Unsteady Optimization with SU2: Application to Turbomachinery Design

An overview

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SUII, University of Strathclyde, Glasgow

Outline

- Introduction and past work
- Current status of development
- Outlook and ongoing work
- Conclusions

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Introduction

Why Unsteady Design?

- Sometimes a “necessity” (e.g. open rotors, rotorcraft, turbomachinery, propellers…)
- A step forward in performance gain over steady design methods
- Pathway to MDO (e.g. fluid-structure, noise, …)

Introduction

Methods for unsteady optimization in SU2

- Time-domain harmonic balance discrete adjoint
- Time-accurate discrete adjoint
- Time-accurate continuous adjoint

Introduction

Methods for unsteady optimization in SU2

- **Time-domain harmonic balance discrete adjoint**
- Time-accurate discrete adjoint
- Time-accurate continuous adjoint

HB Method in a Nutshell

The Open-Source CFD Code

$$\Omega \frac{\Delta \mathbf{U}^{q+1}}{\Delta \tau} + \Omega \mathcal{D}_t(\mathbf{U}^{q+1}) + \mathcal{R}(\mathbf{U}^{q+1}) = 0$$

Source Term

$$\mathcal{D}_t(\tilde{\mathbf{U}}) = \mathbf{E}^{-1}\mathbf{D}\mathbf{E}$$

- Time derivative → Matrix multiplication (time independent!)

Time-Domain Implementation

- Unsteady → Steady State + Source terms
- Solve just for blade passing frequency harmonics
- DFT to obtain interpolated time accurate solution

SU2
The Open-Source CFD Code

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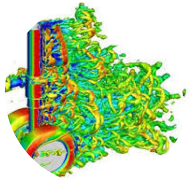
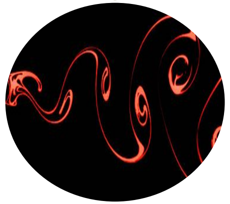
Introduction

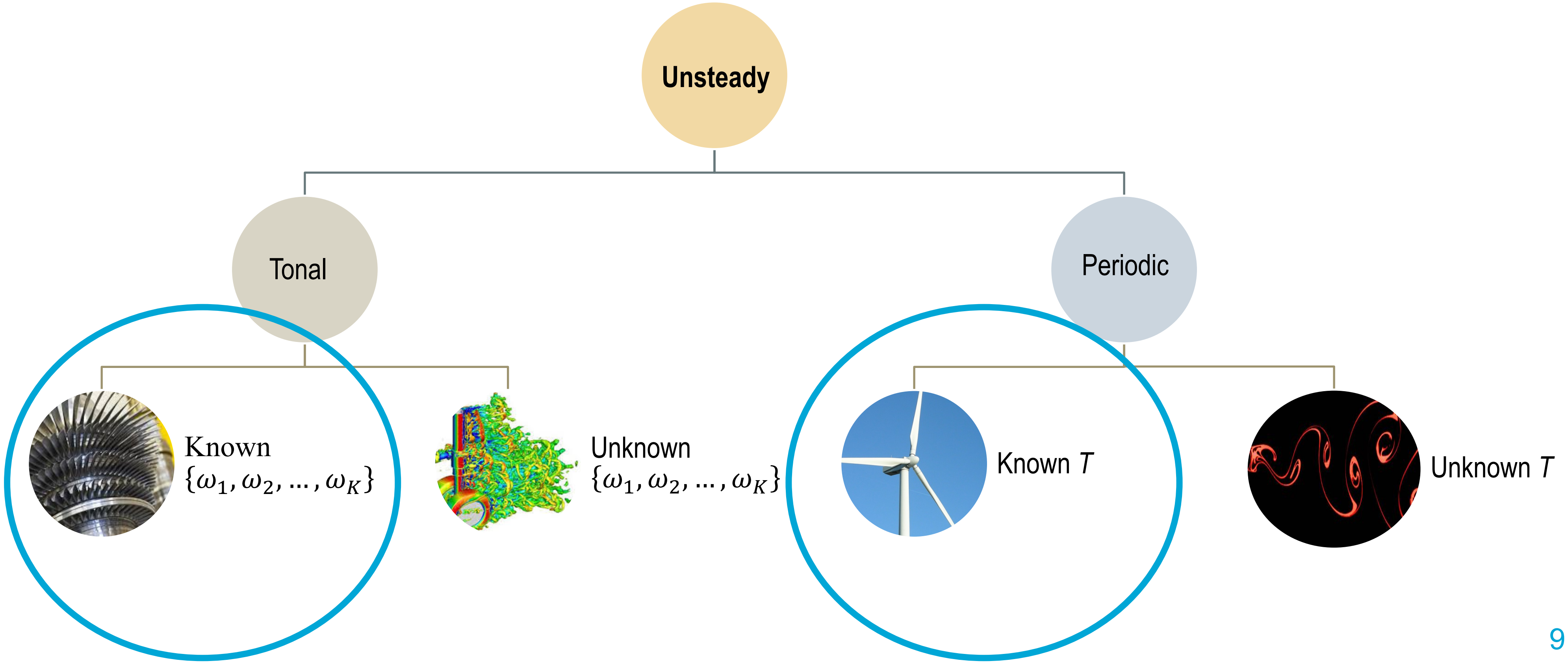
What unsteady design problems can be resolved with SU2 and HB?

- Unsteady
  - Tonal
    -  Known $\{\omega_1, \omega_2, \dots, \omega_K\}$
    -  Unknown $\{\omega_1, \omega_2, \dots, \omega_K\}$
  - Periodic
    -  Known T
    -  Unknown T

