TURBOMACHINERY CFD

Key Concepts and Applications

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TU Delft, 13/03/2019

About Myself …

SAPIENZA
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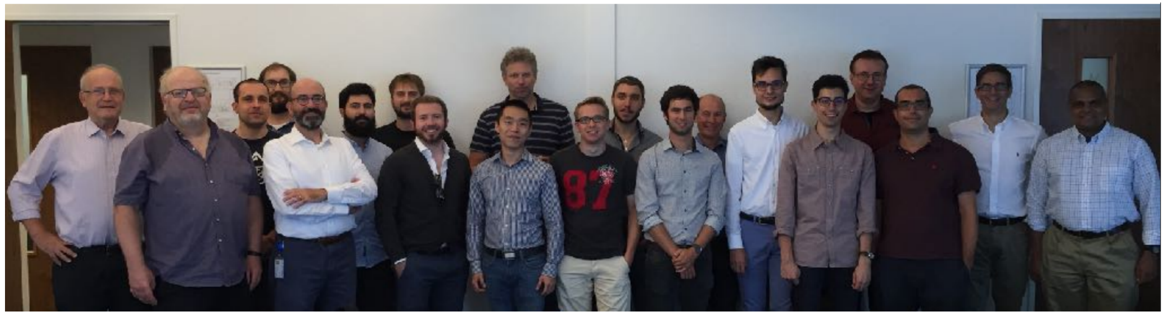
TU Delft

SU2
The Open-Source CFD Code



Outline

- Introduction
- CFD models and methods
- Multi-row calculation methods
- Limitations of turbomachinery CFD
- Concluding remarks

Learning Objectives

- Ability to describe the main CFD models and methods used for turbomachinery simulations

- Ability to select a proper CFD model/method for the problem at hand

- Critically assess results and limitations of CFD results

INTRODUCTION

Why Turbomachinery CFD?

- Gain understanding of the flow-physics and loss mechanisms within turbomachinery flow passages
- Cheap and (very often) fast!
- Make design adaptations/optimization based on simulation results → Unconventional results

What is NOT CFD?

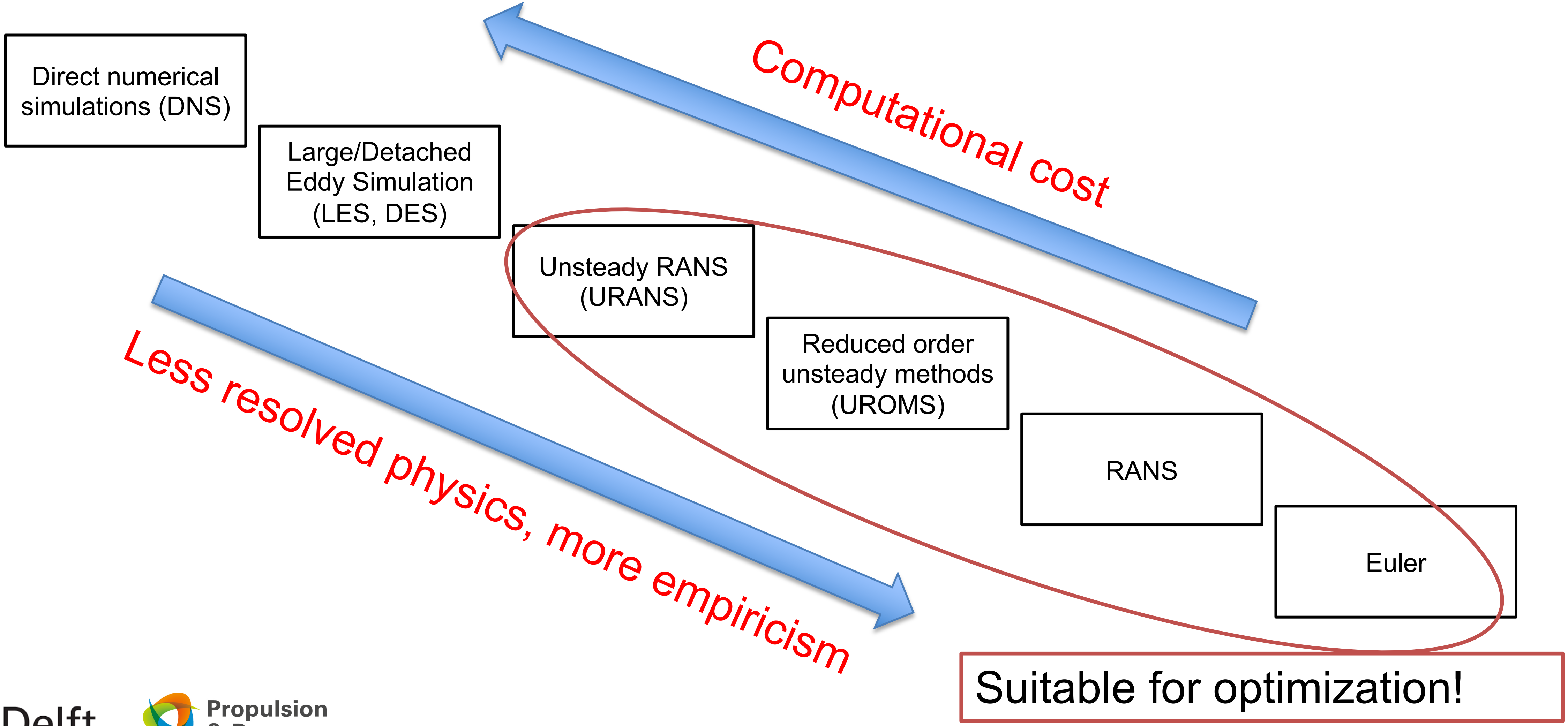
- Not (yet) a replacement of preliminary design methods
- Not a black-box to trust without uncertainties
- Not a replacement of experiments

At P&P We Have in Use Three Turbomachinery CFD Tools

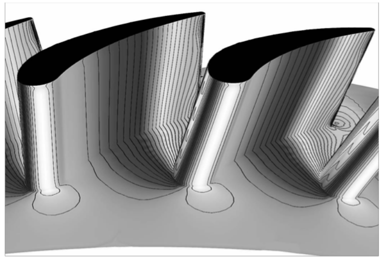
- SU2 (open-source), flagship tool for research on cutting-edge design methods
- MULTALL (open-source), main tool for turbomachinery education
- Ansys CFX (commercial), tool to support research

https://su2code.github.io
https://sites.google.com/site/multallopen/home

Hierarchy of CFD Methods

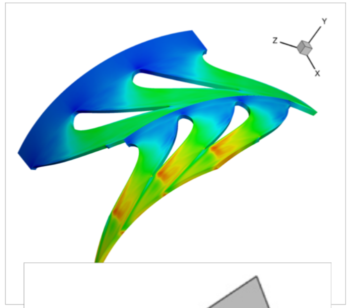


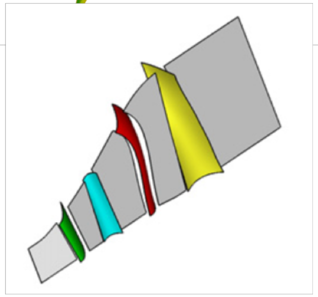
Modeling Levels in Turbomachinery

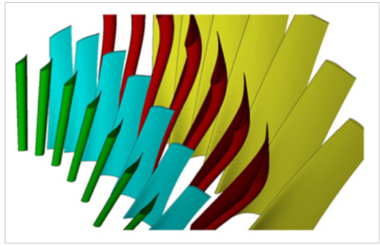


Turbomachinery

- Single passage
  - BL2BL, Q3D, 3D
- Blade row calculations
  - Throughflow
  - BL2BL, Q3D, 3D

