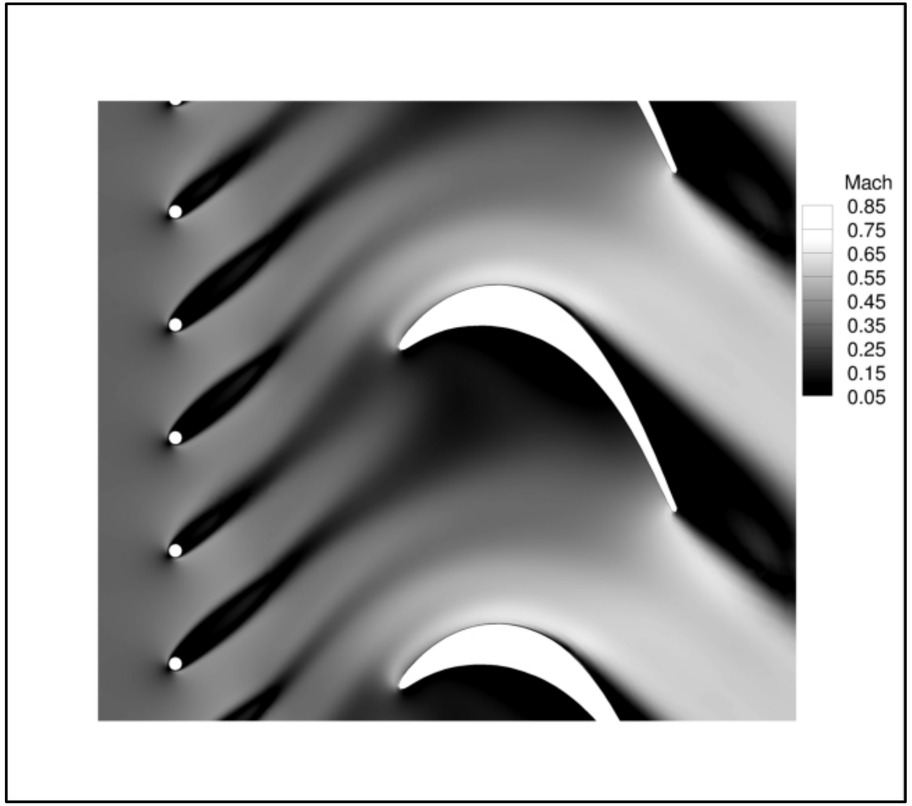
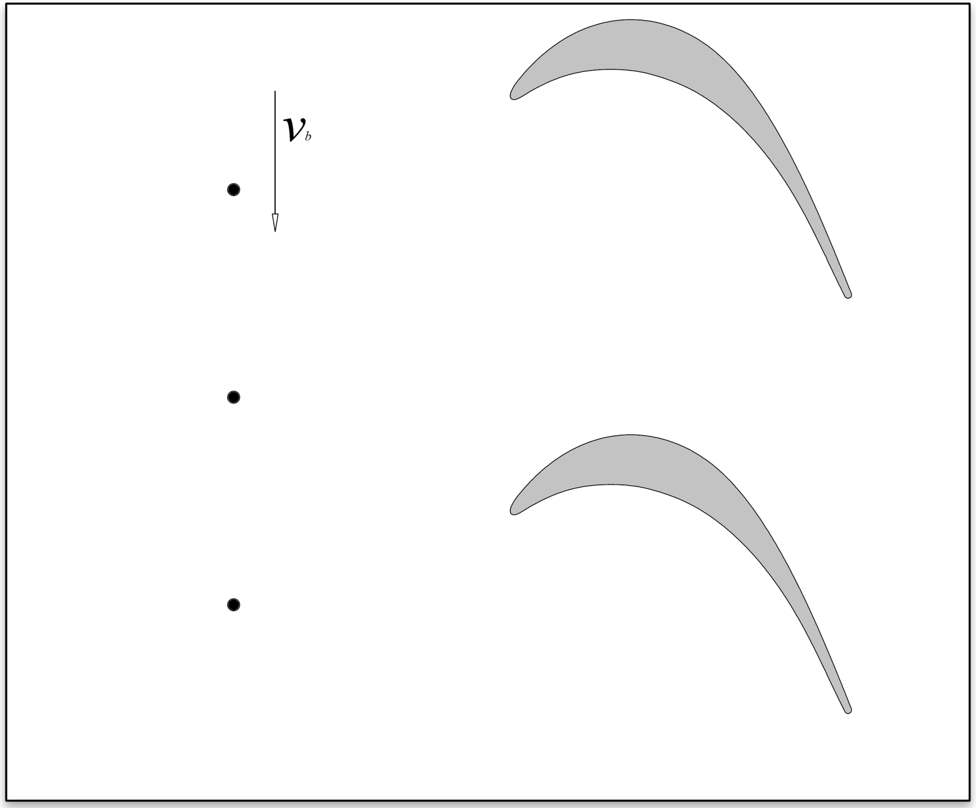
Unsteady Design Problem

Wake-rotor interaction





$$\frac{\text{running time HB}}{\text{running time unsteady}} = 0.3$$

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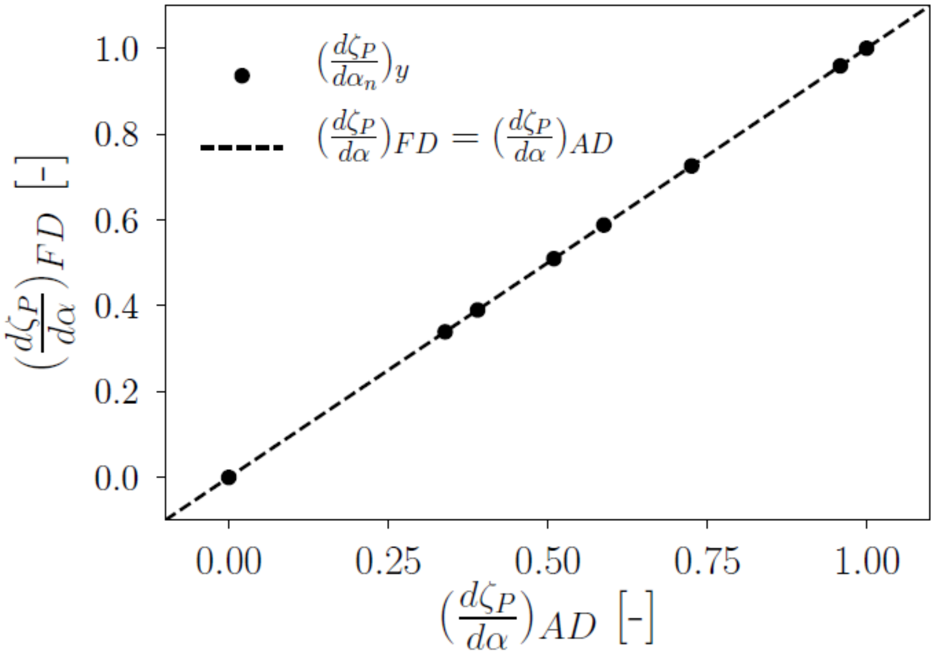
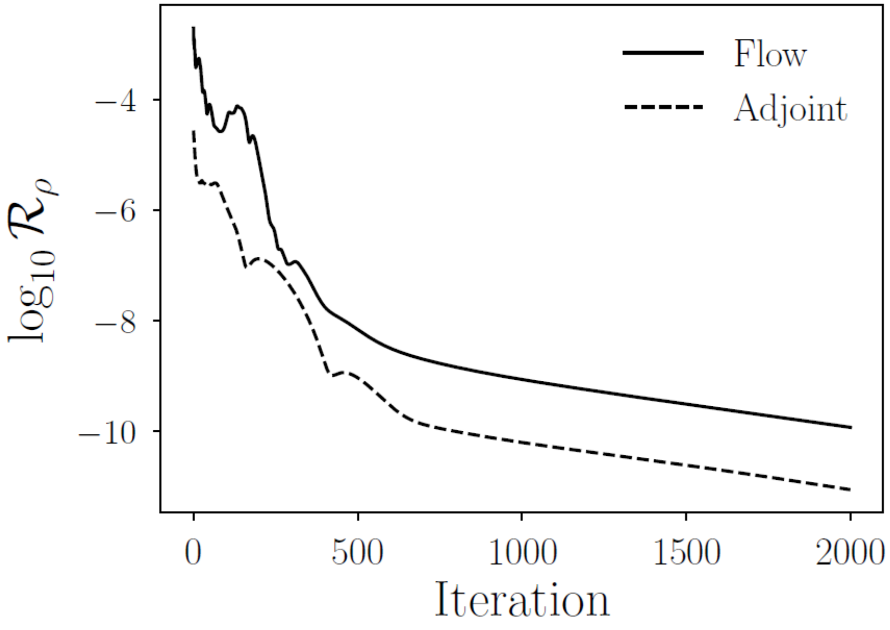
Unsteady Design Problem

Adjoint harmonic balance gradient validation



Gradient validation
(RMSE < 1E-5)