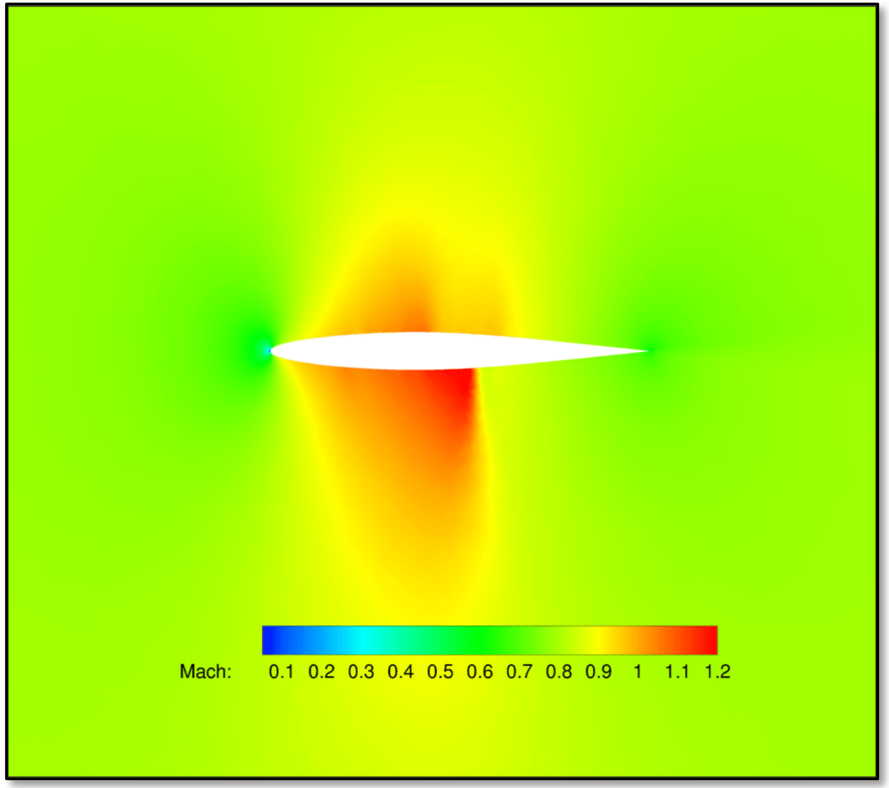
Thanks to Dr. K Naik

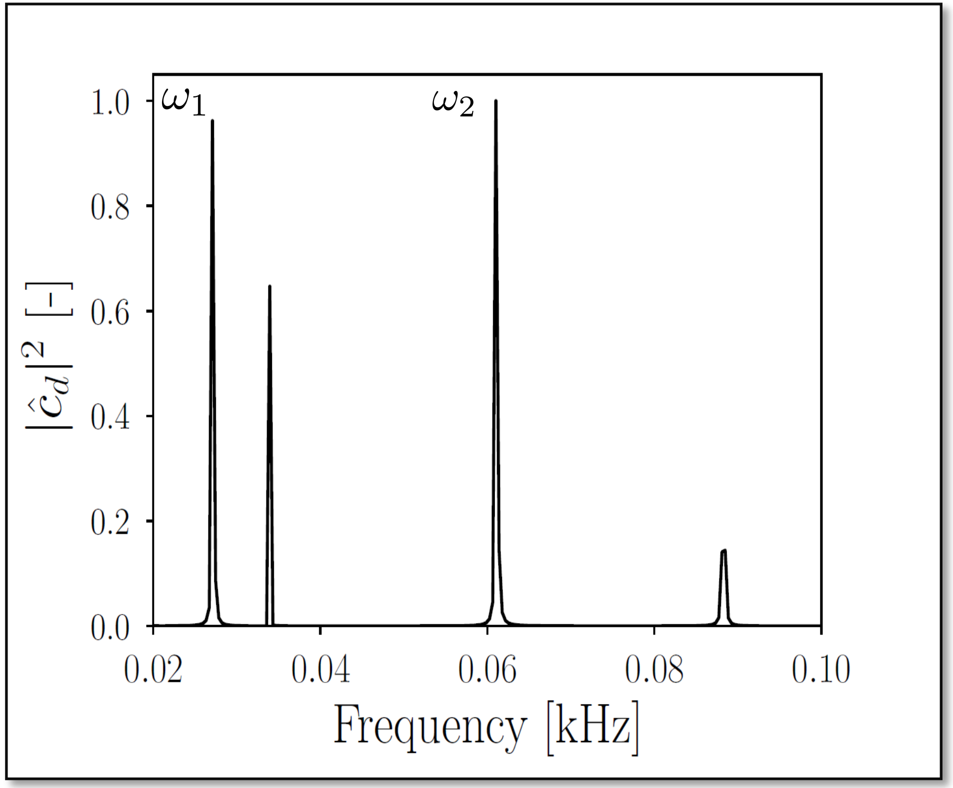
Introduction

What unsteady design problems can be solved with SU2 and HB?



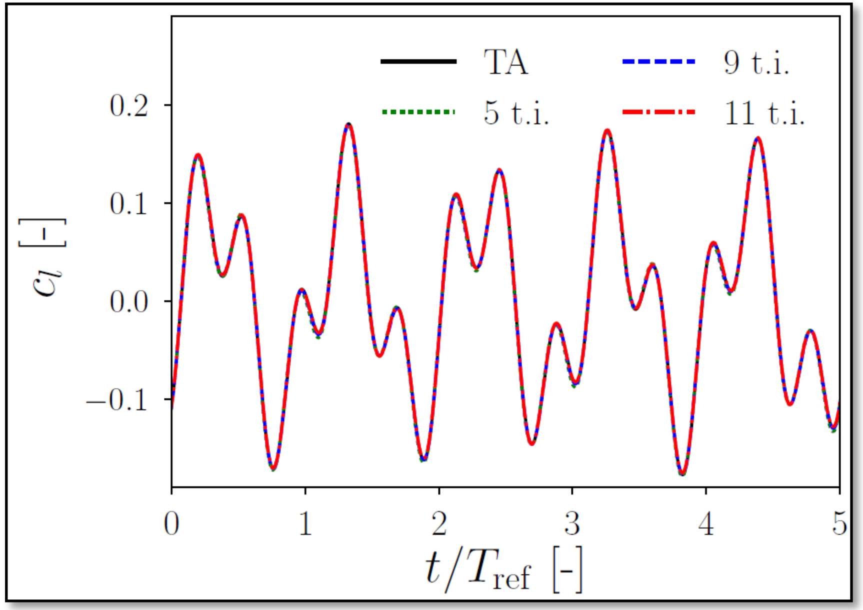
Application: Pitching Airfoil *NACA64A010*

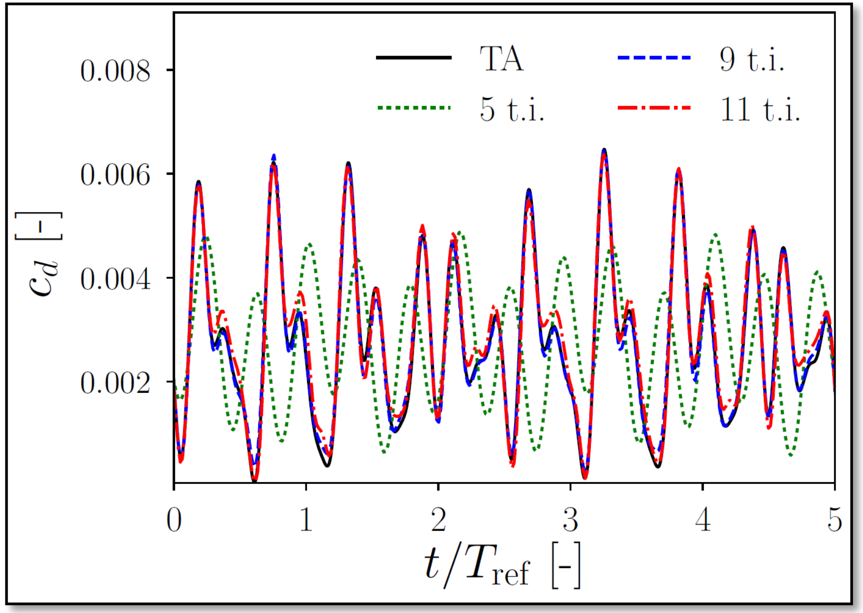




	Symbol	Value	Units
Mach number	Ma_∞	0.78	[-]
Pitching frequencies	$[\omega_1, \omega_2]$	[106.70, 277.42]	[rad/s]

Results Pitching Airfoil *NACA64A010*





Number input time instances	Input frequencies
5	$0, \pm\omega_1, \pm\omega_2$
7	$0, \pm\omega_1, \pm\omega_2, \pm 2\omega_2$
9	$0, \pm\omega_1, \pm(\omega_2 - \omega_1), \pm 2\omega_1, \pm\omega_2$
11	$0, \pm\omega_1, \pm(\omega_2 - \omega_1), \pm 2\omega_1, \pm\omega_2, \pm(\omega_2 + \omega_1)$

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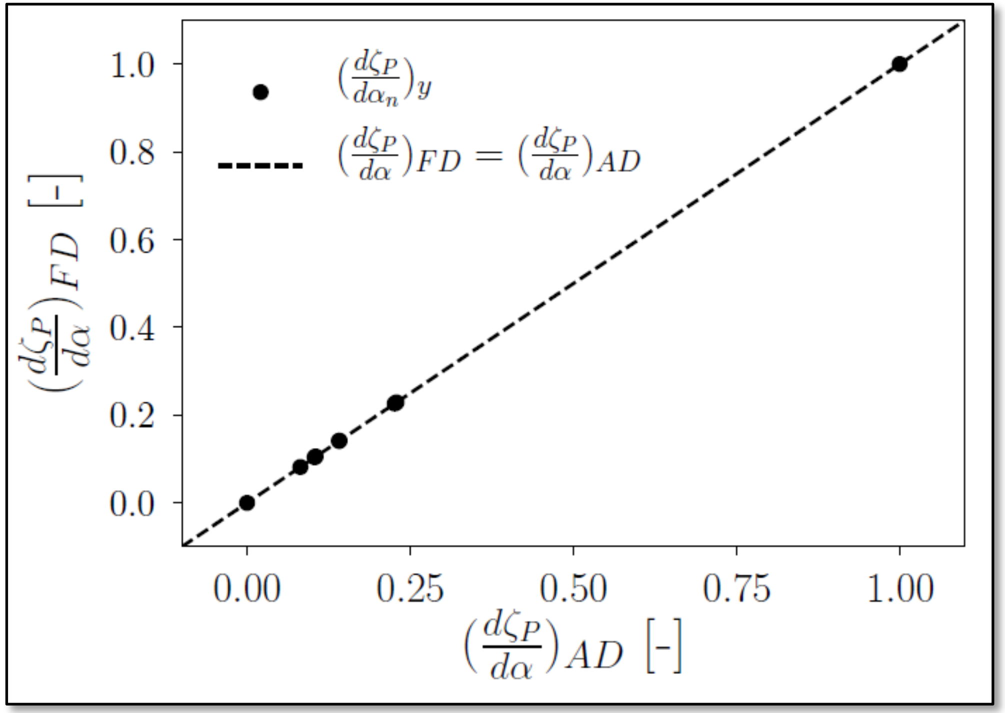
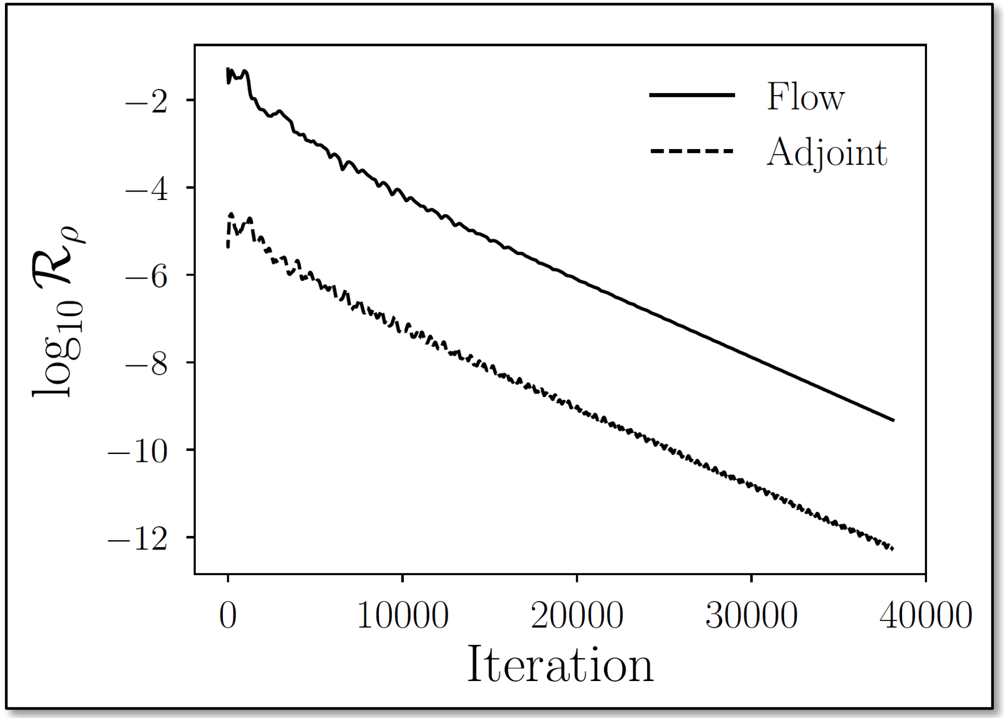
Adjoint-based Shape Optimization