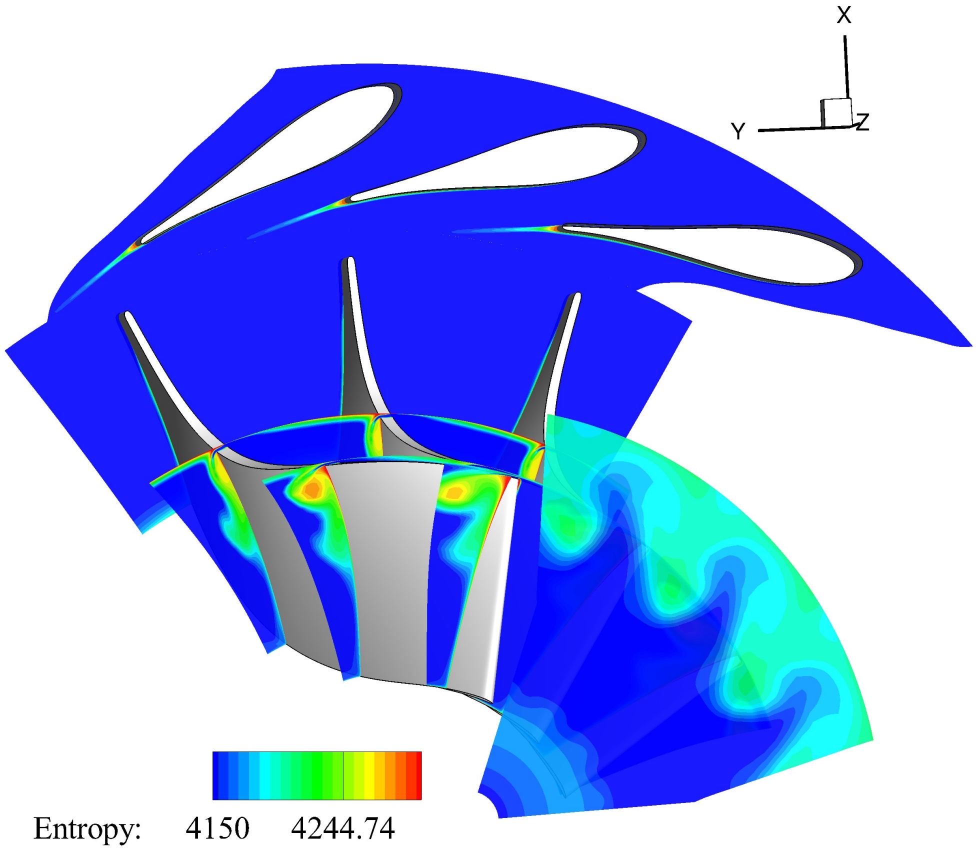




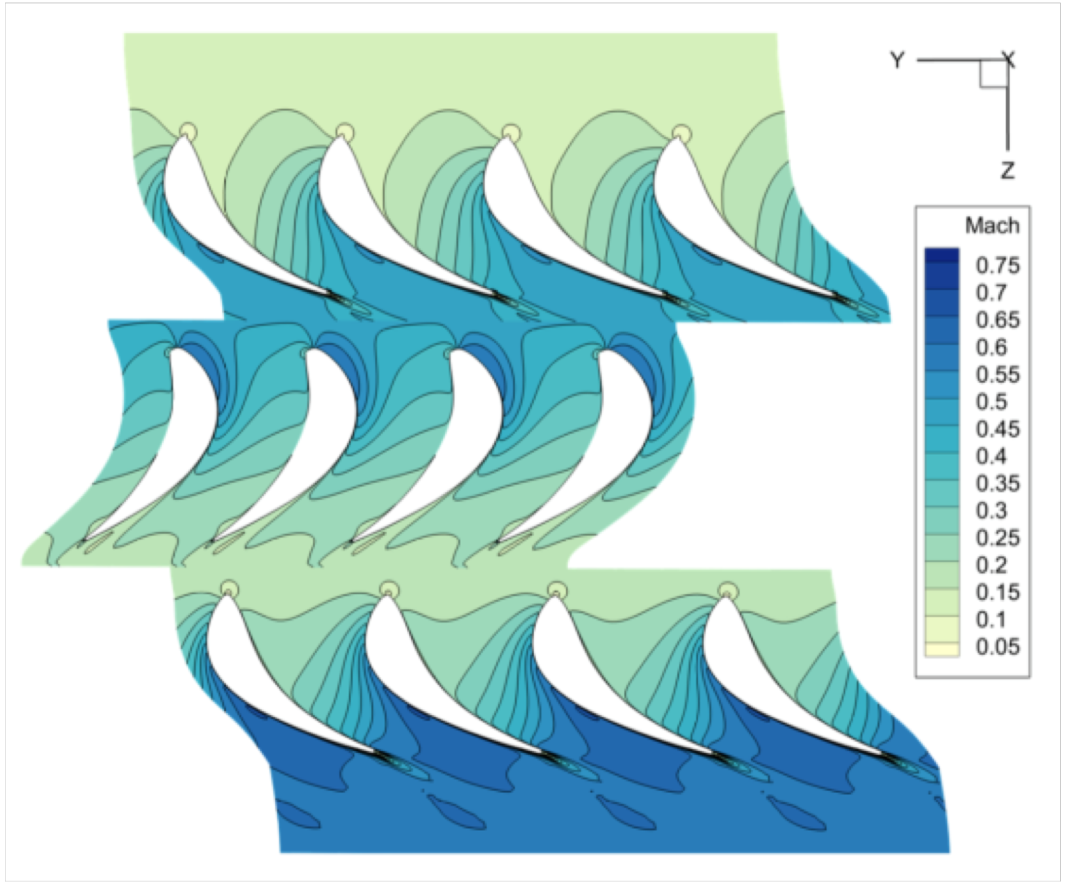


BL2BL = blade to blade, Q3D = quasi 3D

Examples



3D blade row calculation

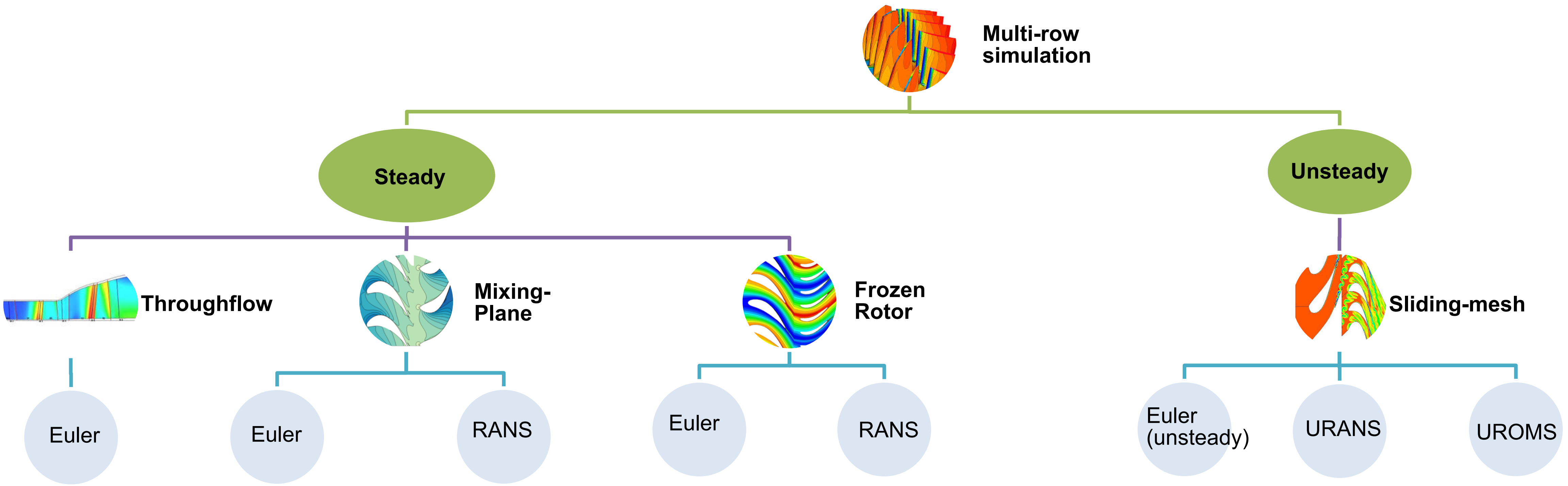


BL2BL blade row calculation

Simulations performed with SU2 code

BLADE ROW CALCULATION METHODS

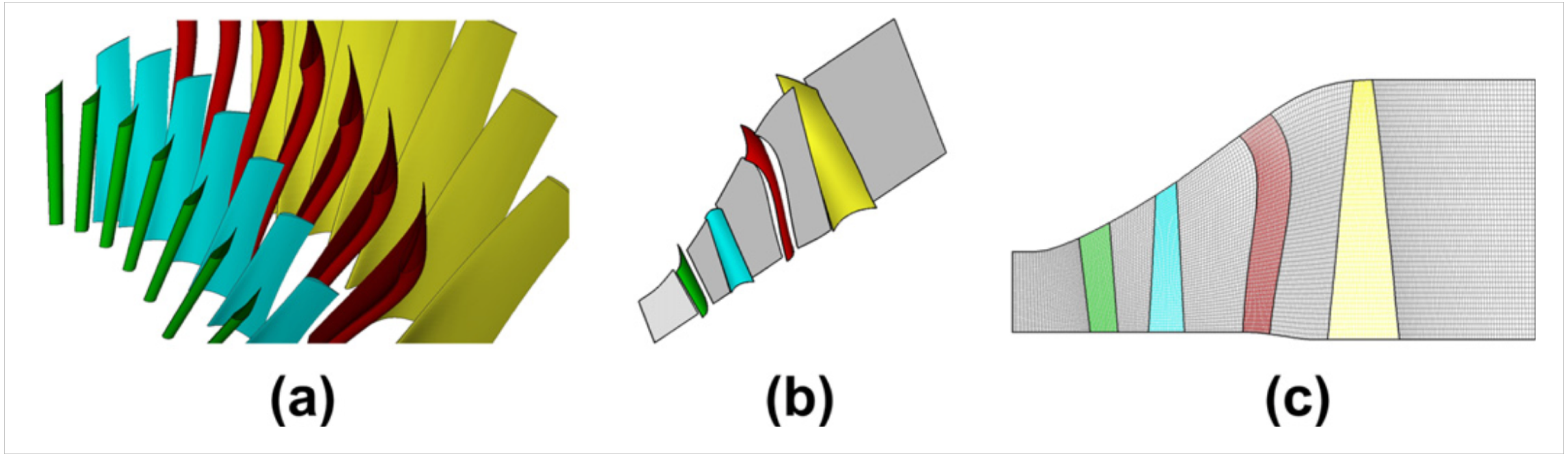
Multi-row simulations



STEADY SIMULATION

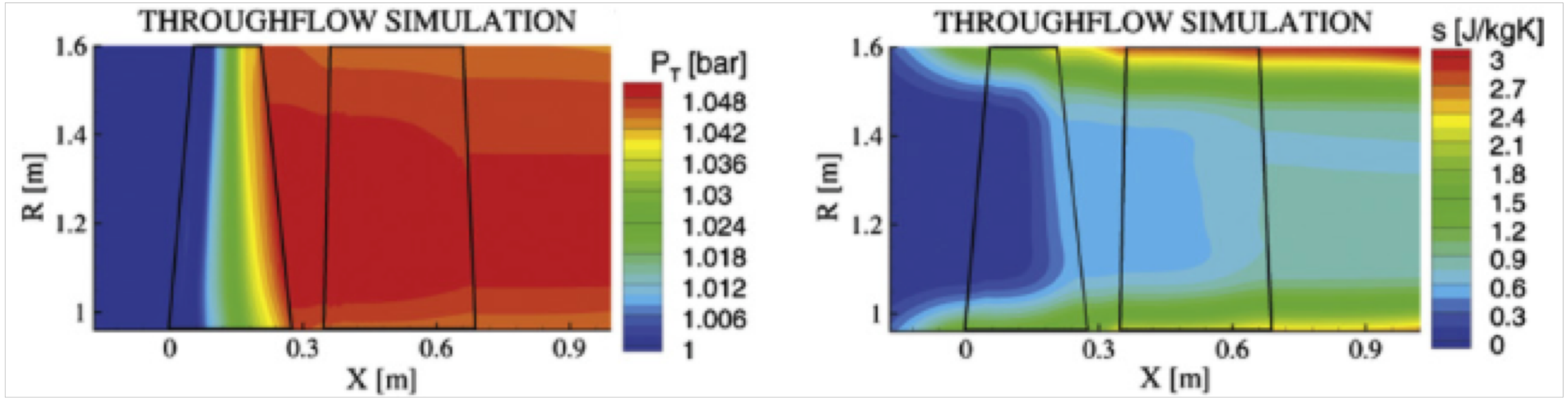
Throughflow computation

Important step in turbomachinery design. Key of the model is that the flow of the turbomachine is assumed to be circumferentially averaged, axisymmetric. This leads to the solution of a 2D problem **(c)** in the meridional plane.