Adjoint vs Flow
convergence rate

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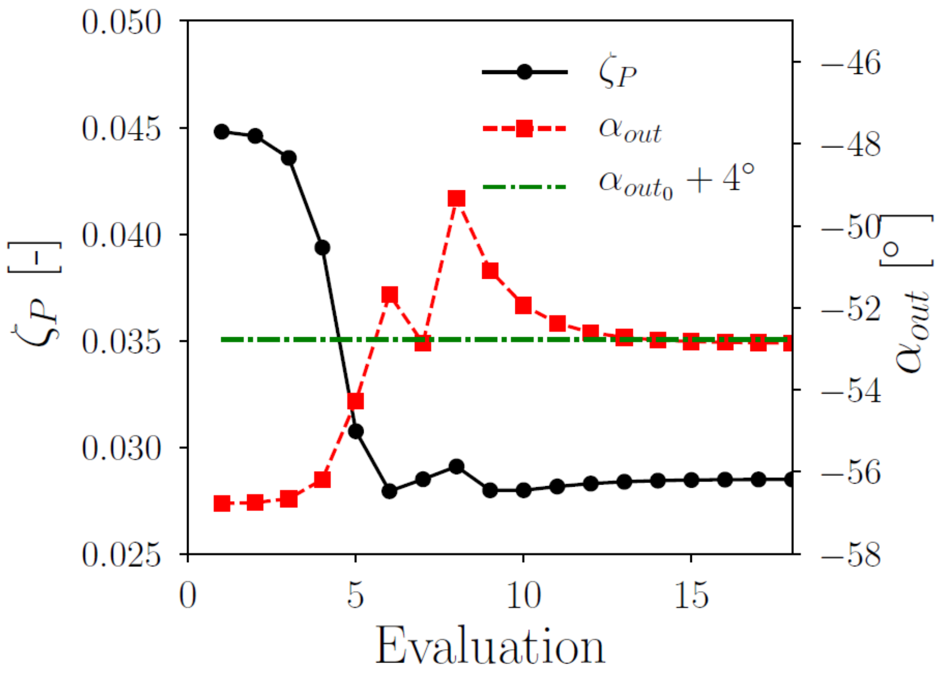
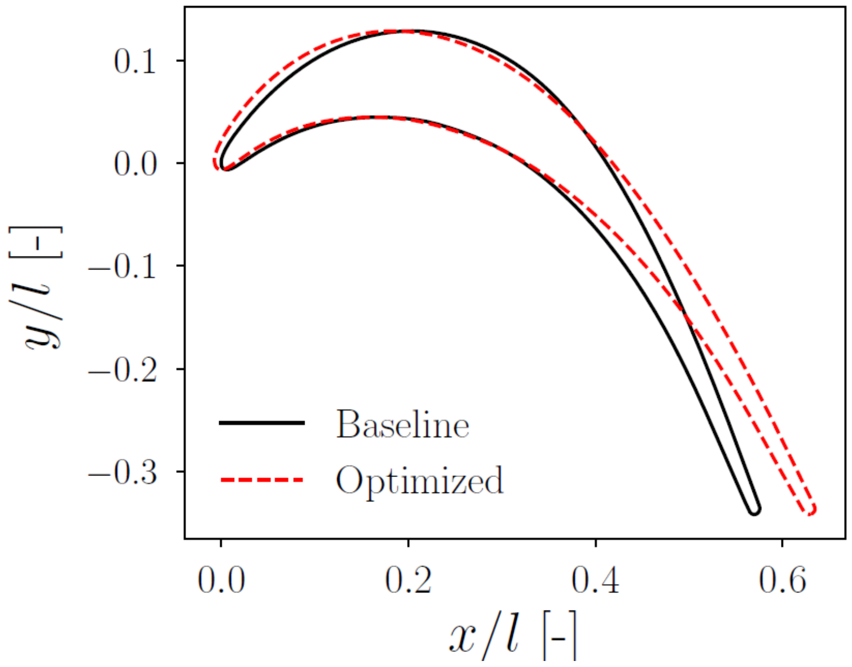
Unsteady Design Problem

Optimization results



Optimization History



Baseline vs Optimized Blade Profile

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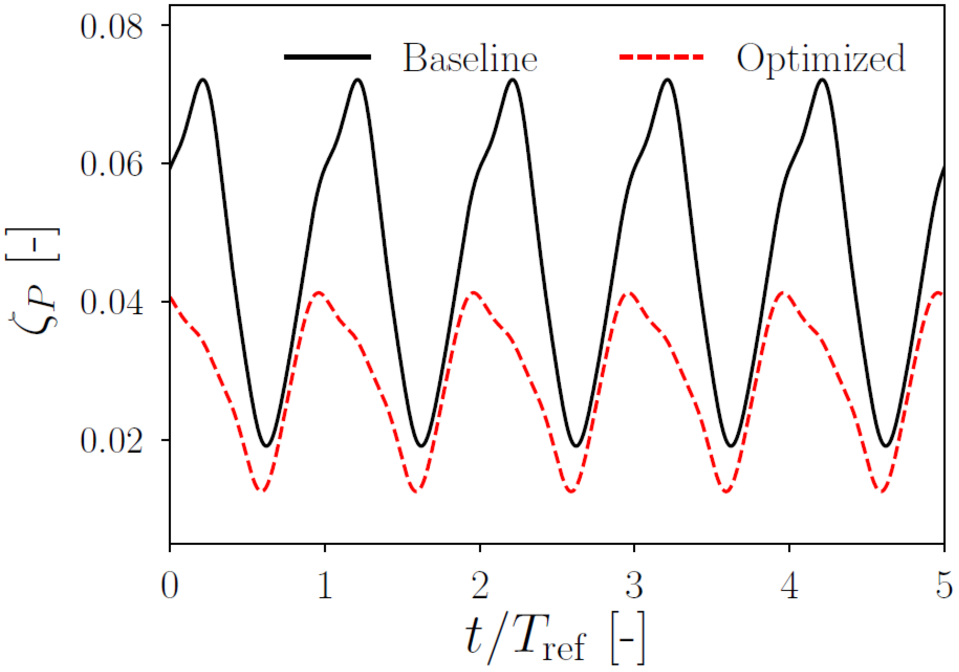
Unsteady Design Problem

Performance gain



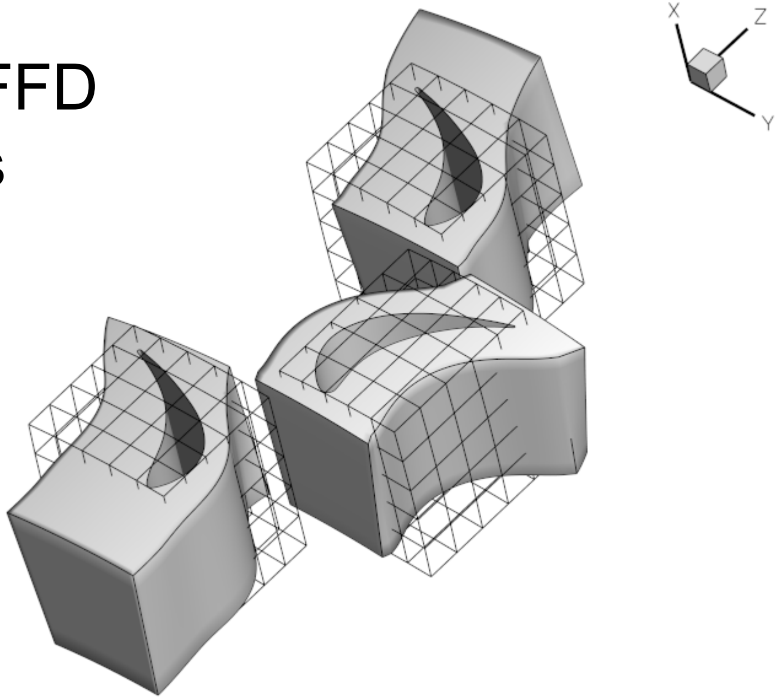
- Mean Loss reduction: ***38%***
- Peak reduction: ***44%***
- Amplitude reduction: ***54%***
- CPU time: ~ ***5* x Steady Opt**.