Adjoint gradient validation





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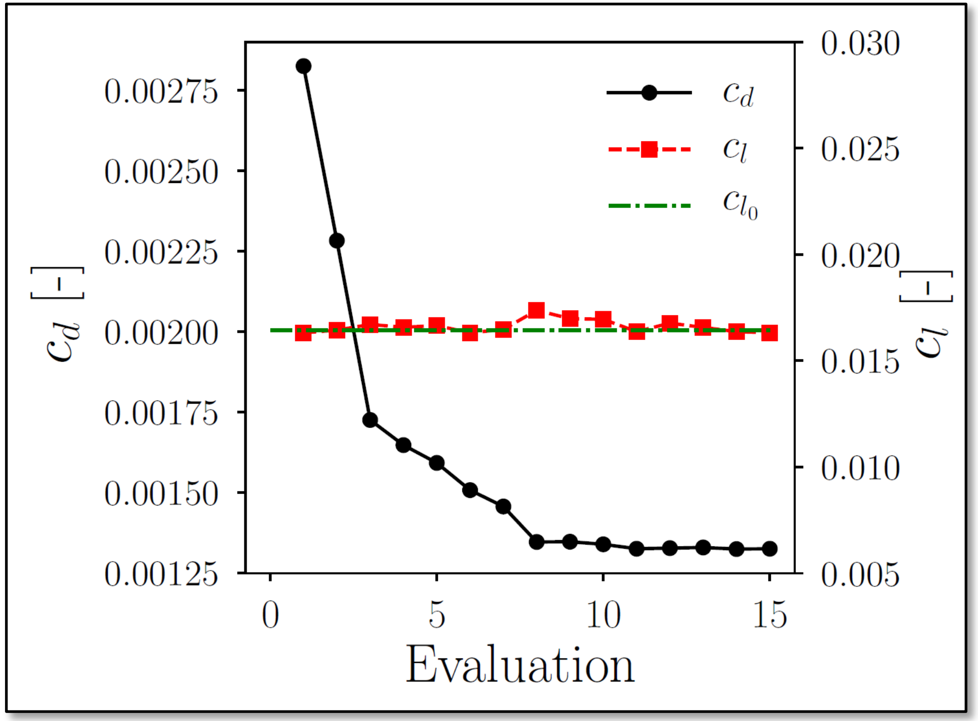
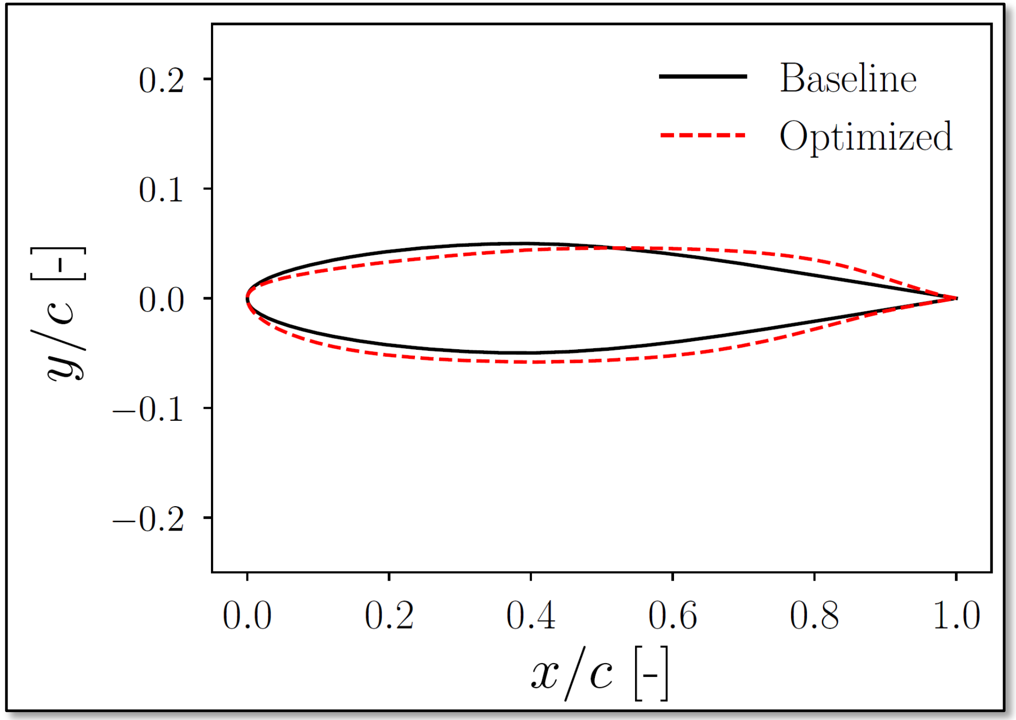
Adjoint-based Shape Optimization

Optimization evolution and final shape





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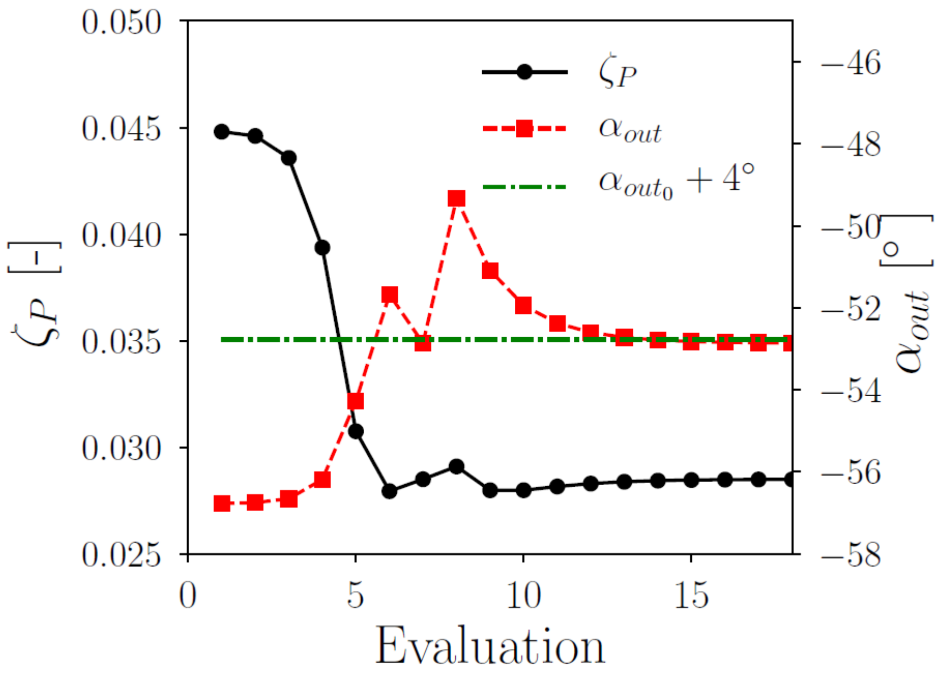
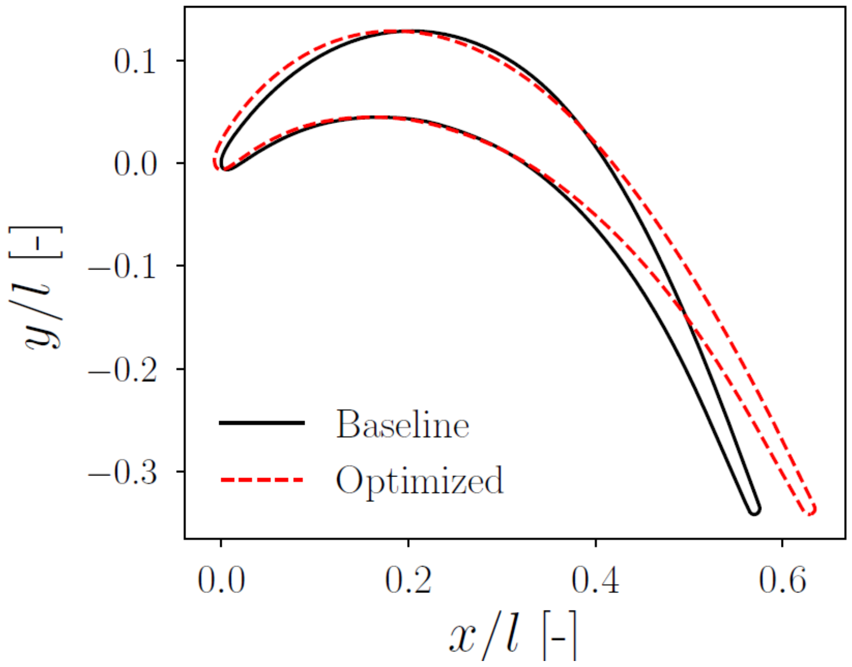
Adjoint-based Shape Optimization