Full machine **(a)** → mean stream surface **(b)** → S2 projection **(c)**

Example: 1-Stage Axial Fan



Loss and deviation correlations remain an essential part of any throughflow method.

In fact the method may be thought of as a means of applying the correlations to a non-uniform flow. The accuracy of the results is determined more by the accuracy of the correlations than by that of the numerical method.

[Denton]

Question

Which of the following flow-induced effects cannot be predicted by using a throughflow model?

1. Profile, secondary, and tip-leakage losses
2. Aerodynamic forces on the blade
3. Flow separation on the endwall
4. Flow separation on the blade surface
5. Blade blockage
6. Shock waves

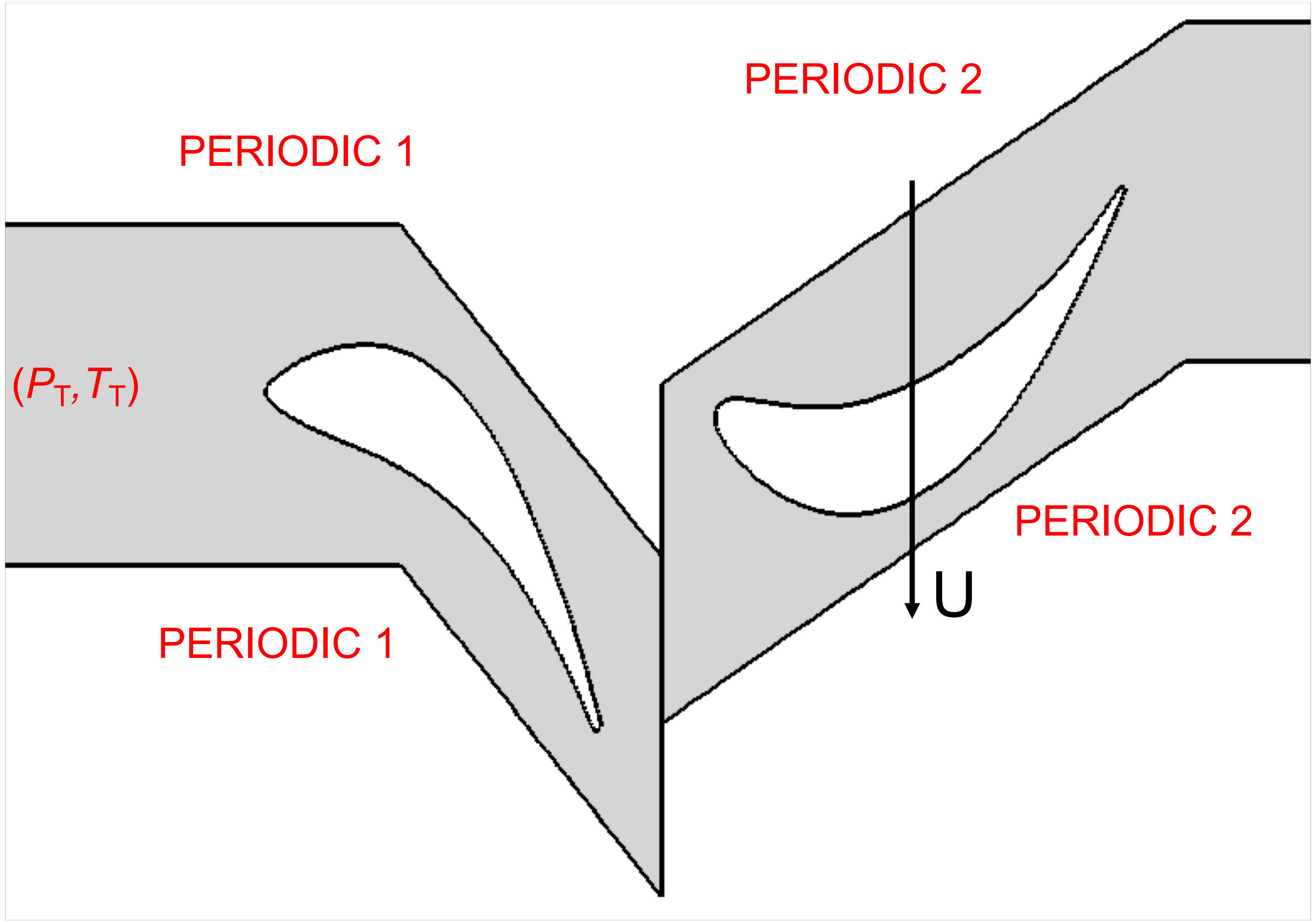
Answer

Which of the following flow-induced effects cannot be predicted by using a throughflow model?

1. Profile, secondary, and tip-leakage losses
2. Aerodynamic forces on the blade
3. Flow separation on the endwall
4. **Flow separation on the blade surface**
5. Blade blockage
6. Shock waves

Mixing-Plane

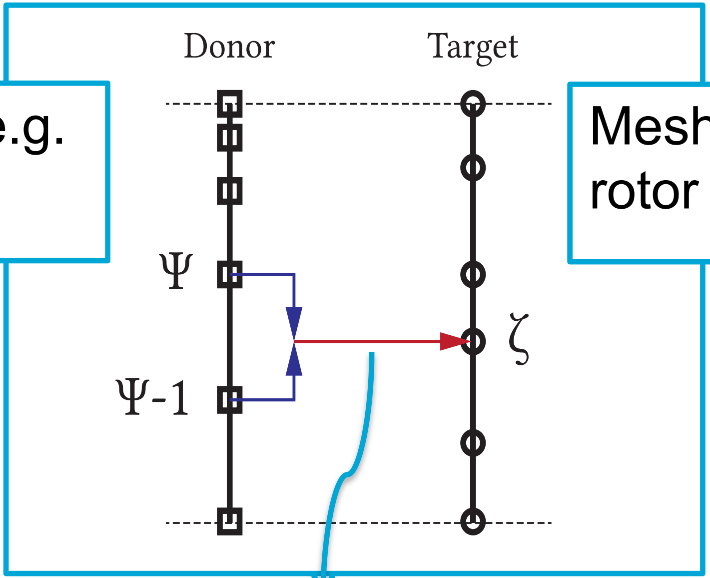
INFLOW:
- Total conditions (P_T, T_T)
- Flow direction