TUDelft

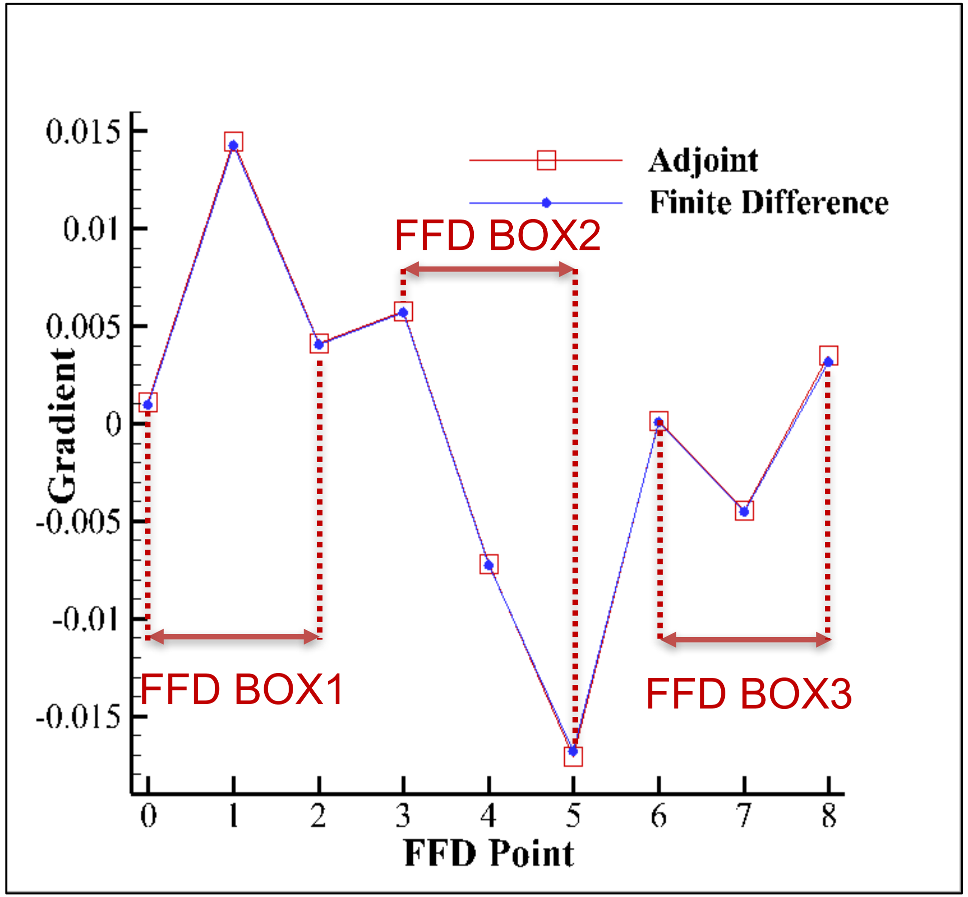
Steady Coupled Design Problem

Mixing-plane gradient validation (obj = stage efficiency)

79 FFD DVs

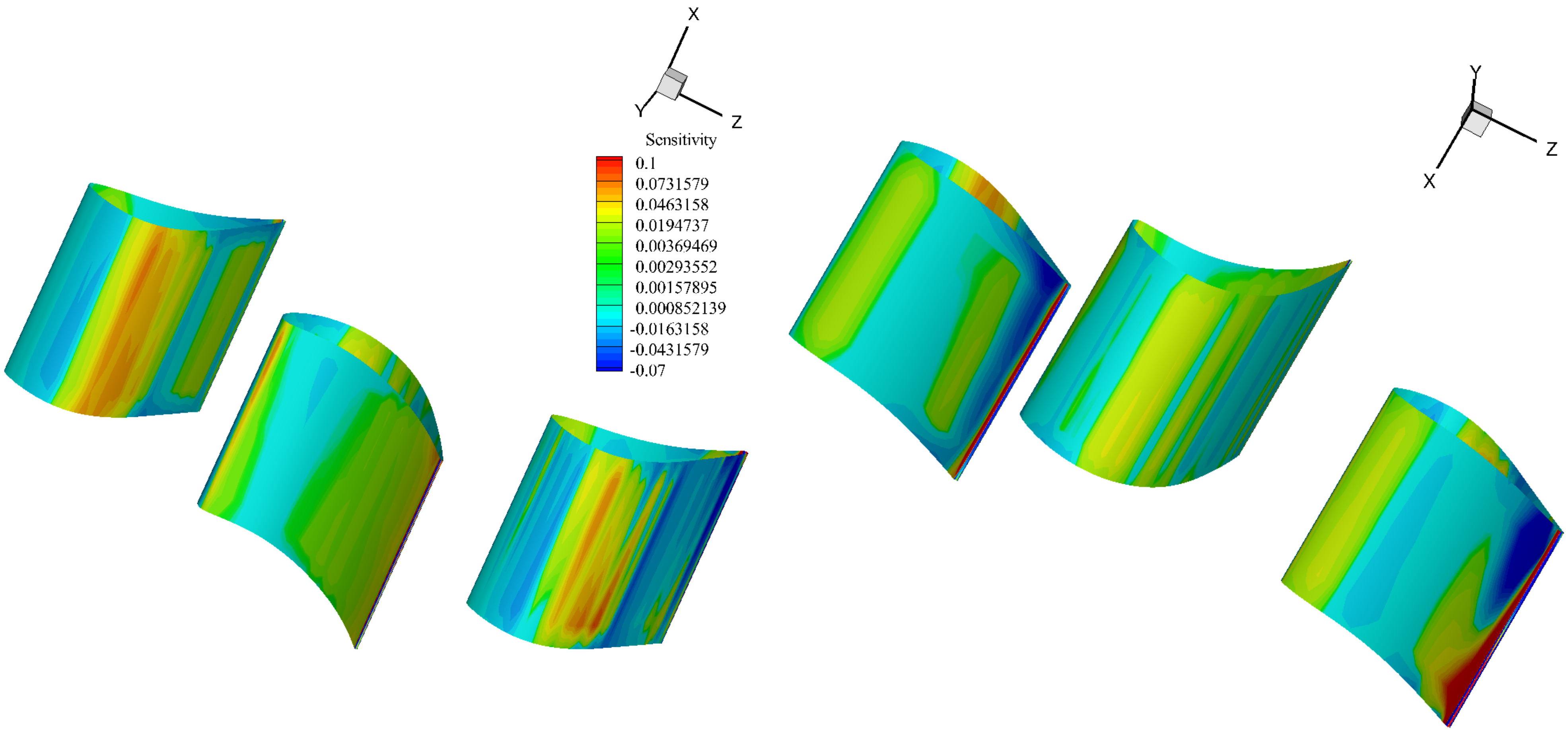


Only 3 points per each FFD Box are selected for the validation



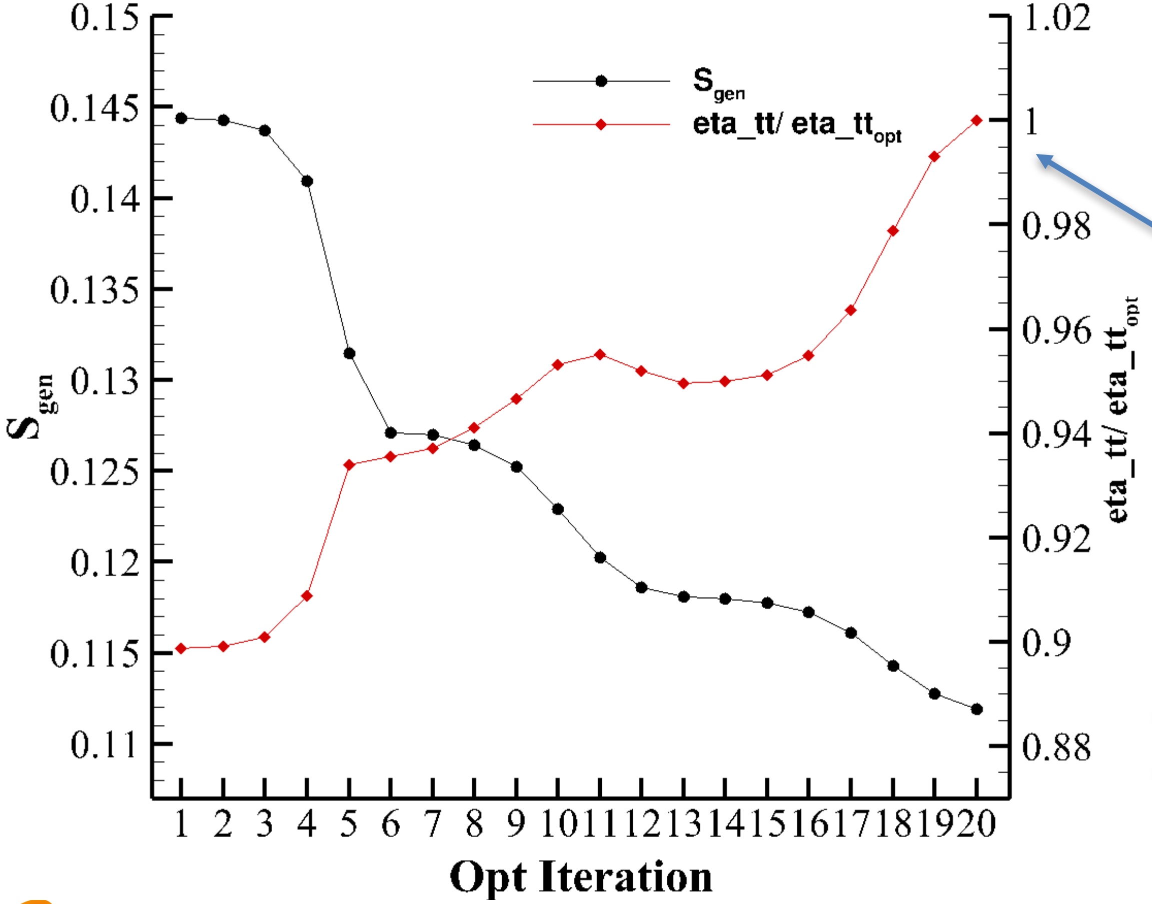
Steady Coupled Design Problem

3D sensitivity of stage efficiency



Steady Coupled Design Problem

Optimization results



- Efficiency gain: ***15%***
- CPU time: 4 hours (100k nodes per row)