Turbine Cascade Optimization



Optimization History



Baseline vs Optimized Blade Profile

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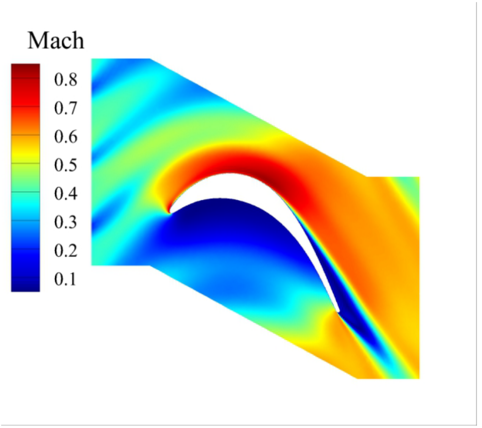
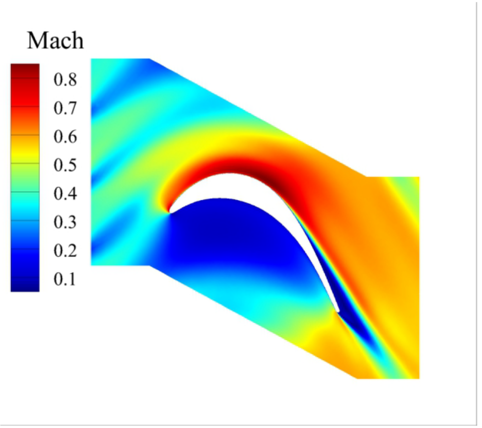
Adjoint-based Shape Optimization

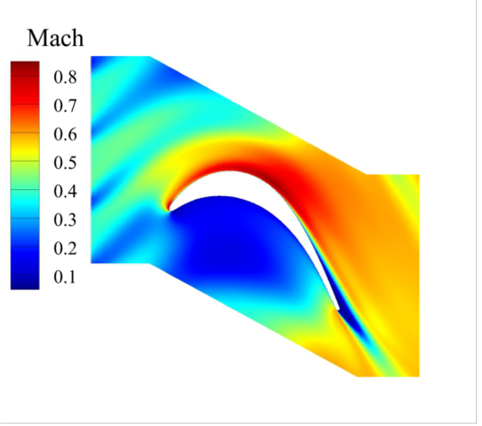
Mach contour



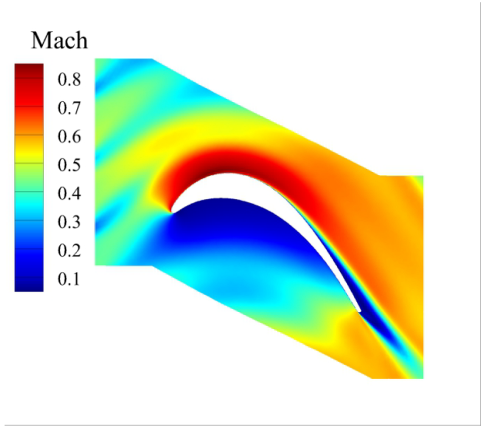
(a) Baseline, $t = 0$.



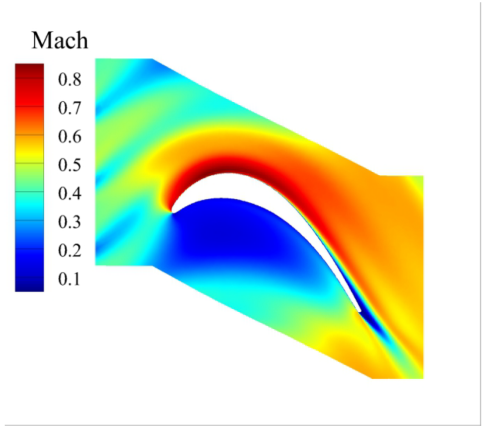
(b) Baseline, $t = \frac{2}{5}T$.



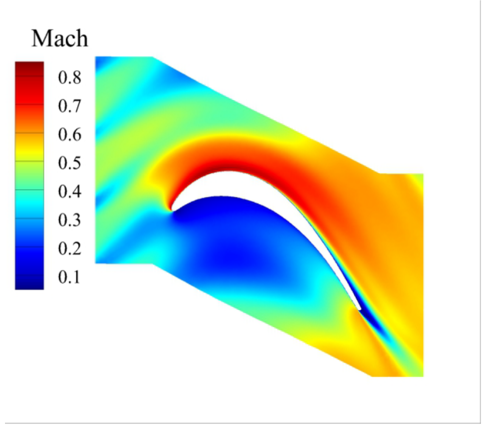
(c) Baseline, $t = \frac{4}{5}T$



(d) Optimized, $t = 0$.



(e) Optimized, $t = \frac{2}{5}T$.



(f) Optimized, $t = \frac{4}{5}T$

Previous Limitations

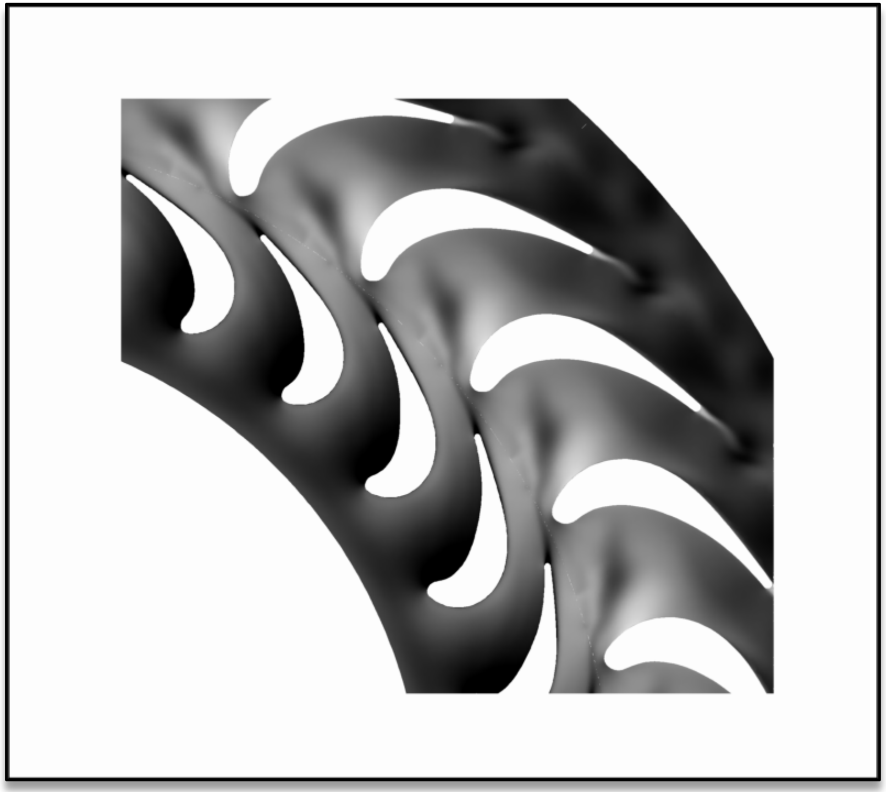
- Single geometrical zone HB-based flow and adjoint solver
- Tested on 2D problems only
- No general turbomachinery multi-row interface (machine type, periodic BC, …)
- Single-row HB-based shape optimization