OUTFLOW
- Static backpressure P_s

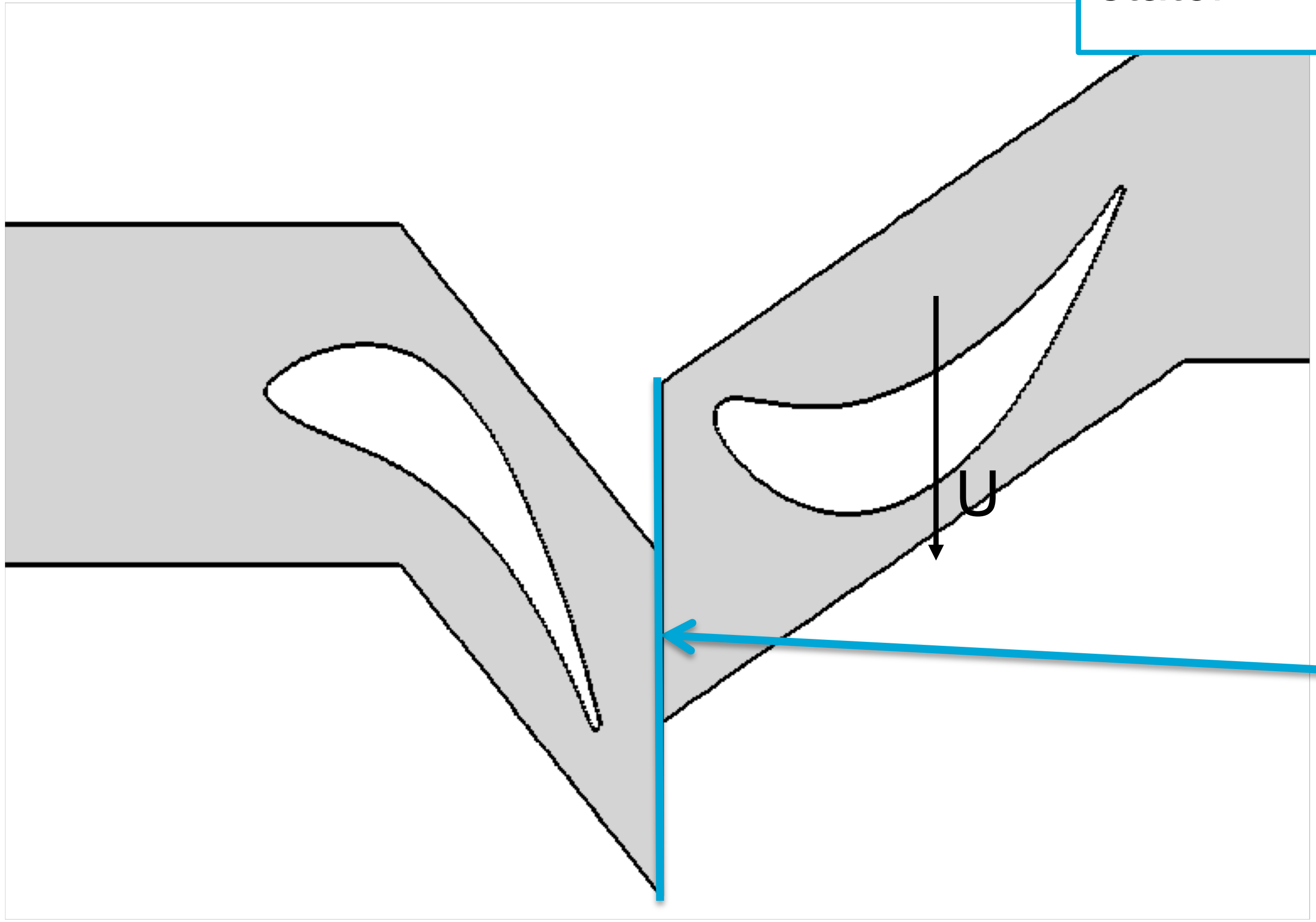
Mixing-Plane

Mesh 1, e.g. stator



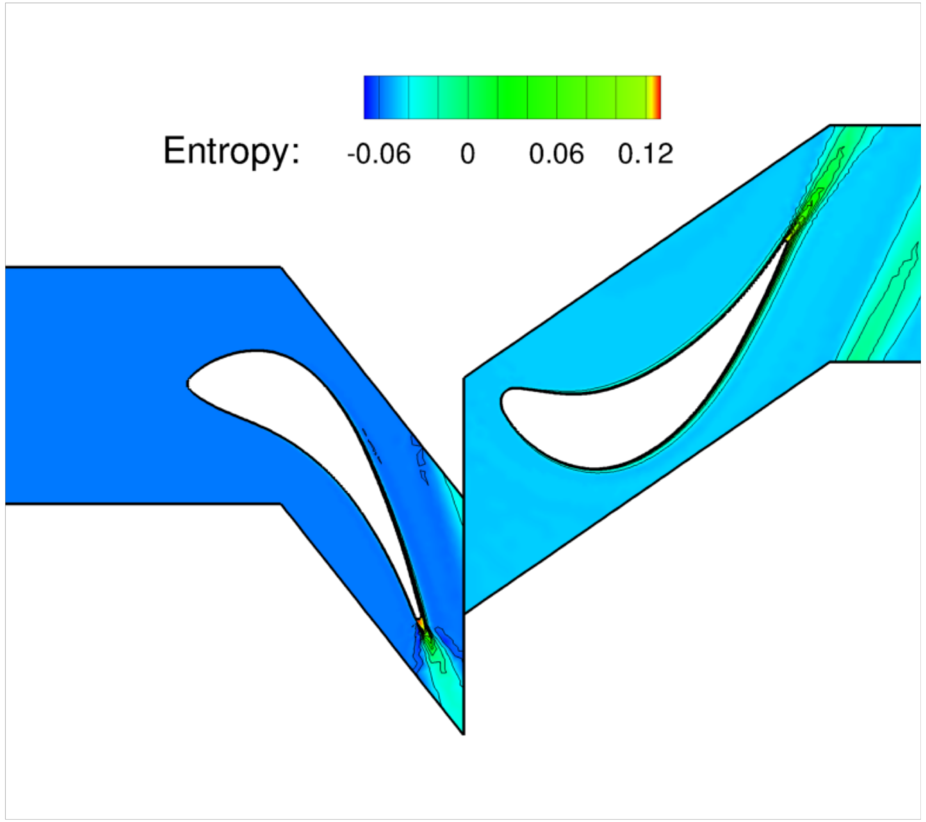
Mesh 2, e.g. rotor

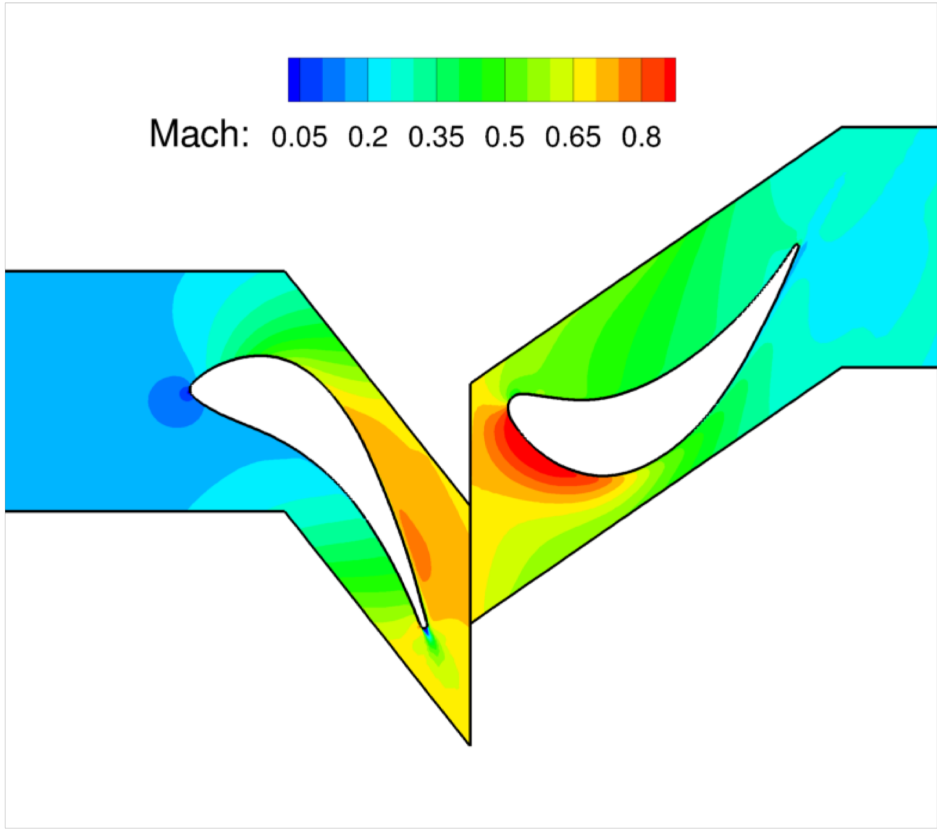
Mixing/averaging



Flow instantaneously mixes-out at the mixing plane rather than undergoing a continuous and gradual mixing downstream.