baseline
optimal

Take-Aways

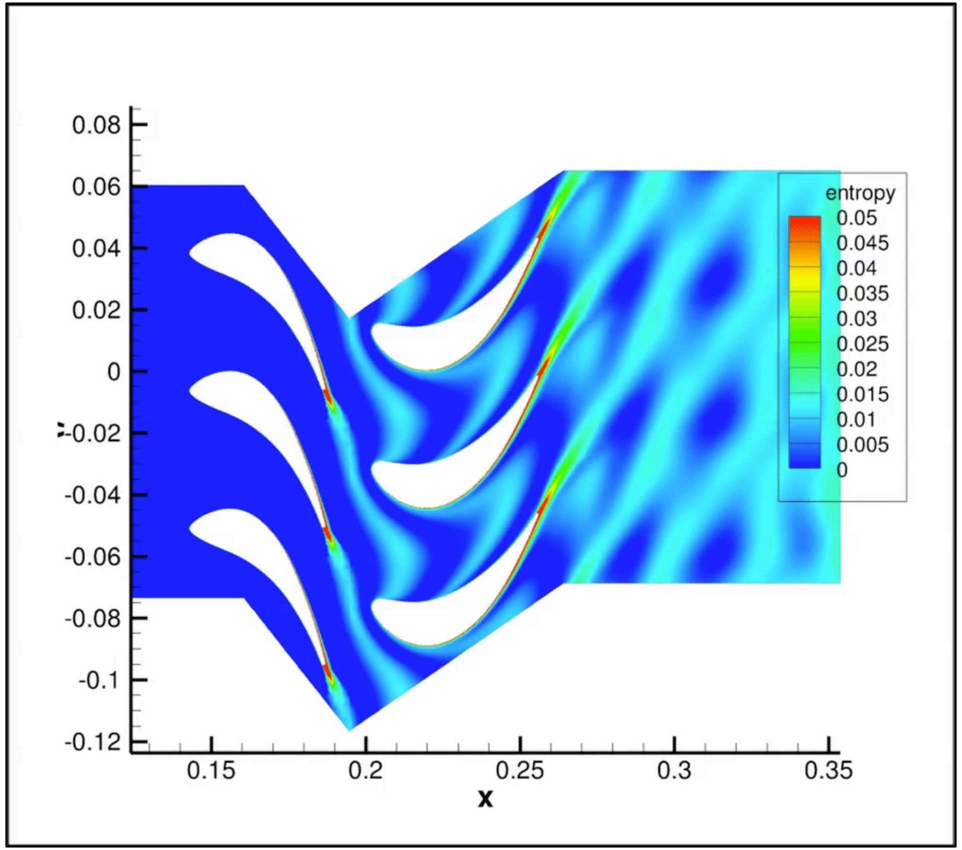
- SU2 accurate for (compressible, NICFD) turbomachinery flows
- First-ever fully turbulent unsteady optimization
- Multi-row design at manageable cost now possible
- Lots of modeling and adjoint-related work remains

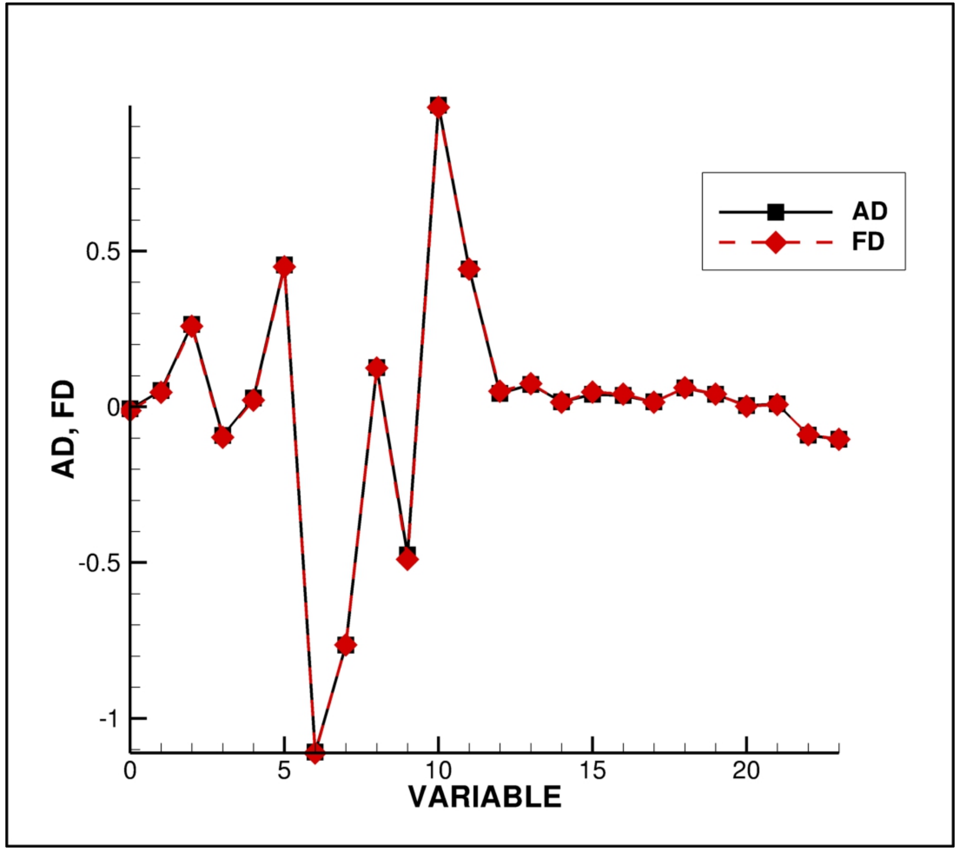
Future…

- Release of "turboSU2" (6.0)
- Engage further turbomachinery companies and research institutes
- Partner with other (new) groups to extend capabilities
- Become reference for innovation in automated turbomachinery design

Next: Unsteady Stator-Rotor Design

HB for Modeling and Design of Multiple Rows

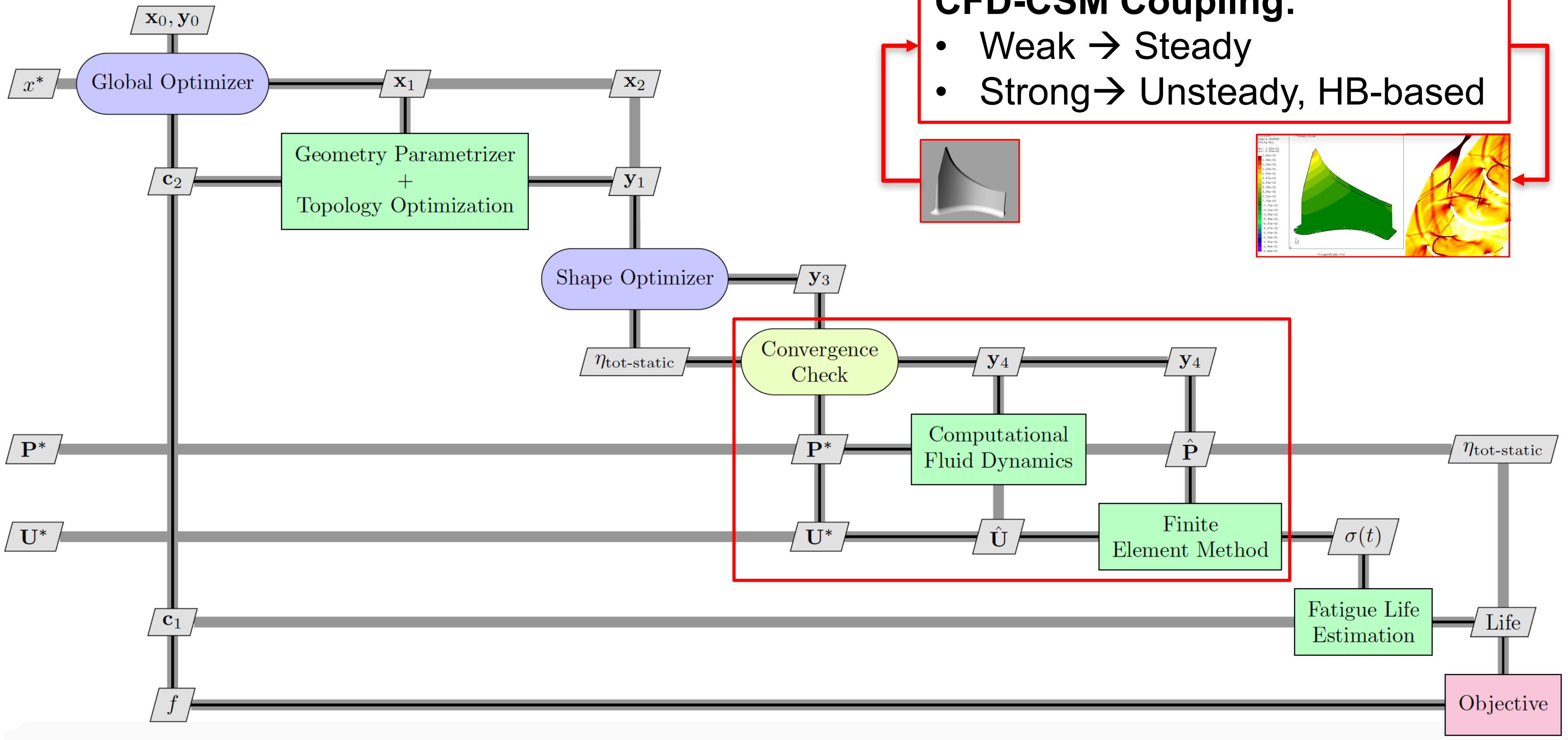




Next: CAD-based MDO Design

SU2 + OpenFEM with adjoints

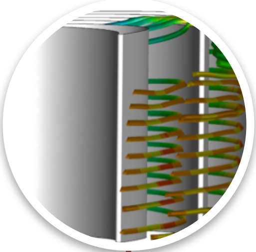
CFD-CSM Coupling:
- Weak → Steady
- Strong→ Unsteady, HB-based



Further info upon request @
m.pini@tudelft.nl

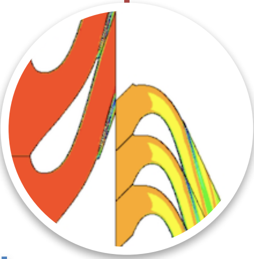
Development Roadmap

SU2 for Turbomachinery

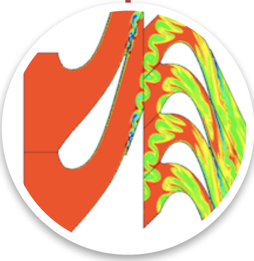


Steady-state computations

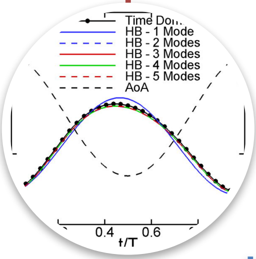
Unsteady computations



Mixing-Plane (DONE!)



