Unsteady Optimization with SU2: Application to Turbomachinery Design
An overview

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Outline

• Introduction and past work
• Current status of development
• Outlook and ongoing work
• Conclusions
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
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HB Method in a Nutshell

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

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

- Time derivative → Matrix multiplication (time independent!)
Time-Domain Implementation

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

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

Unsteady

- **Tonal**
  - Known $\{\omega_1, \omega_2, \ldots, \omega_K\}$
  - Unknown $\{\omega_1, \omega_2, \ldots, \omega_K\}$

- **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

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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M a_\infty$</td>
<td>0.78</td>
<td>[-]</td>
</tr>
<tr>
<td>Pitching frequencies</td>
<td>$[\omega_1, \omega_2]$</td>
<td>$[106.70, 277.42]$</td>
</tr>
</tbody>
</table>
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 | $0, \pm \omega_1, \pm (\omega_2 - \omega_1), \pm 2\omega_1, \pm \omega_2, \pm (\omega_2 + \omega_1)$
Adjoint-based Shape Optimization

Adjoint gradient validation

\[ \left( \frac{\partial \xi_P}{\partial \alpha_n} \right)_y \]

\[ \left( \frac{\partial \xi_P}{\partial \alpha} \right)_{FD} = \left( \frac{\partial \xi_P}{\partial \alpha} \right)_{AD} \]

\[ \log_{10} R_p \]

Iteration

TU Delft
Adjoint-based Shape Optimization
Optimization evolution and final shape
Adjoint-based Shape Optimization

Turbine Cascade Optimization

Optimization History

Baseline vs Optimized Blade Profile
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 $\sim 2N_f + 1$
HB Optimization of Turbine Stage

Total-to-Static Efficiency Gain $\rightarrow \sim 2$ Percentage Points
3D Multi-row HB Results

Entropy contours

Adjoint-based surface sensitivity
Outlook and Ongoing Work
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

IBPA = 45

\[ \eta_{\text{STRU}}, \eta_{\text{AERO}} \]

Optimizer

\[ D \]

Aero-Elastic Analysis

Surface Deformation

CFD Damping Calculation

FEM Modal Analysis

CFD Forcing Calculation

TU Delft
Thank you!