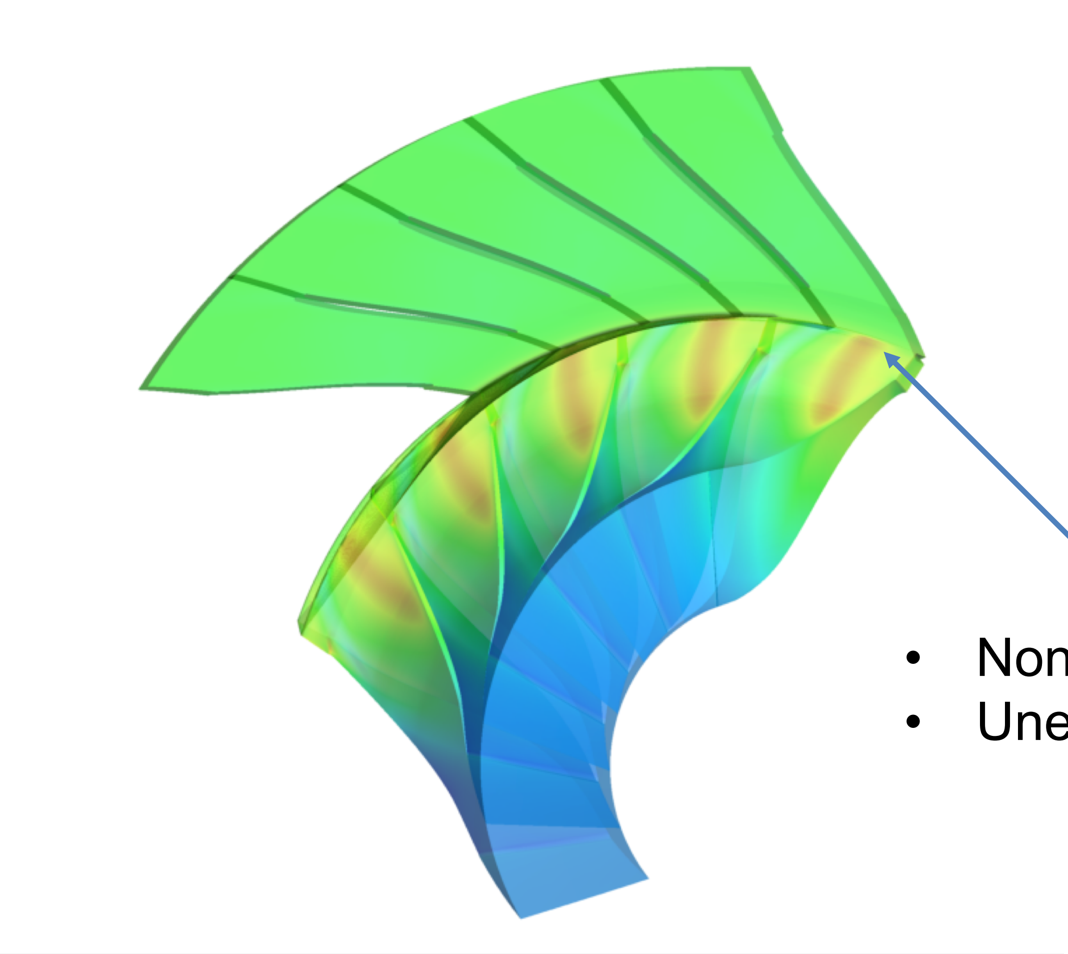
Flow is Not Uniform After Mixing-Plane



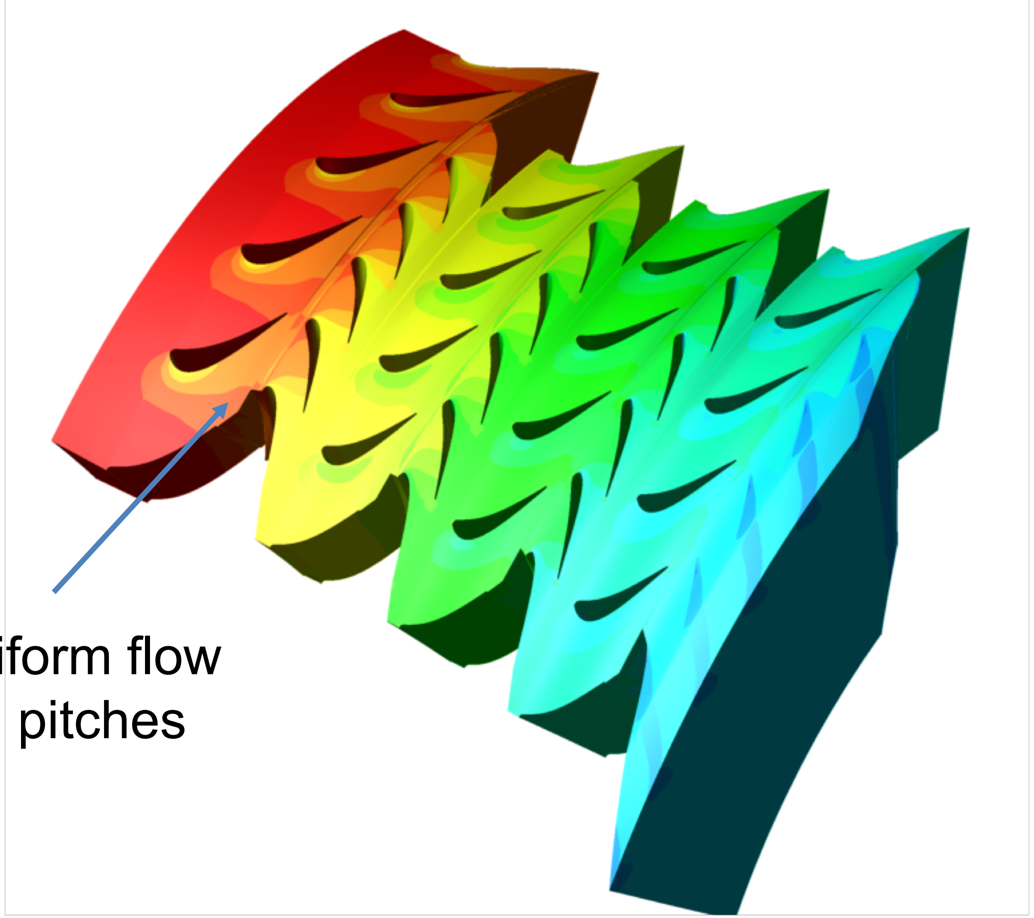


The mixing plane must conserve the pitchwise averaged fluxes of mass, momentum, and energy (and of any other scalar quantity), but it must not impose pitchwise uniform conditions on the flow.

Application to Industrial Machines



Centrifugal compressor



Multi-stage axial turbine

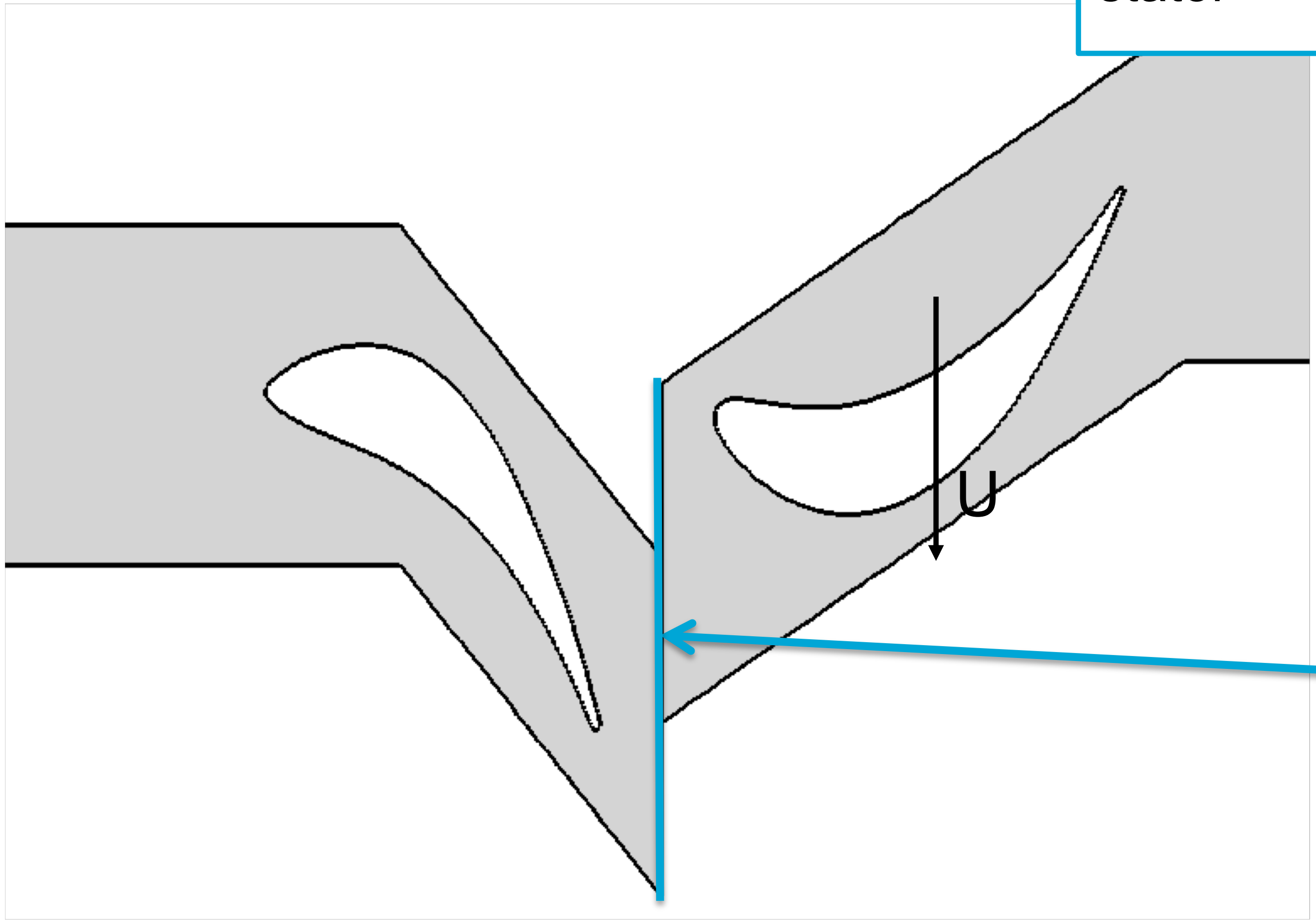
- Non-uniform flow
- Uneven pitches

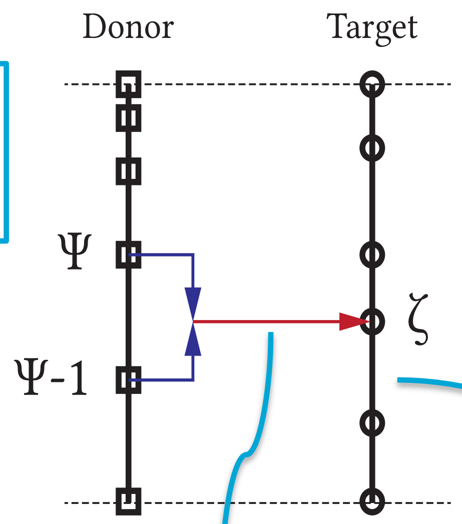
Simulations performed with MULTALL code

Summary Mixing-Plane

- Mixing-plane enabled steady multi-row calculations at manageable costs for routine use in industry
- Several variants of the method exist, but the underlying idea (instantaneous mixing) is common to all
- Though departure from real flow physics, steady multi-row calculations with mixing-plane work remarkably well for efficiency characterization of turbomachinery