Time-accurate multi-row (ONGOING)



Harmonic Balance (ONGOING)

Flow + Adjoint!

Governing Equations for NICFD

Inviscid equations for mono-component fluid at chemical and thermodynamic equilibrium

$$\begin{cases} \partial_t \rho + \nabla \cdot (\rho \boldsymbol{u}) = 0, \\ \partial_t (\rho \boldsymbol{u}) + \nabla \cdot (\rho \boldsymbol{u} \otimes \boldsymbol{u} + P) = 0, \\ \partial_t E^{\mathrm{t}} + \nabla \cdot [(E^{\mathrm{t}} + P)\, \boldsymbol{u}] = 0, \end{cases}$$

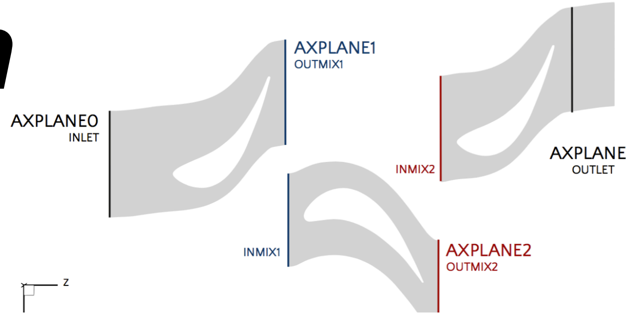
→

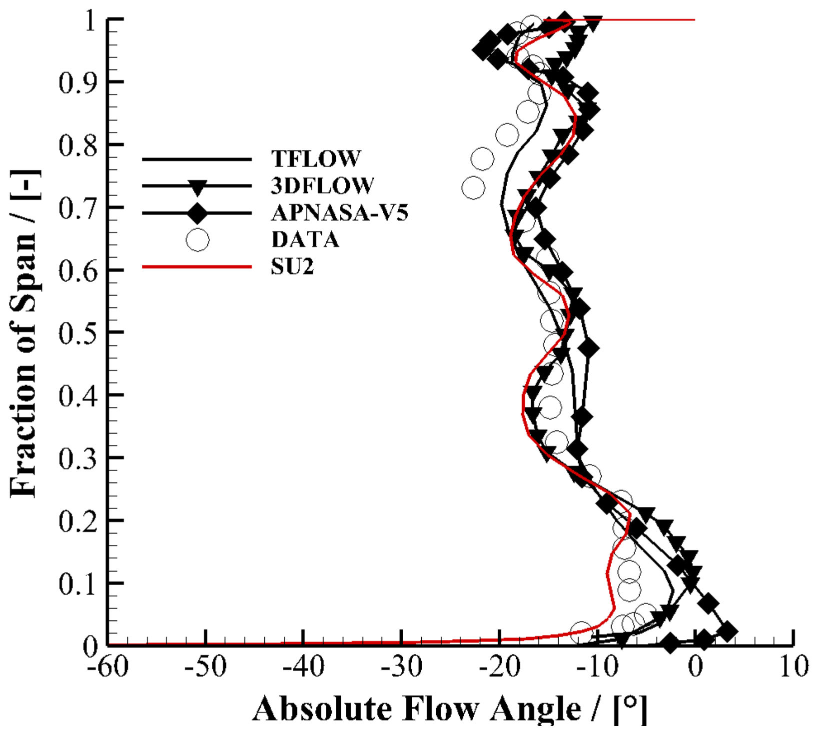
$$E^{\mathrm{t}} = \rho e + \frac{1}{2} \rho\, |\boldsymbol{u}|^2$$

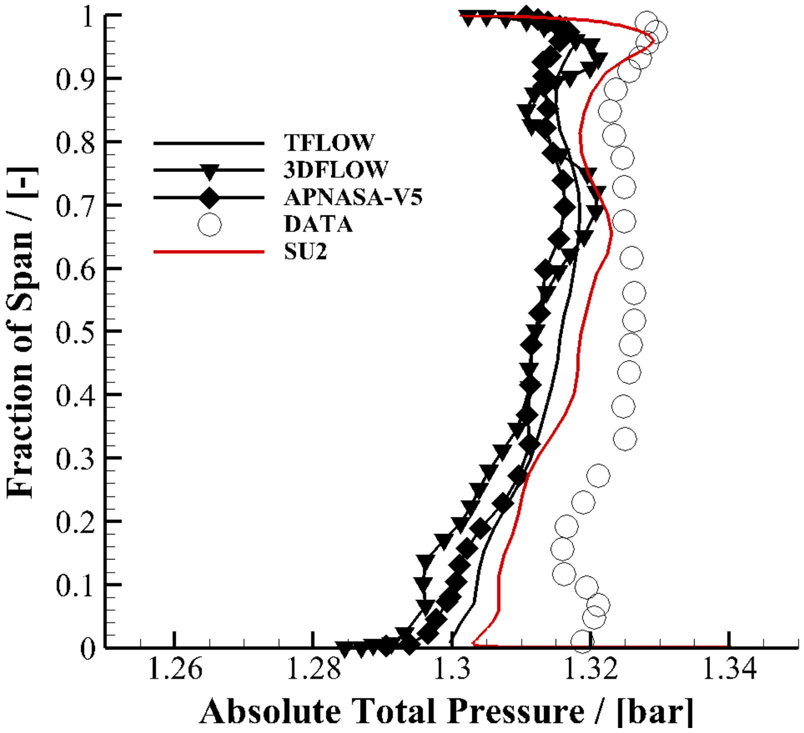
We need a thermodynamic closure → $P = P(\rho, e) = (\gamma - 1)\rho e$ Perfect gas