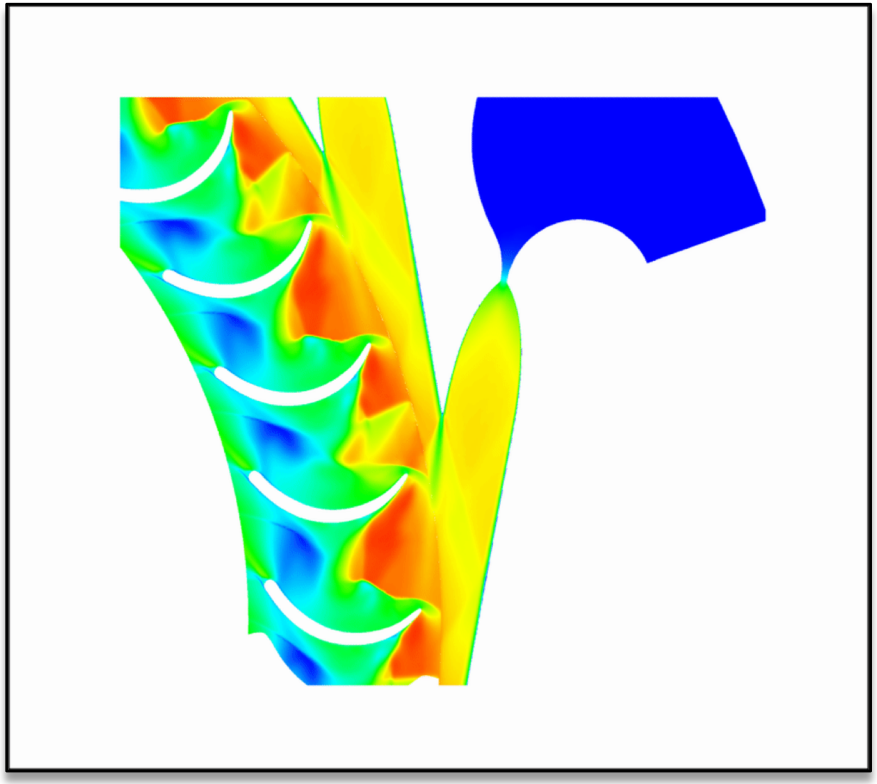
Current Status of Development

Unsteady Turbo Interface

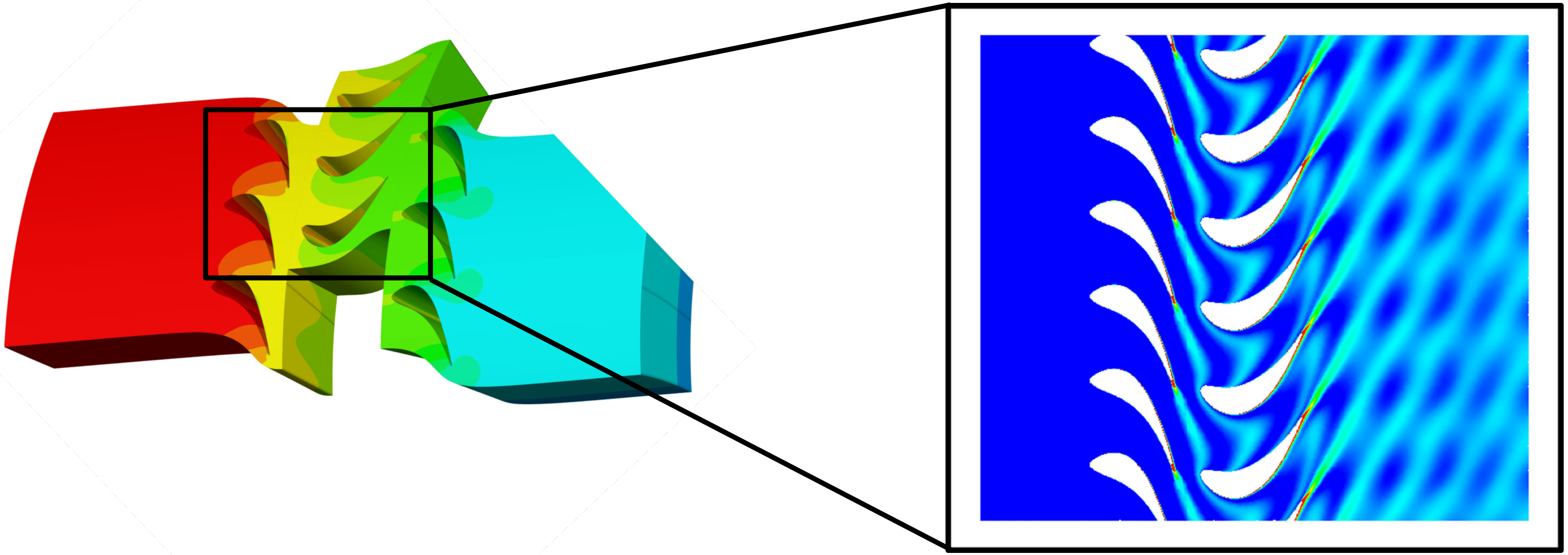
- New Turbomachinery Interpolation based on turbo-vertex data structure
- General for any turbomachinery configuration (e.g. radial, axial, …)
- Handling periodic BC and periodic grid movement for turbomachinery applications (no phase-lag yet ☹)
- Limited (currently) to 3D structured turbomachinery meshes