Frozen-Rotor





Mesh 1, e.g. stator

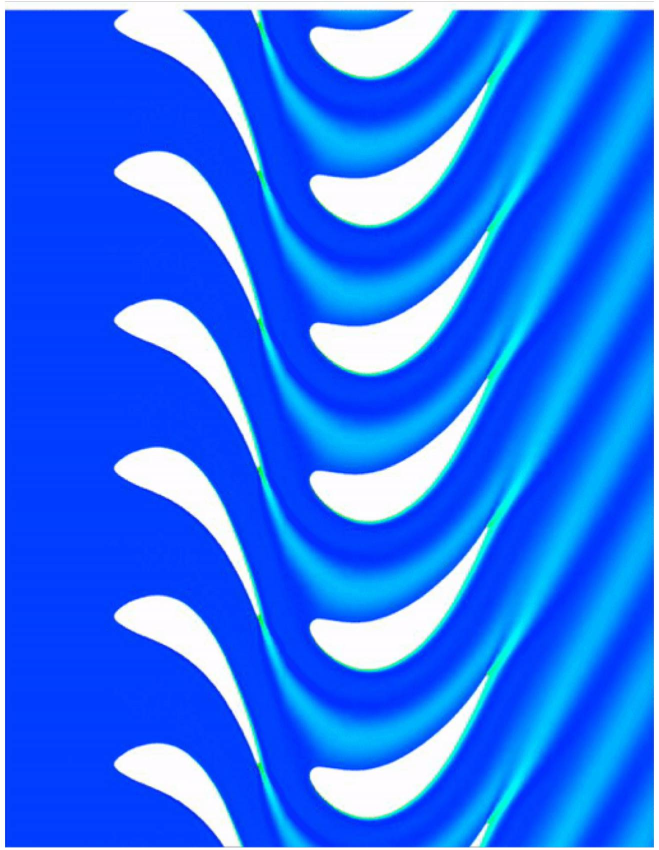
Mesh 2, e.g. rotor

Interpolation

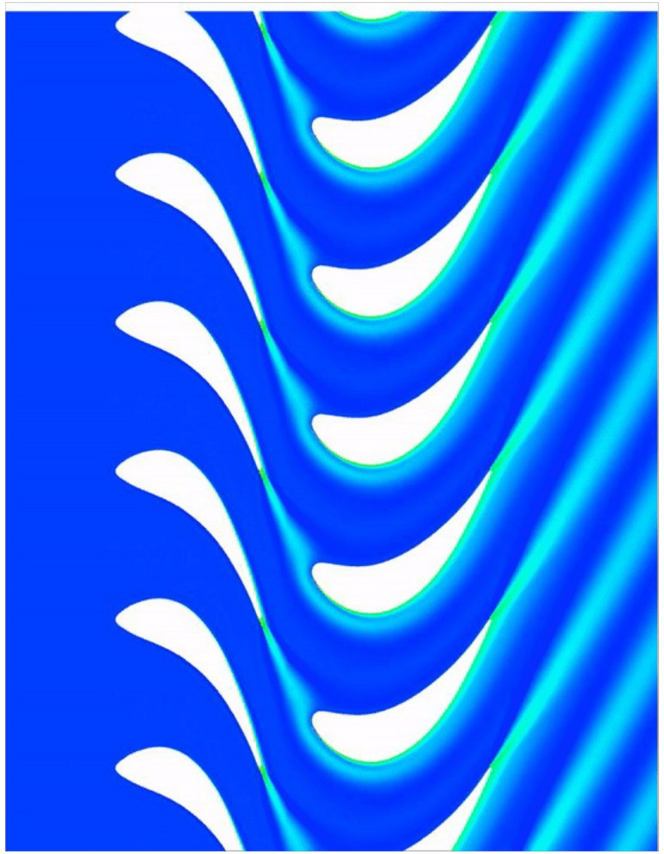
Steady

Rotor kept “frozen” with respect to the one of the stator. All non-uniform features of the flow are passed from one flow domain to the other.

Challenge 1: Relative Position



$t = t_1$

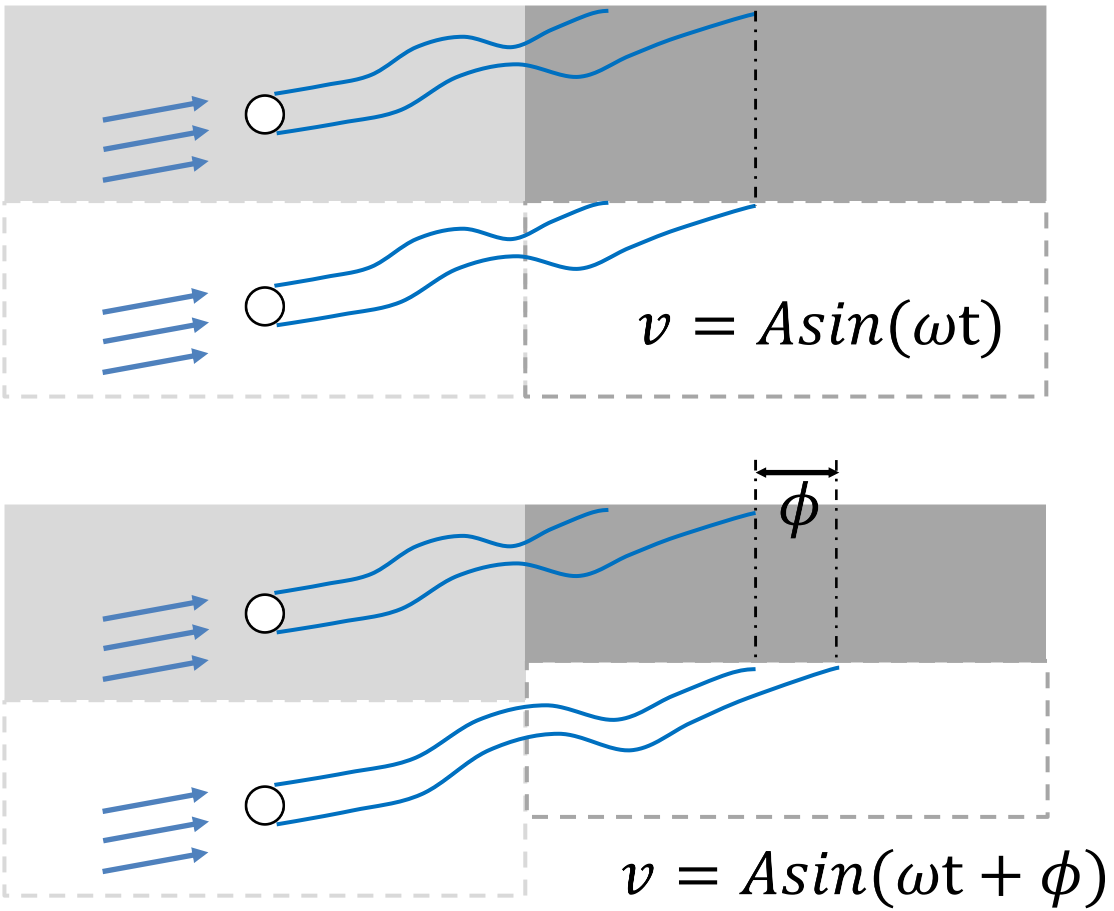


$t = t_2$

Since the rotor position is frozen, the flow dynamic of the two interacting components is strongly dependent on their relative position.