Verification and Validation

Aachen Turbine: plane 2



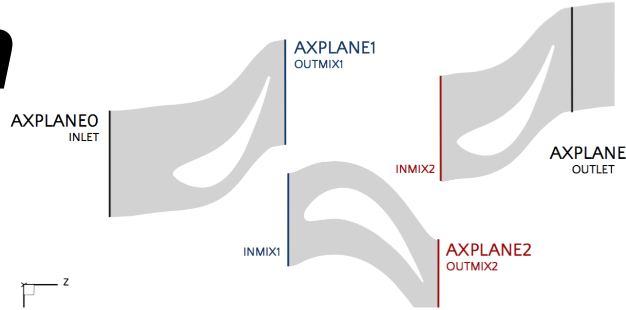


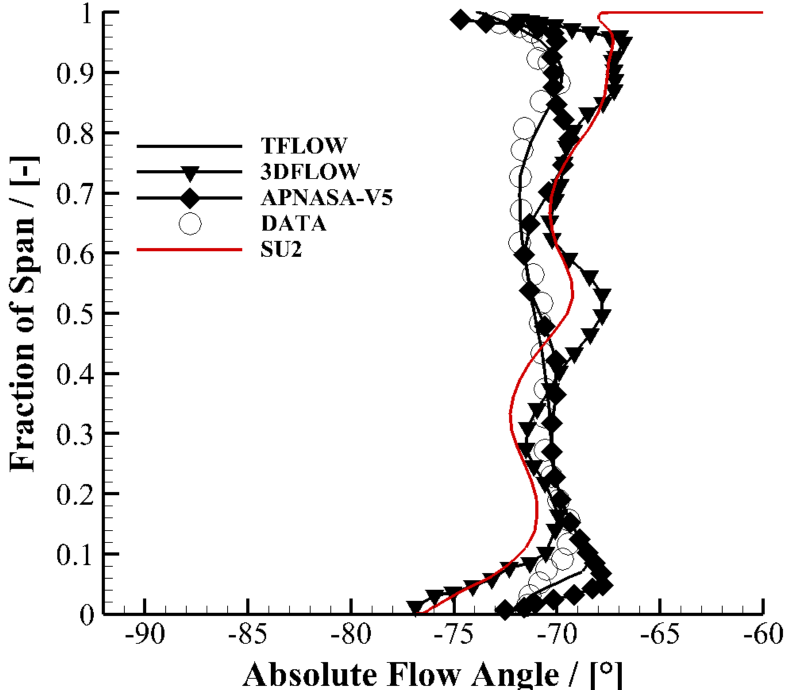


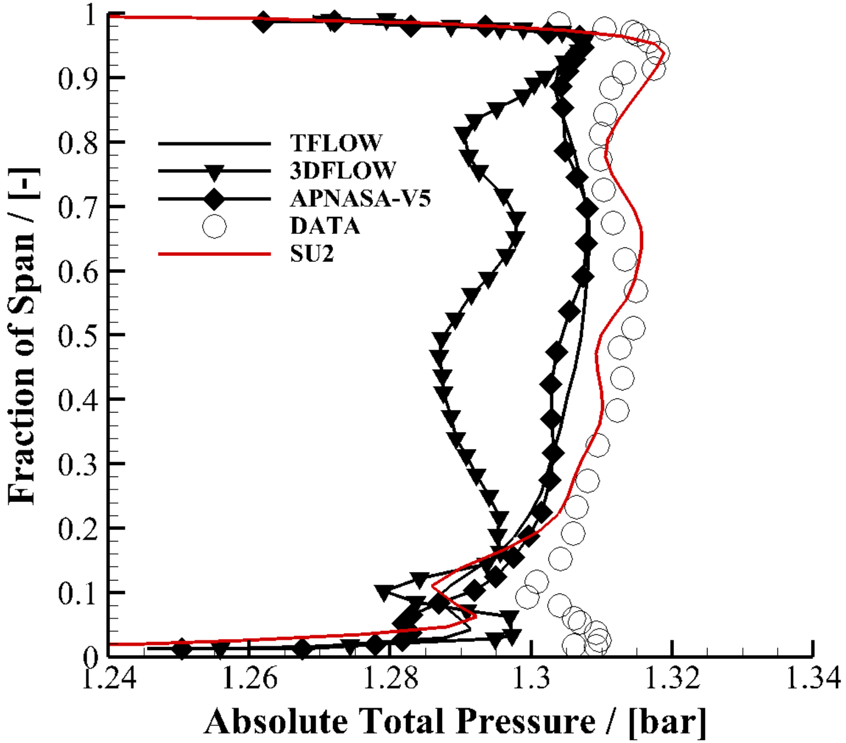
Source → *Yao et al.*, "Development and Validation of a Massively Parallel Flow Solver for Turbomachinery Flows", 2001

Verification and Validation

Aachen Turbine: plane 3

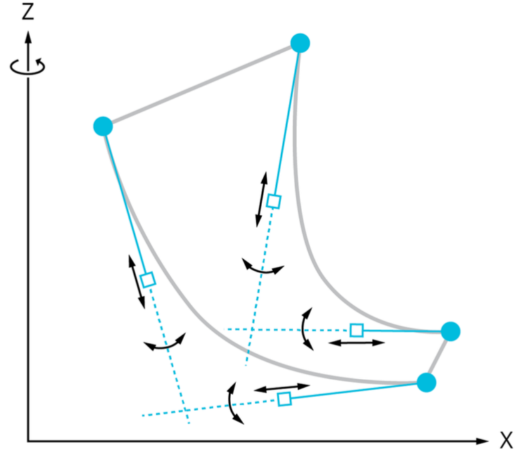






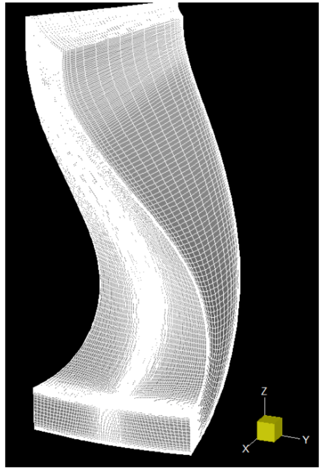
Source → *Yao et al.*, "Development and Validation of a Massively Parallel Flow Solver for Turbomachinery Flows", 2001

Geometry and Meshing



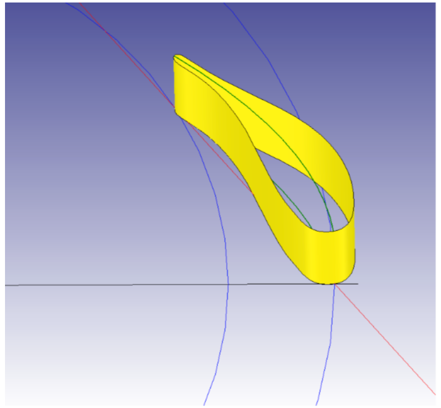
OptiBlade

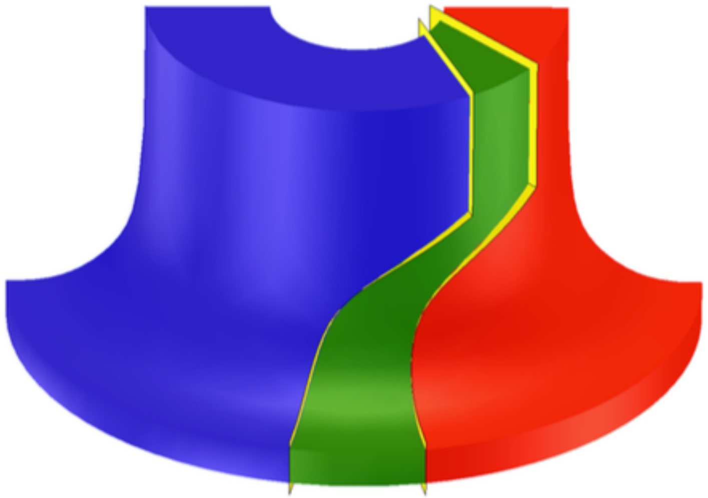
- Based on OC
- Parametric
- Axial and Radial

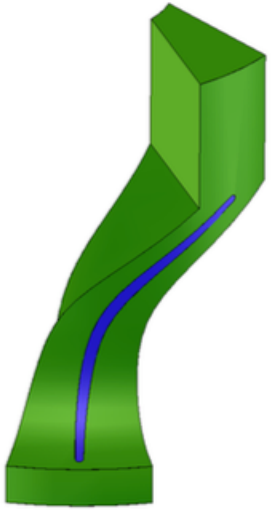


Meshing

- Autogrid
- Turbogrid
- Salome







Steady Design of Turbine Cascades

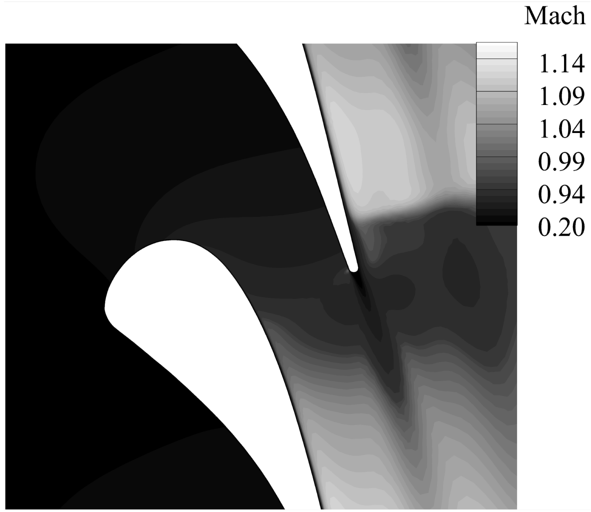
Fluid: Siloxane MDM

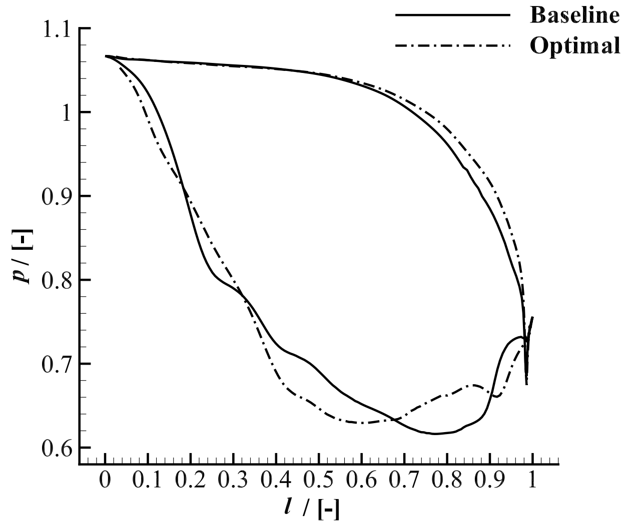
$$\min \quad J = z_{p,tot}$$

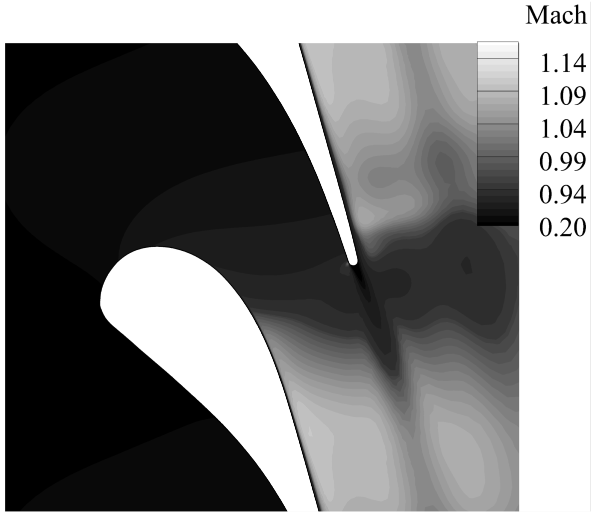
$$\text{subject to} \quad \beta_{out} > 74^{\circ}$$