Simulation of Radial Turbines

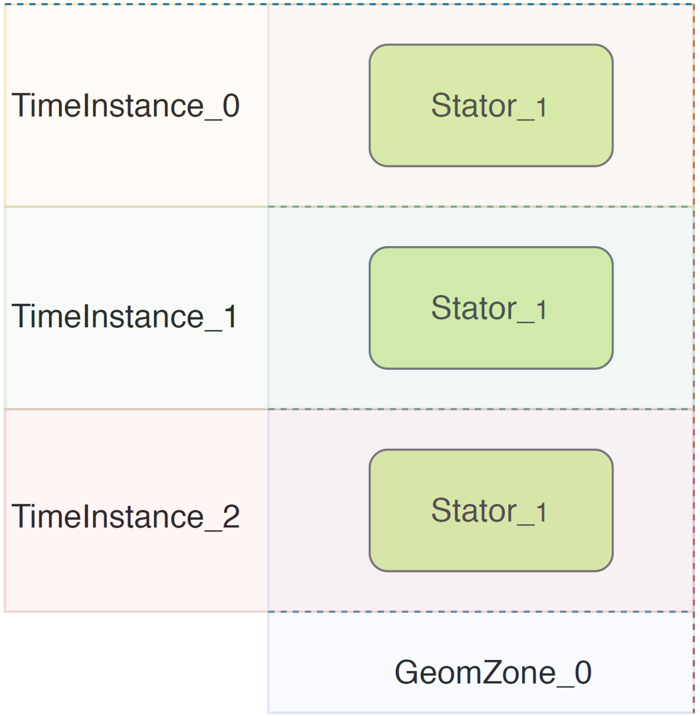




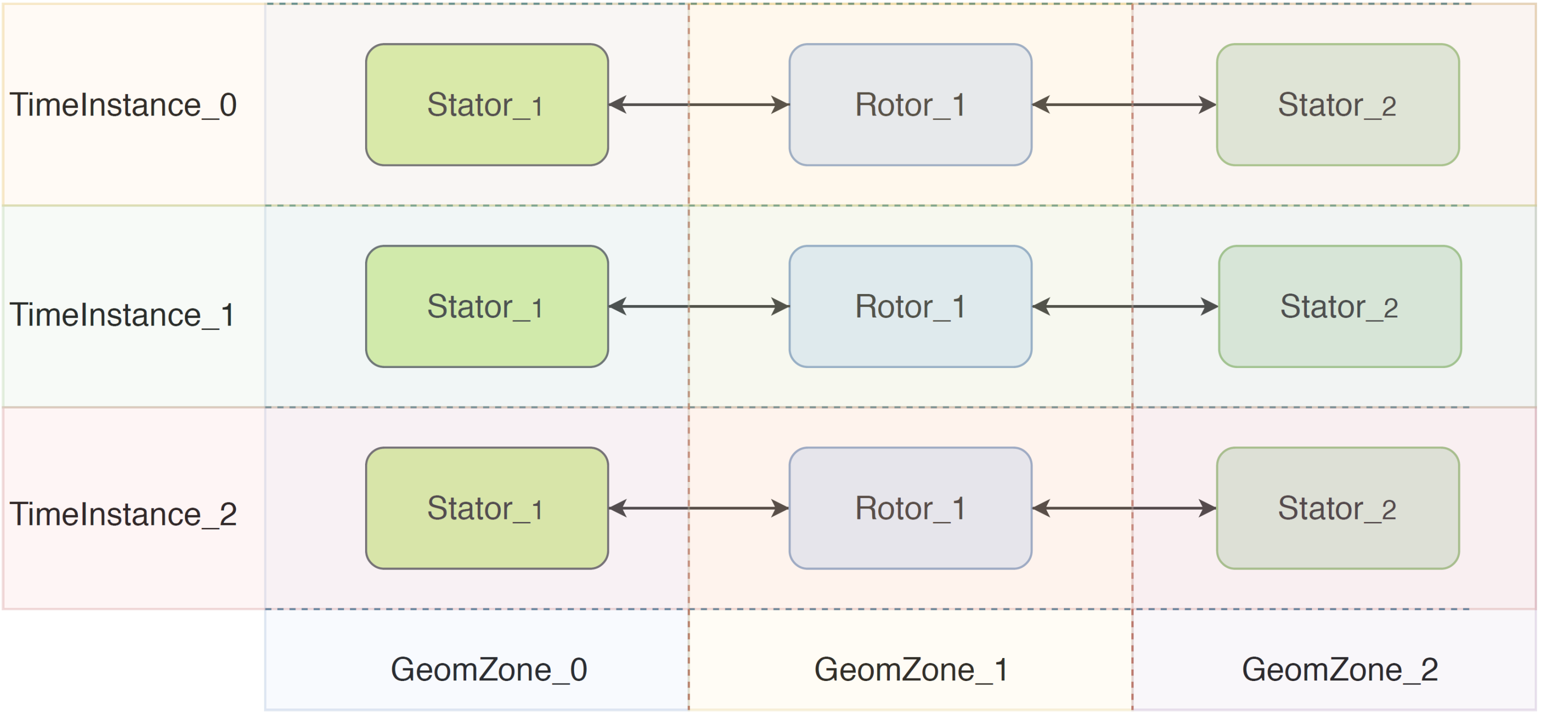
Simulation of Axial Turbines



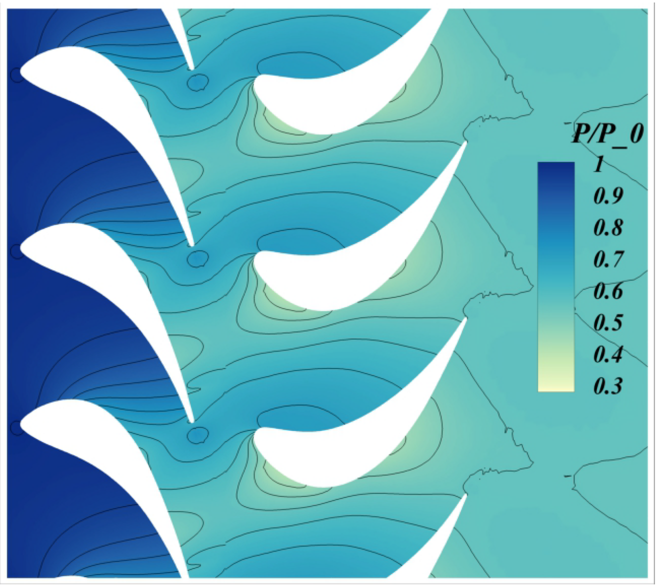
HB for Multi-Row (Flow + Adjoint)

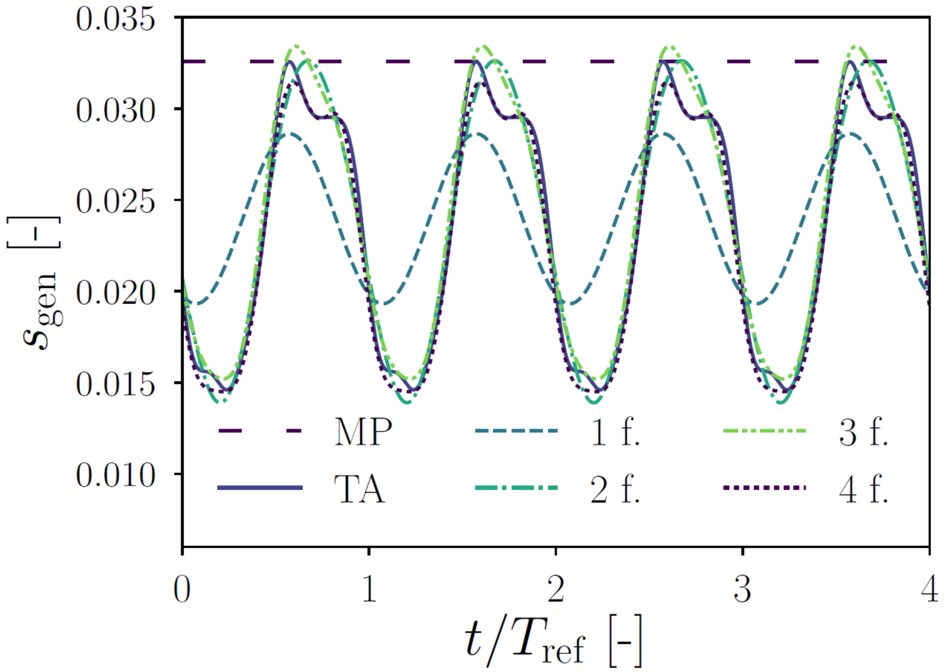


HB for Multi-Row (Flow + Adjoint)