Useful to initialize unsteady computations with sliding-mesh

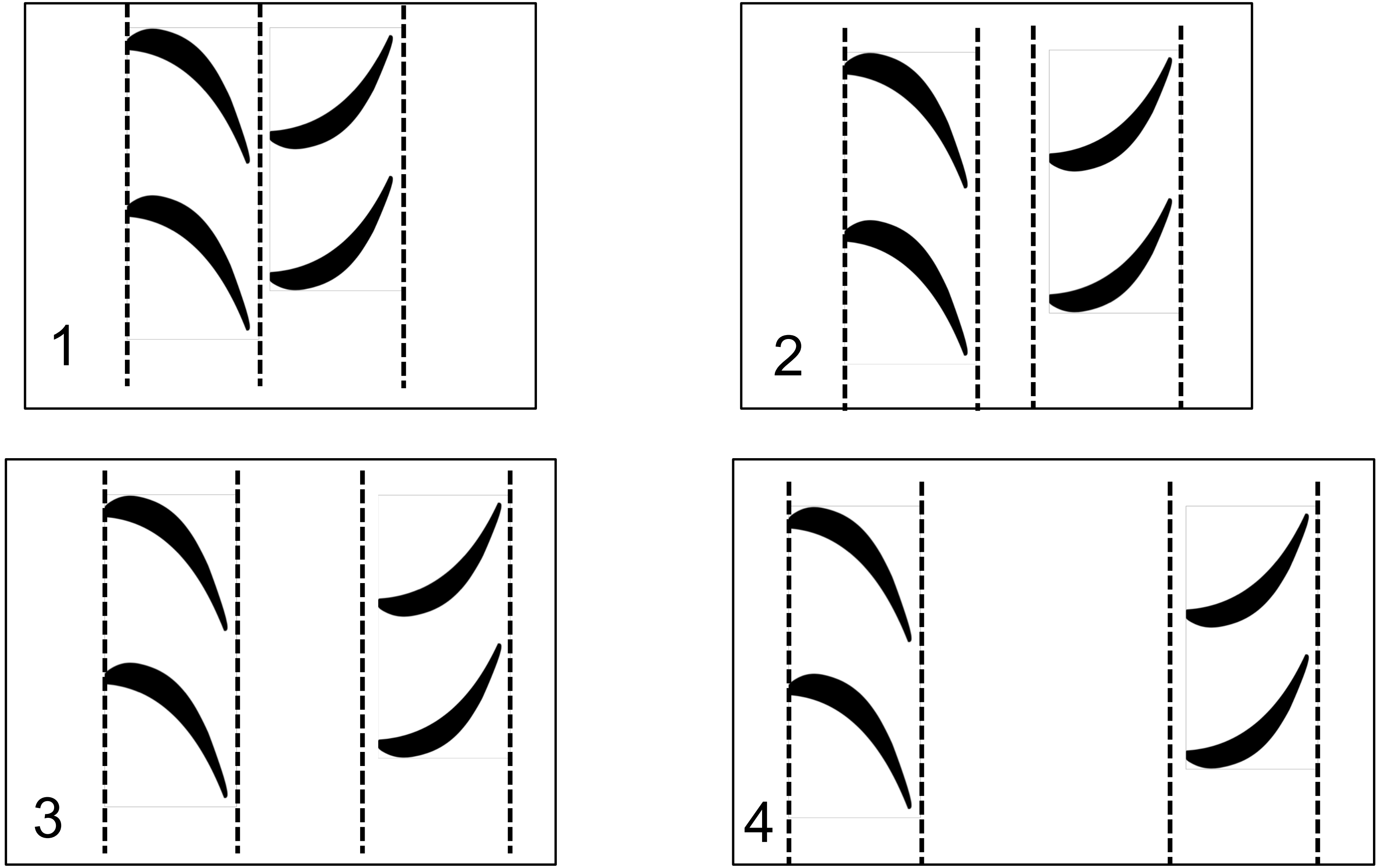
Challenge 2: Phase Lag on Periodic BCs



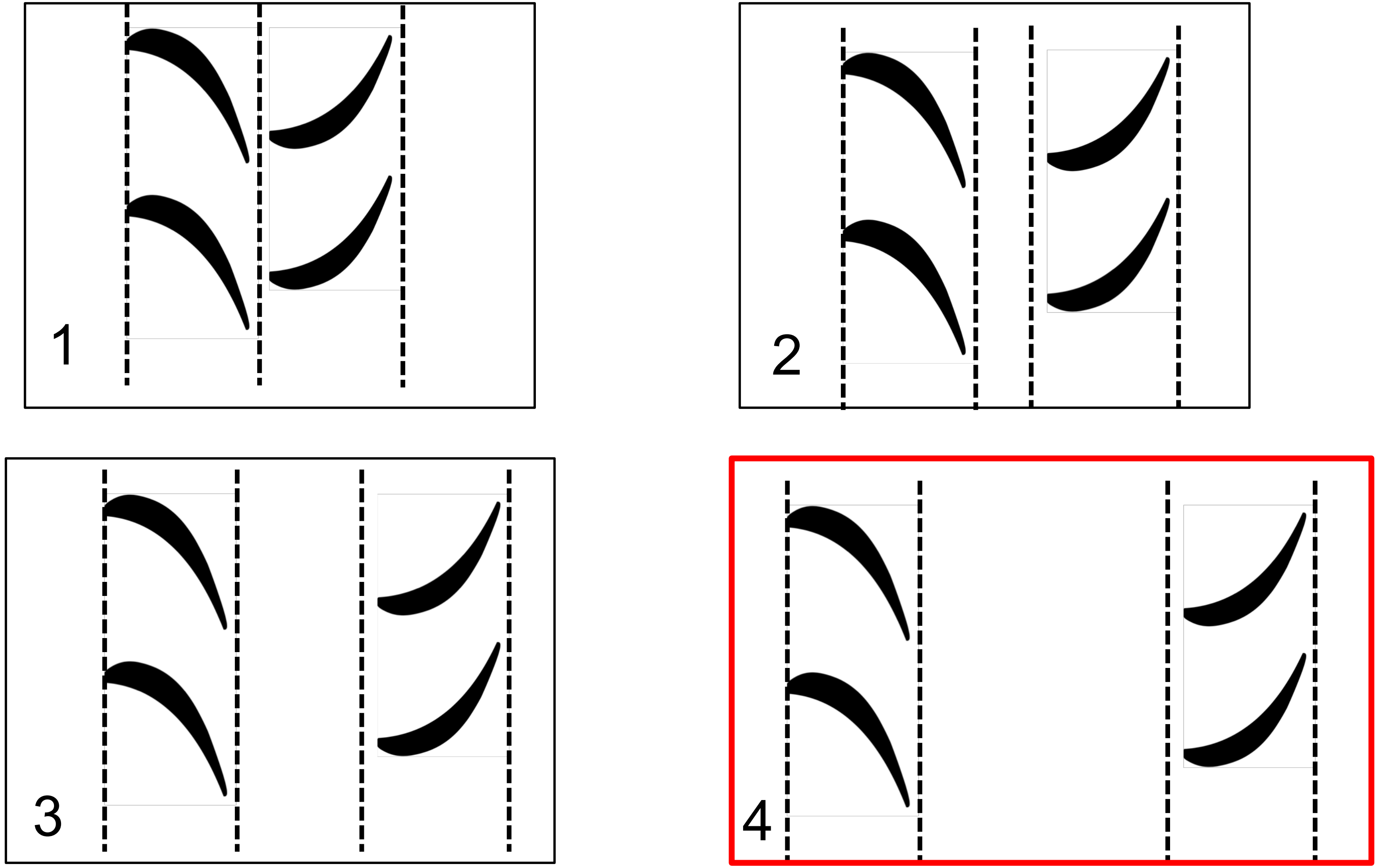
When the pitch ratio between the rows is uneven, i.e. not integer multiple, standard periodic BCs cannot be applied because of a *temporal (or spatial) lag* ϕ in the solution. In this case, so-called *phase-lag* periodic BCs must be used.

Where Would you Use the Frozen-Rotor Method?

go to question



Where Would you Use the Frozen-Rotor Method?



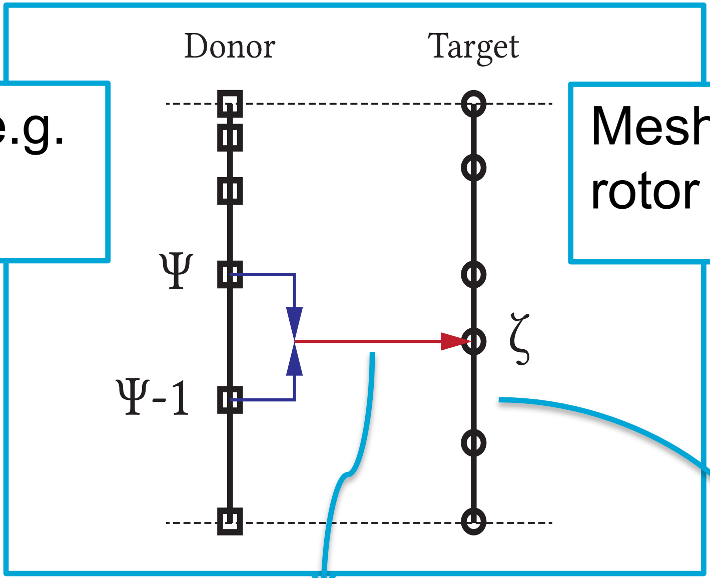
Summary

- Frozen-rotor provides results that are sensitive to the relative position of components, especially in case of tight fluid-dynamic coupling between them.
- Common practice when looking at the interaction between vaned and vaneless turbomachinery components. Typical case is rotor-diffuser, impeller-volute or inlet duct-impeller interaction.
- For uneven pitch ratios, phase-lag BCs are required