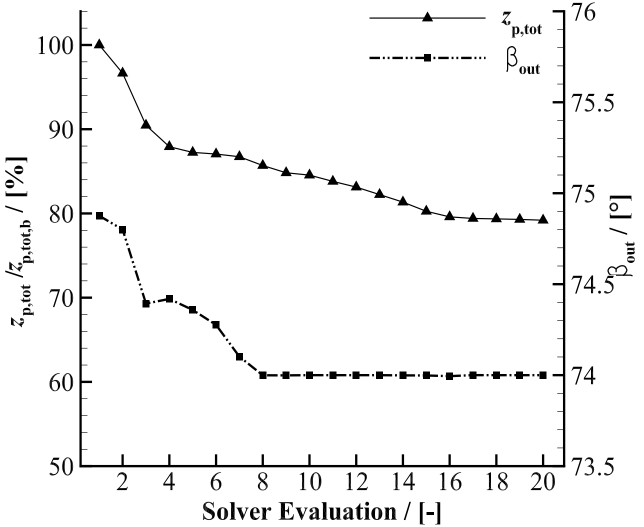
$$\frac{\text{running time adjoint}}{\text{running time flow}} = 1.3$$

$$\frac{\text{memory adjoint}}{\text{memory flow}} = 6 \div 8$$









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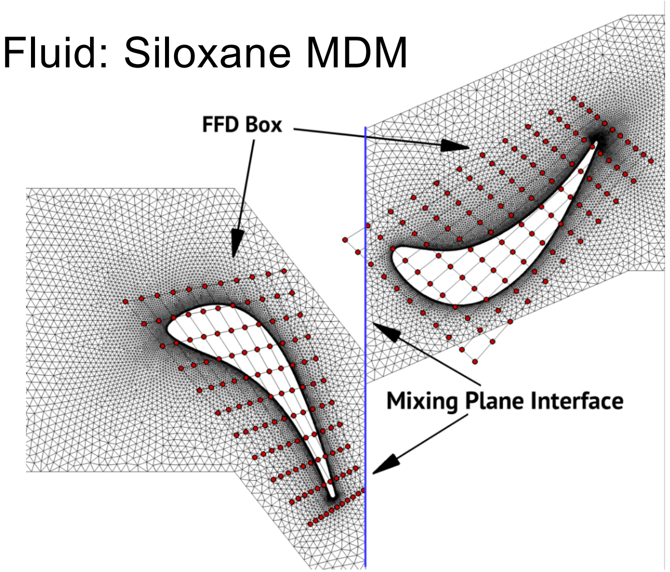
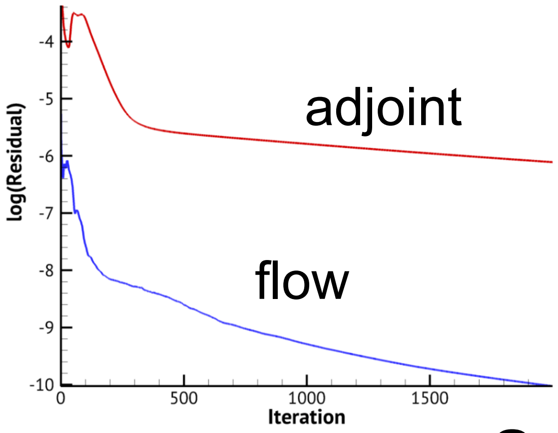
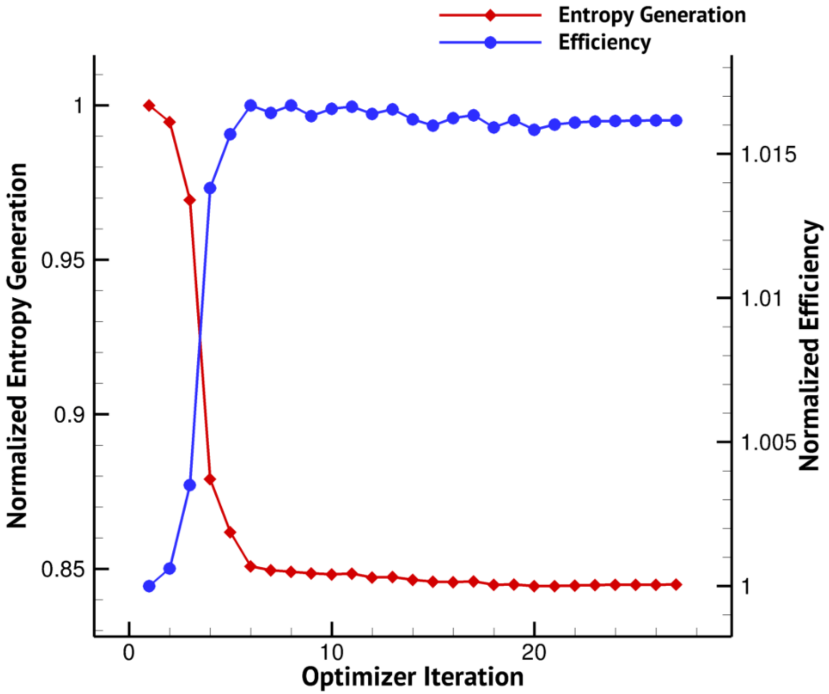
2D Steady Design of Turbine Stages

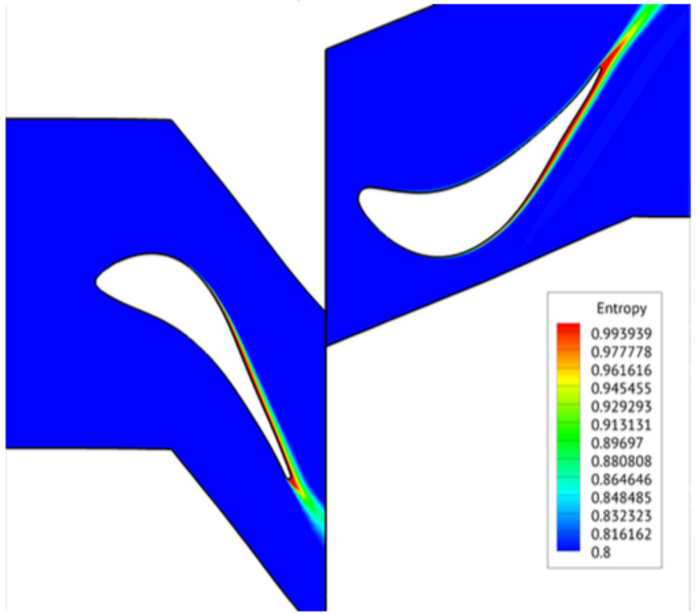
Fluid: Siloxane MDM







Optimized



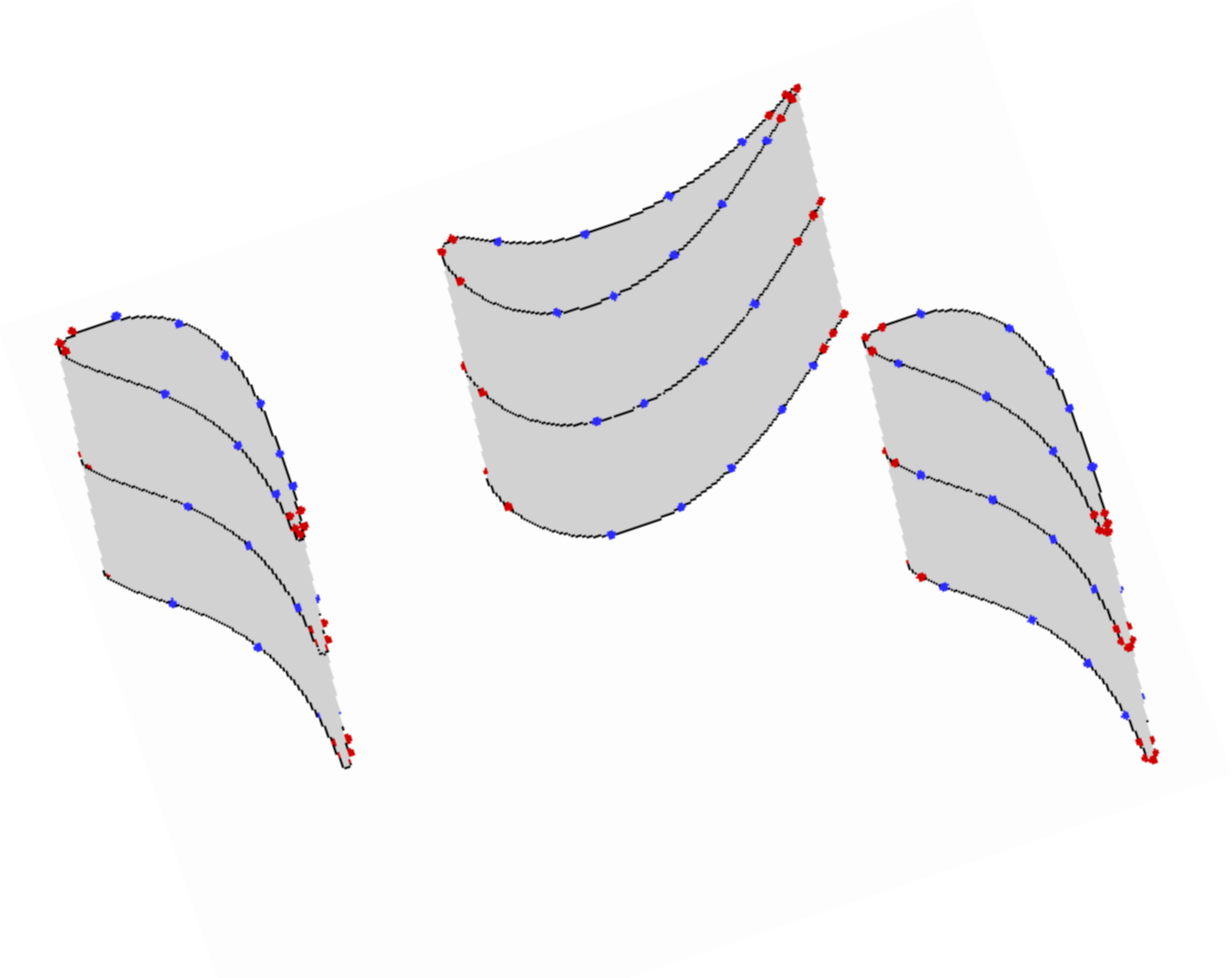
$$\frac{\text{running time adjoint}}{\text{running time flow}} = 1.0 \qquad \frac{\text{memory adjoint}}{\text{memory flow}} = 4.5$$