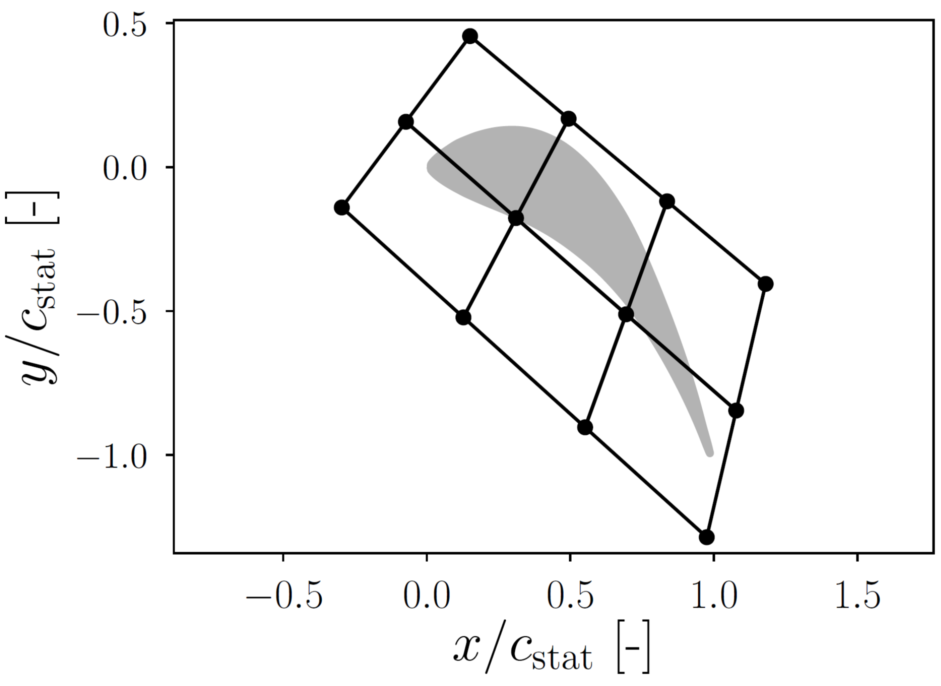


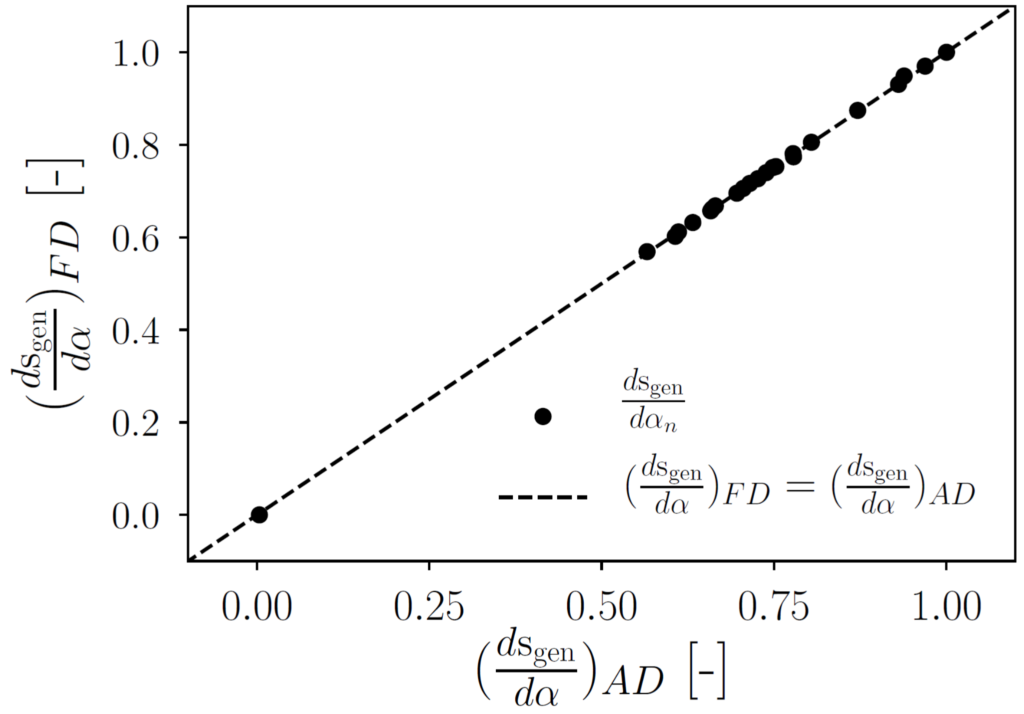
Solver Verified against MP and TA





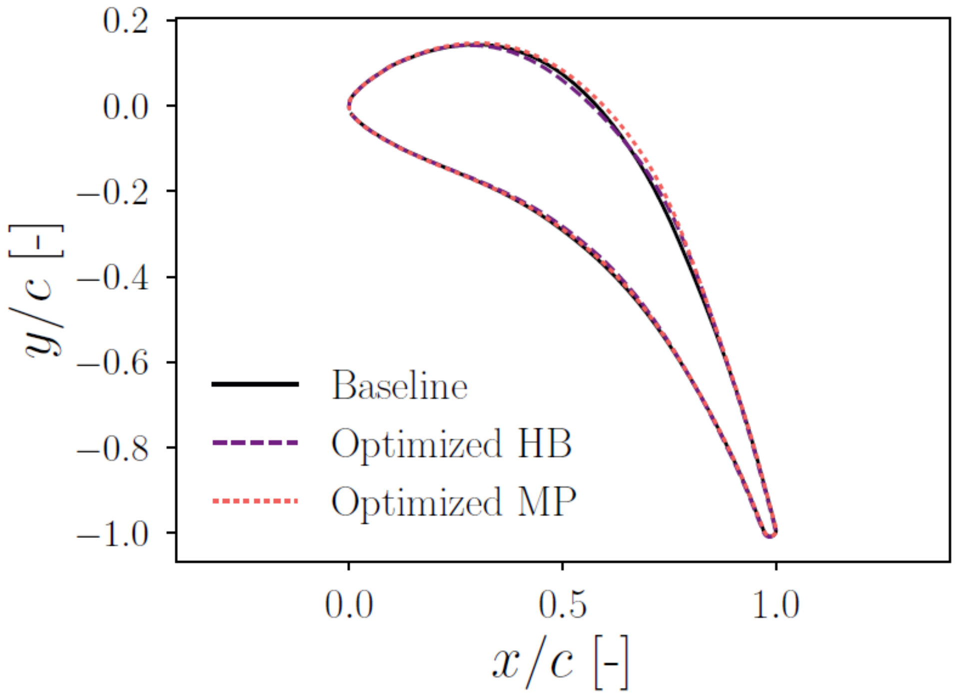
Adjoint vs FD Gradients

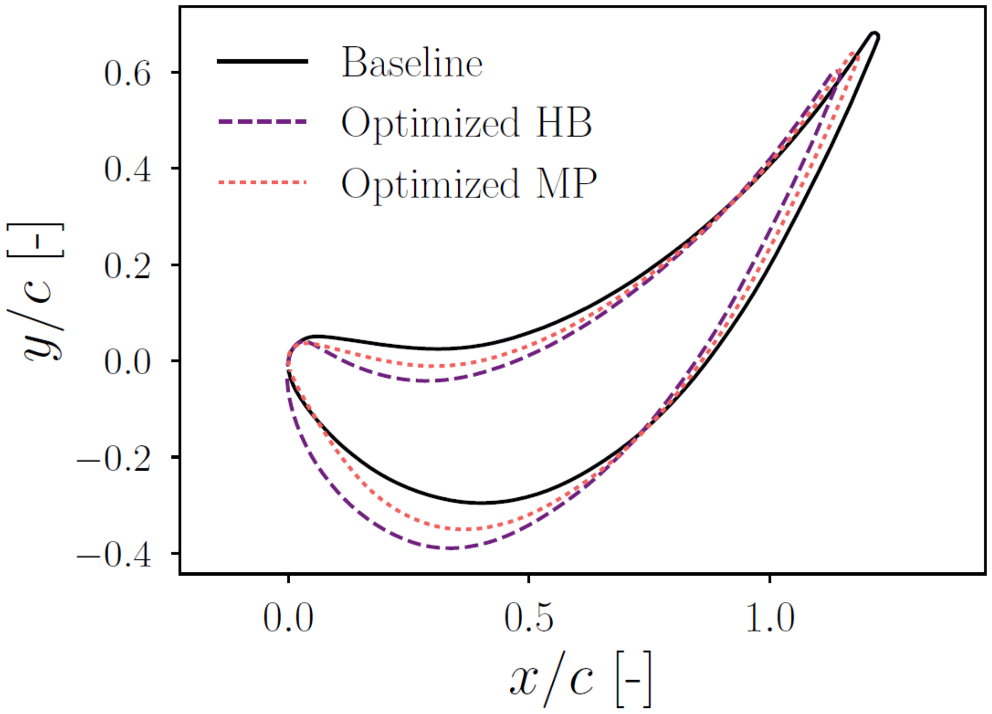




Adjoint memory and CPU time scales ~ $2N_f + 1$

HB Optimization of Turbine Stage





Total-to-Static Efficiency Gain → ~ 2 Percentage Points

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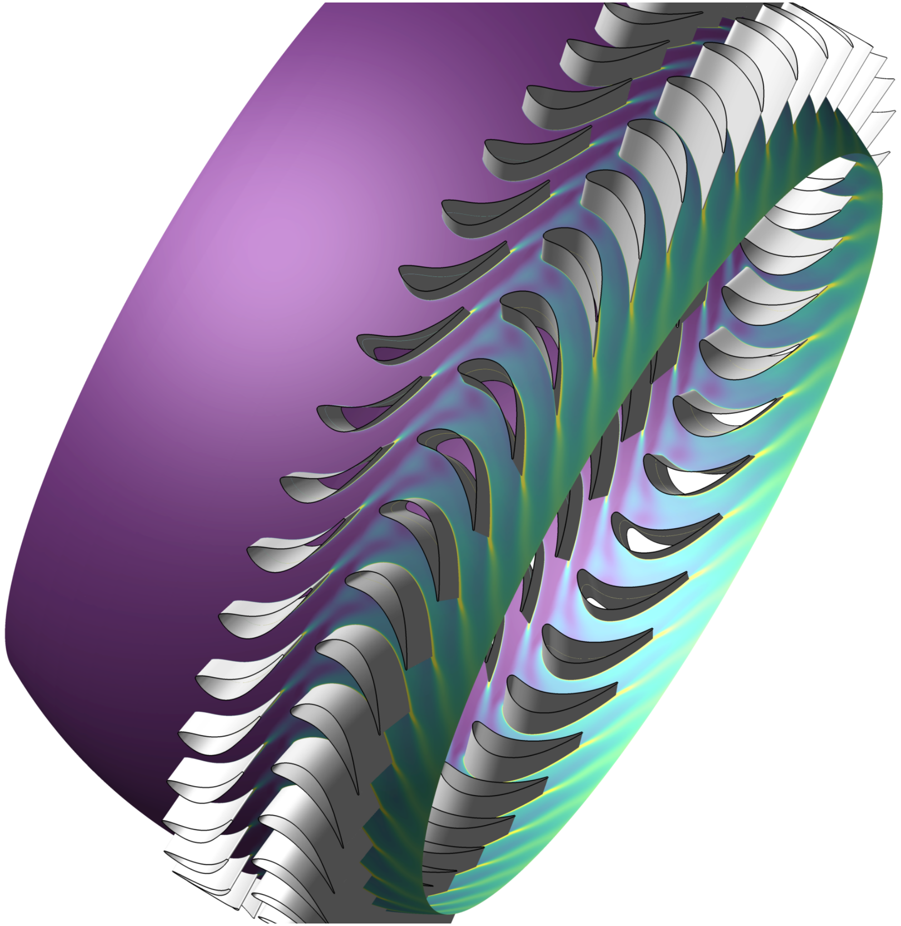
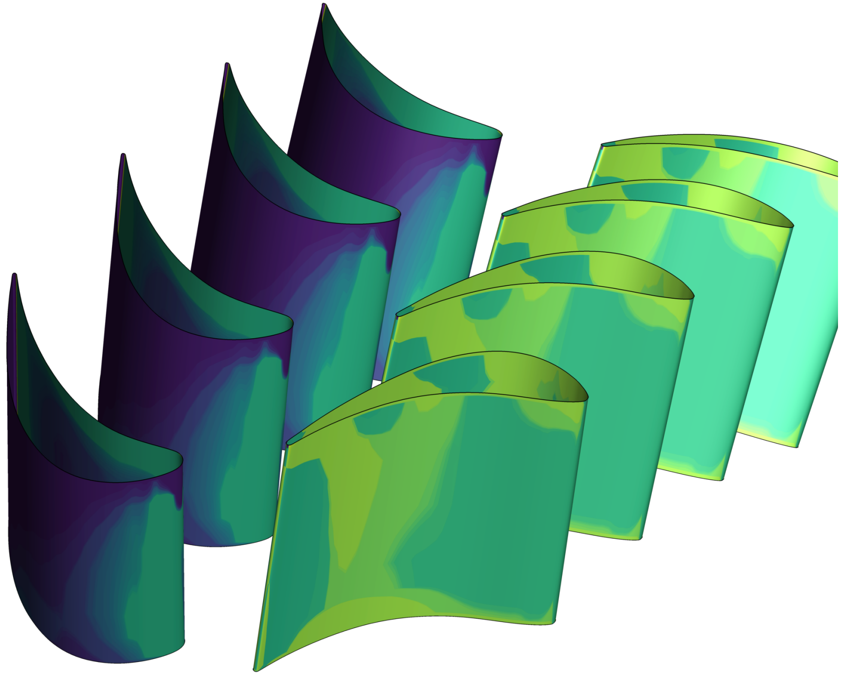
3D Multi-row HB Results