Successful verification of the discrete adjoint mixing-plane

Steady Coupled Design Problem

Parametrization with direct FFD, 79 DVs

3 pilot profile x blade



72 x ● Geometrical Constraint to preserve LE and TE round shape

79 x ● Design Variables

Method of Moments

- 4 Transport Equations for Moments

$$\begin{cases} \frac{\partial}{\partial t}(\rho) + \frac{\partial}{\partial x}(\rho v) = S_c \\ \frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}\left(\rho v^2 + P\right) = S_c v \\ \frac{\partial}{\partial t}(\rho e_0) + \frac{\partial}{\partial x}(\rho h_0 v) = S_c h_{0,l} \end{cases}$$

S_c *Mass exchange at interface*

J_*, G *Nucleation, growth rate*

$$\begin{cases} \frac{\partial}{\partial t}(\rho_m \mu_0) + \frac{\partial}{\partial x}(\rho_m \mu_0 v_m) = \rho_m J_* \\ \frac{\partial}{\partial t}(\rho_m \mu_1) + \frac{\partial}{\partial x}(\rho_m \mu_1 v_m) = \rho_m J_* r_* + G\mu_0 \\ \frac{\partial}{\partial t}(\rho_m \mu_2) + \frac{\partial}{\partial x}(\rho_m \mu_2 v_m) = \rho_m J_* r_*^2 + 2G\mu_1 \\ \frac{\partial}{\partial t}(\rho_m \mu_3) + \frac{\partial}{\partial x}(\rho_m \mu_3 v_m) = \rho_m J_* r_*^3 + 3G\mu_2 \end{cases}$$

- ✓ Upwind flux, $1^{st} - 2^{nd}$ order
- ✓ Implicit time integration
- ✓ Segregated approach

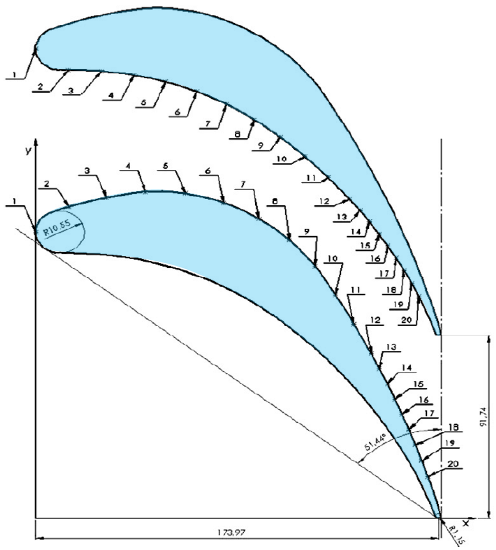
$$\mu_j = \int_0^\infty r^j \frac{\partial N}{\partial r} dr \longrightarrow \frac{\partial}{\partial t}(\rho_m \mu_j) + \frac{\partial}{\partial x}(\rho_m \mu_j v_m) = j\int_0^\infty \rho_m r^{j-1} G \frac{\partial N}{\partial r} dr + \rho_m J_* R_*^j$$

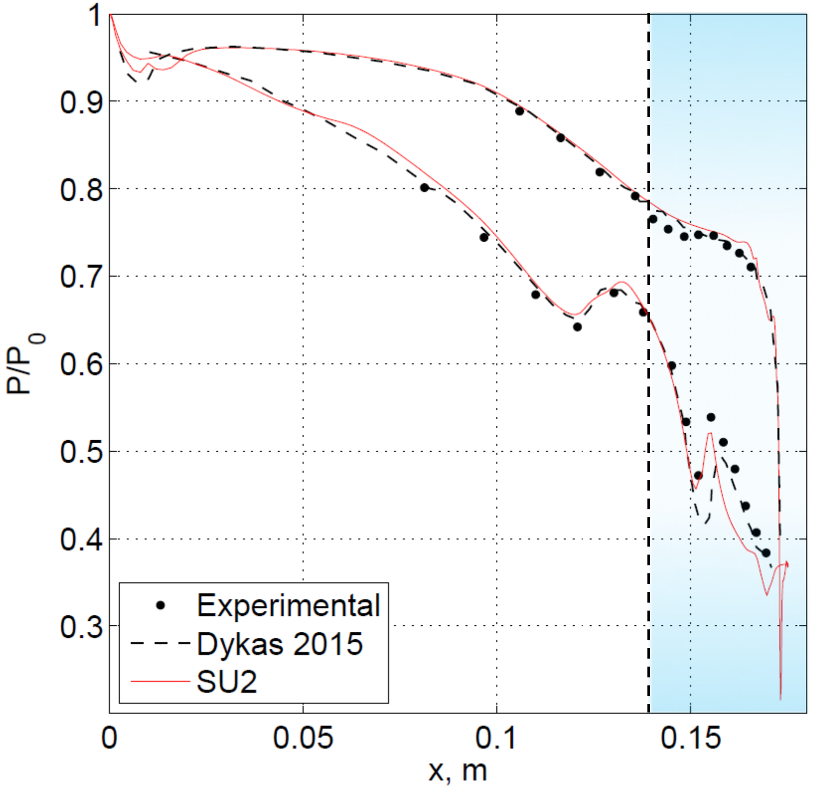
$$\mu_0 = N_{tot} \quad \mu_1 = N_{tot} R \quad \mu_2 = N_{tot} R^2 \quad \mu_3 = N_{tot} R^3$$

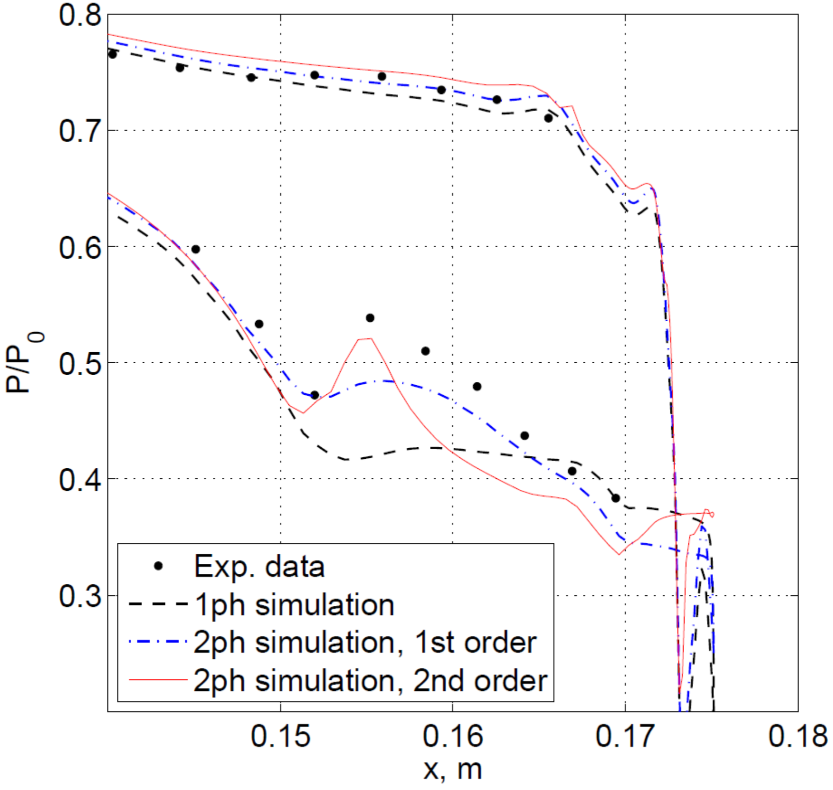
Metastable Condensation with MoM

Cascade [2]

T_0 = 373.15 K
P_0 = 0.89 bar
P_{out} = 0.39 bar







[2] Dykas, S. et al., 2015. Experimental study of condensing steam flow in nozzles and linear blade cascade. International Journal of Heat and Mass Transfer, 80, pp.50–57

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