Entropy contours



Adjoint-based surface sensitivity

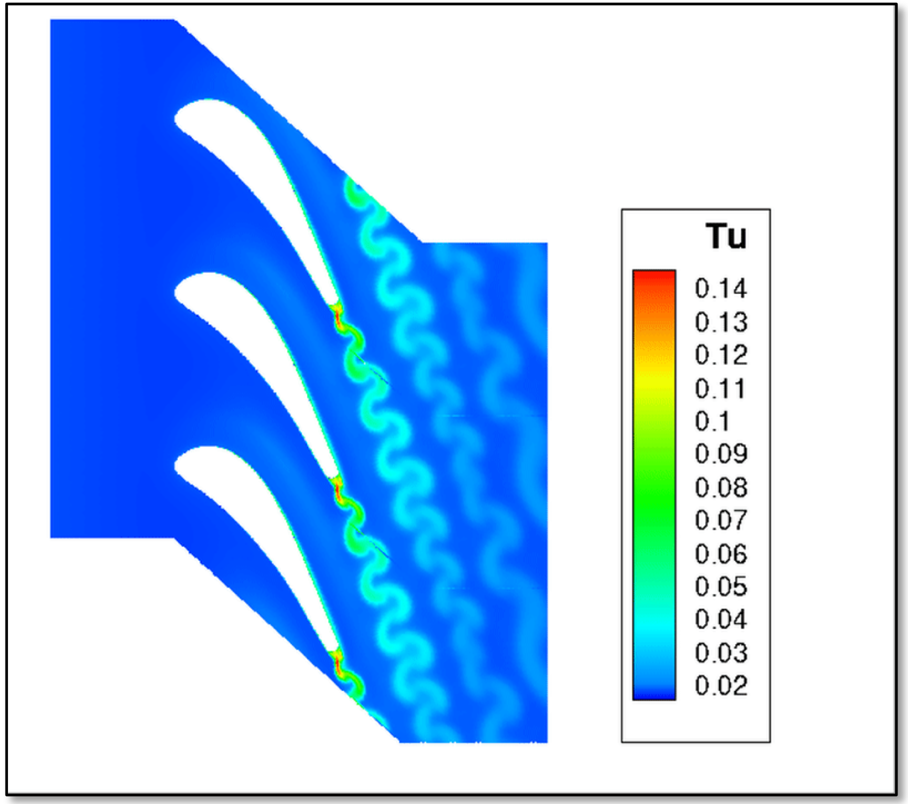
Outlook and Ongoing Work

TU Delft Propulsion & Power

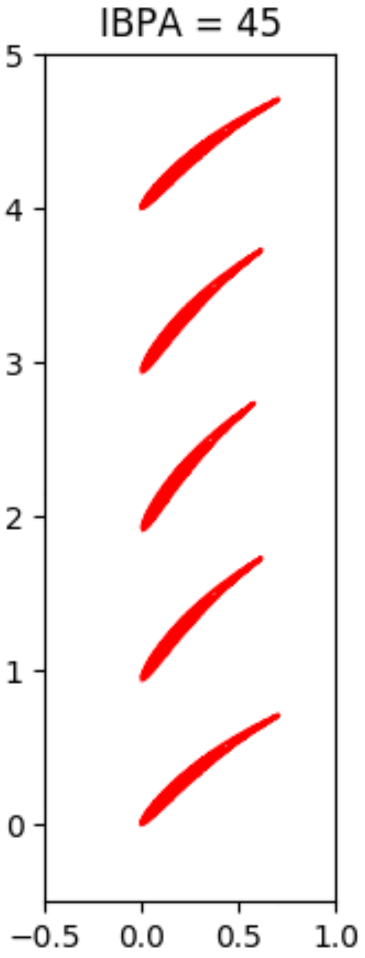
Current Limitations

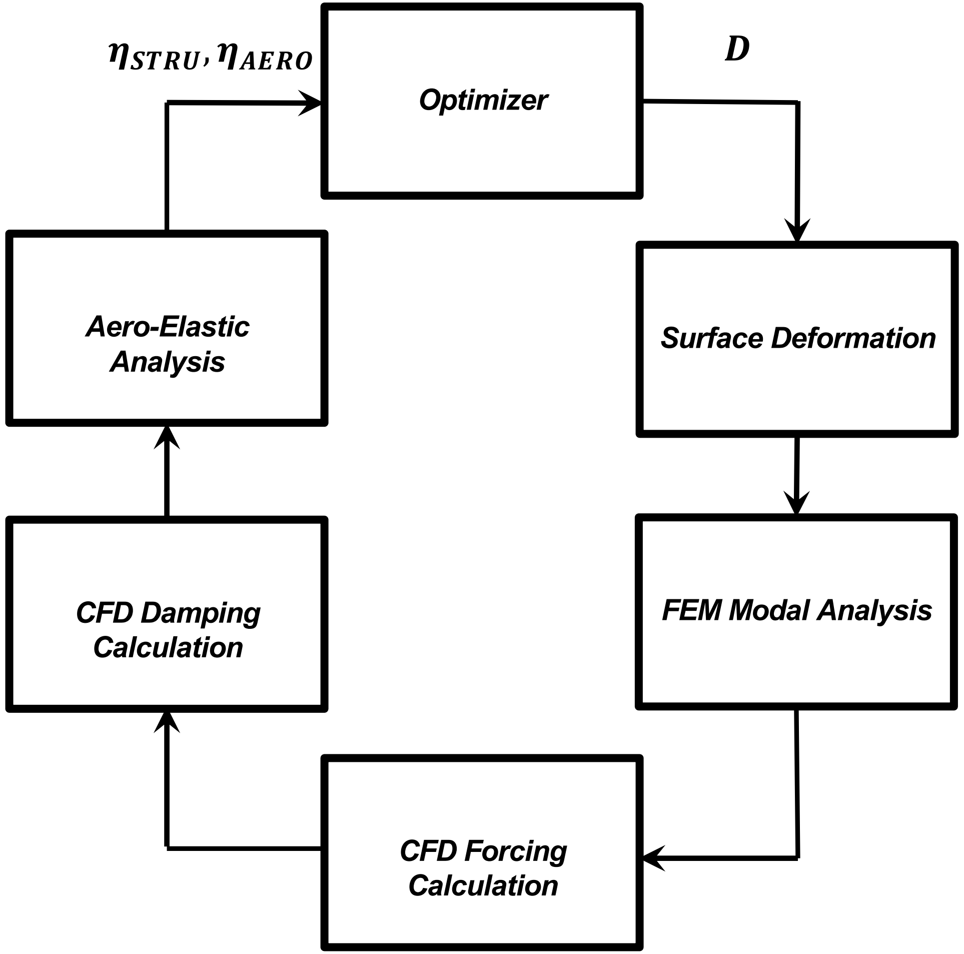
- Phase-lag boundary conditions for both HB and TA
- FFD for 3D Turbomachinery Design → CAD-based
- Time-accurate adjoint for multi-zone
- …

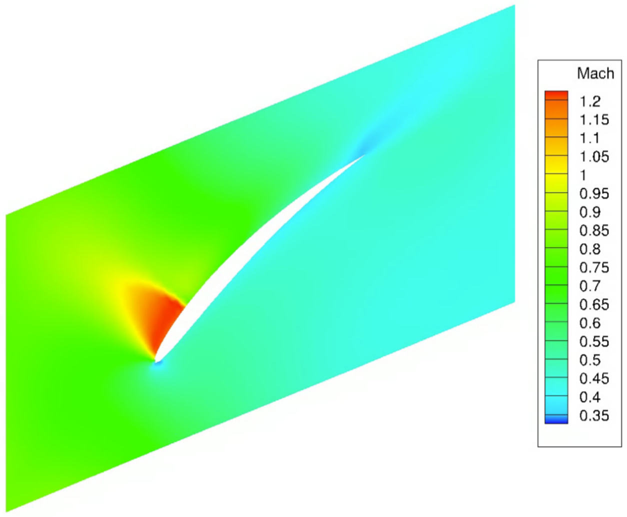
Time Accurate Unsteady Adjoint



Aero-Structure Optimization







Thank you!