UNSTEADY SIMULATION

Sliding-mesh

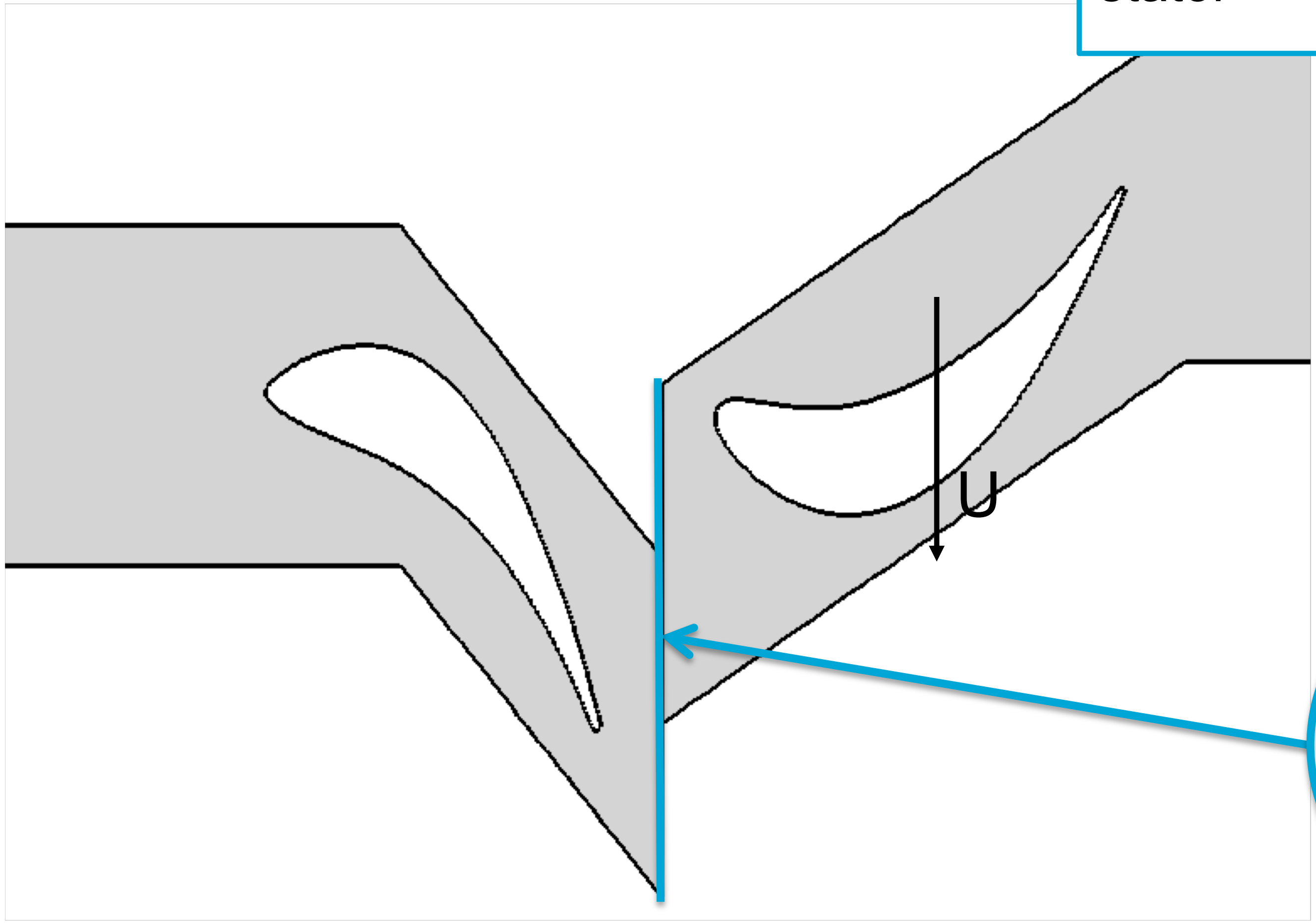
Mesh 1, e.g. stator



Mesh 2, e.g. rotor

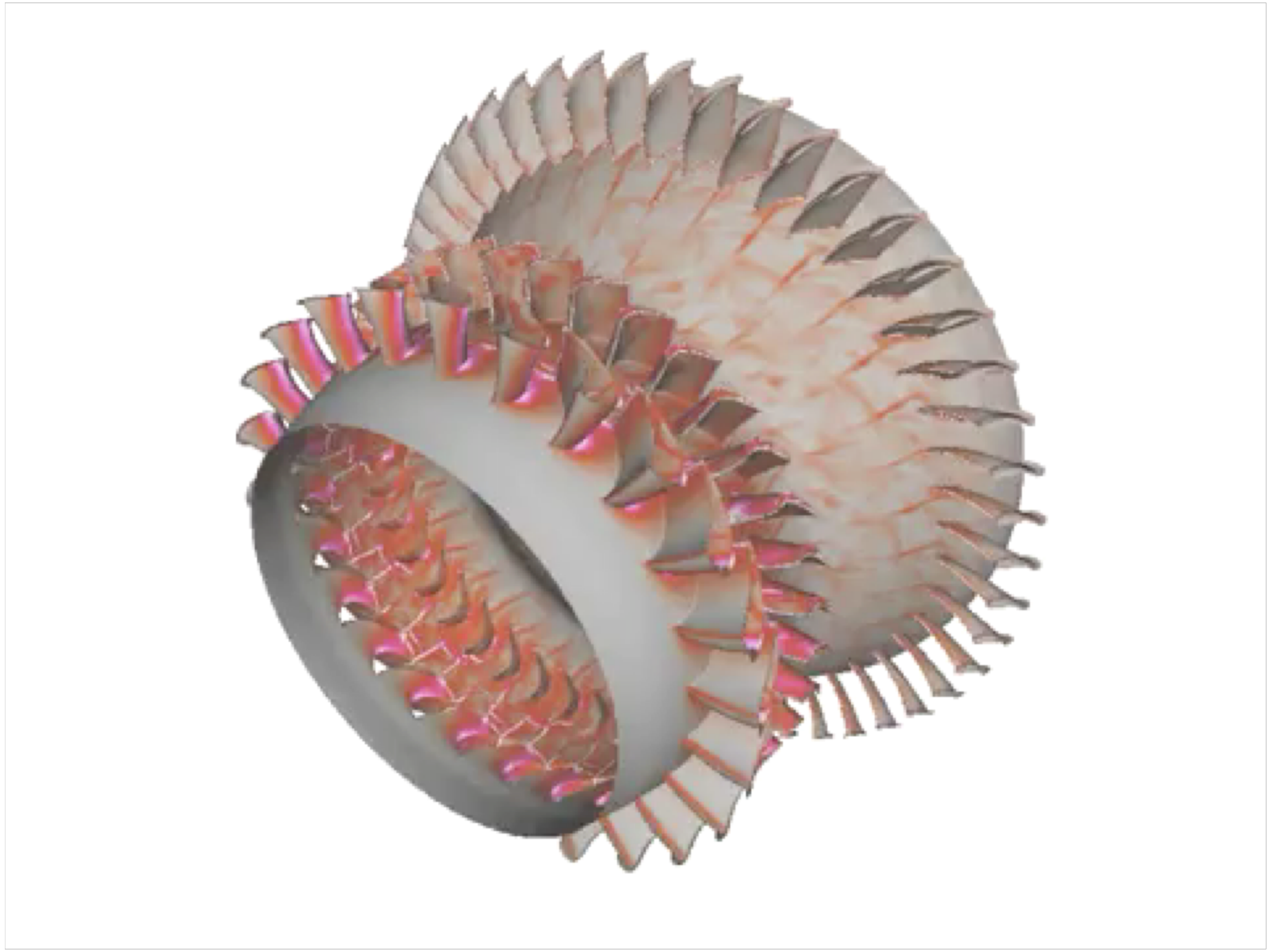
Interpolation

Motion

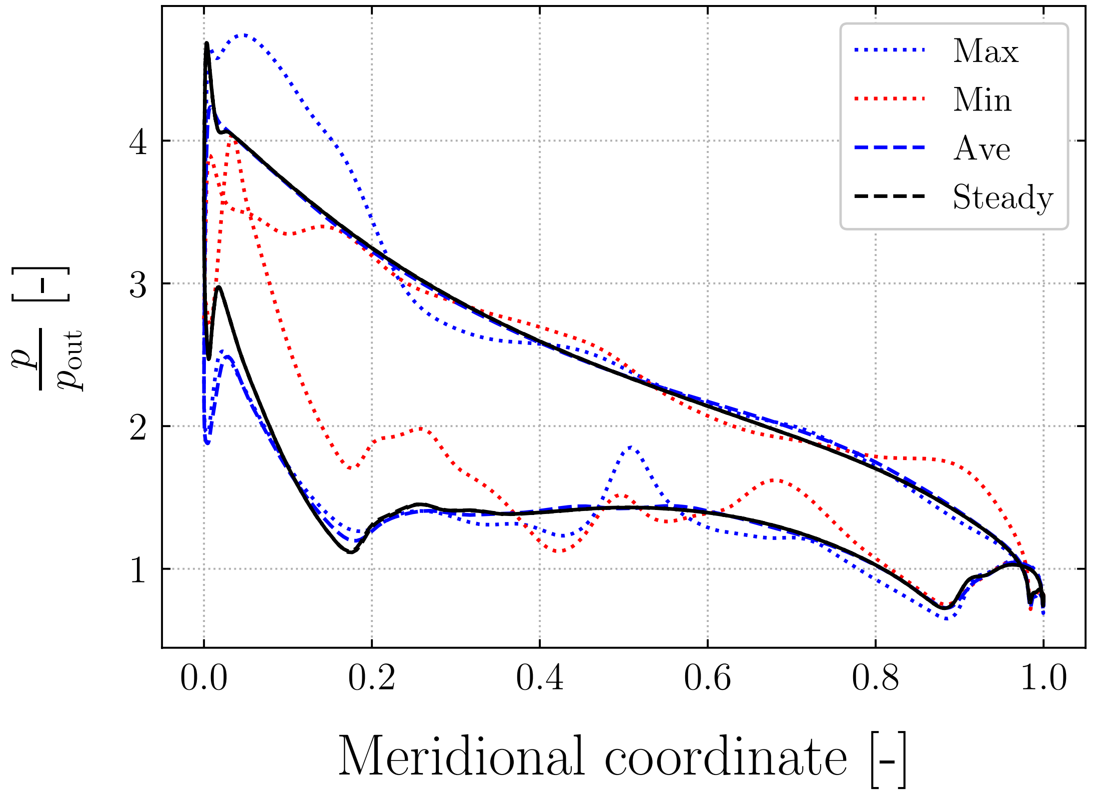


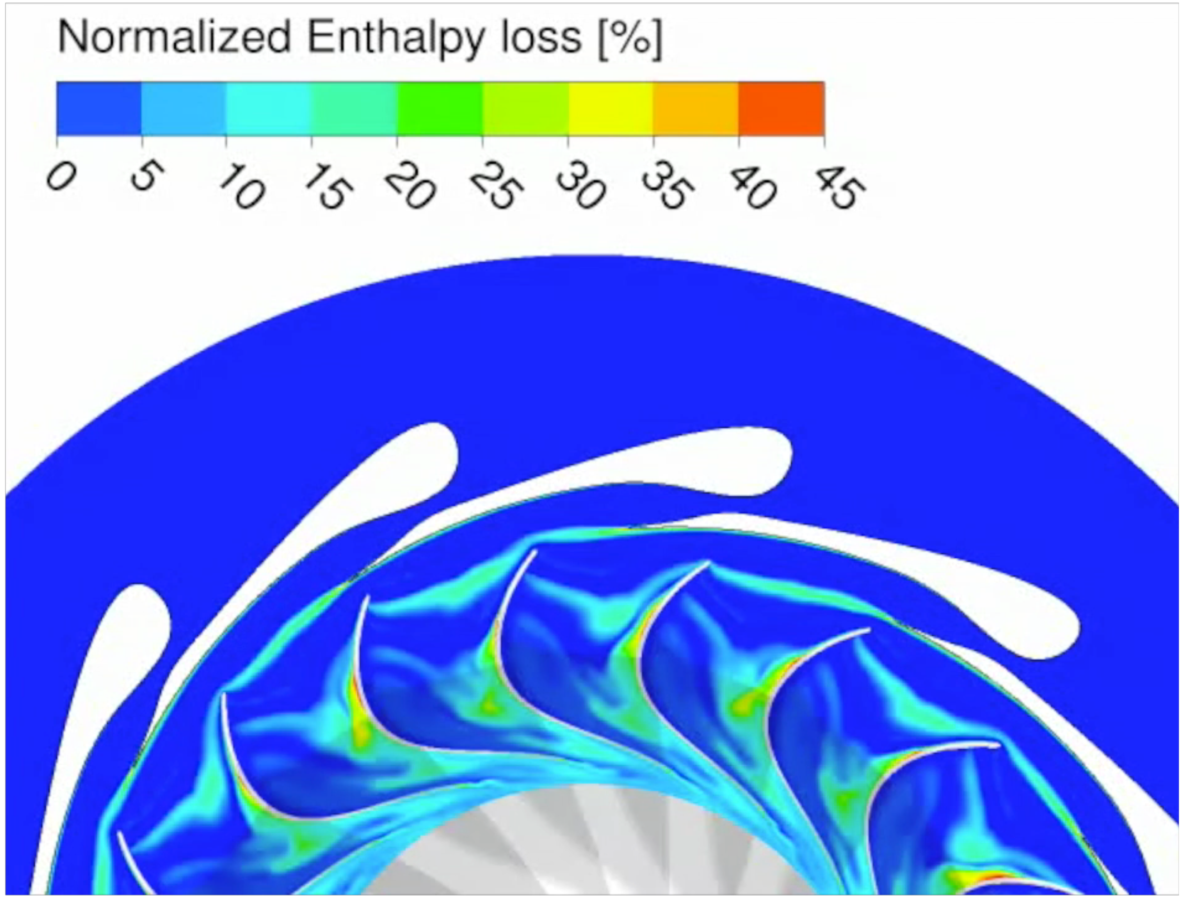
"Sliding" motion between the stationary and the rotating mesh. At each time step of the simulation, the mesh *slides* of a quantity proportional to the speed of revolution of the machine.

Transient Simulation of a Gas Turbine Stage



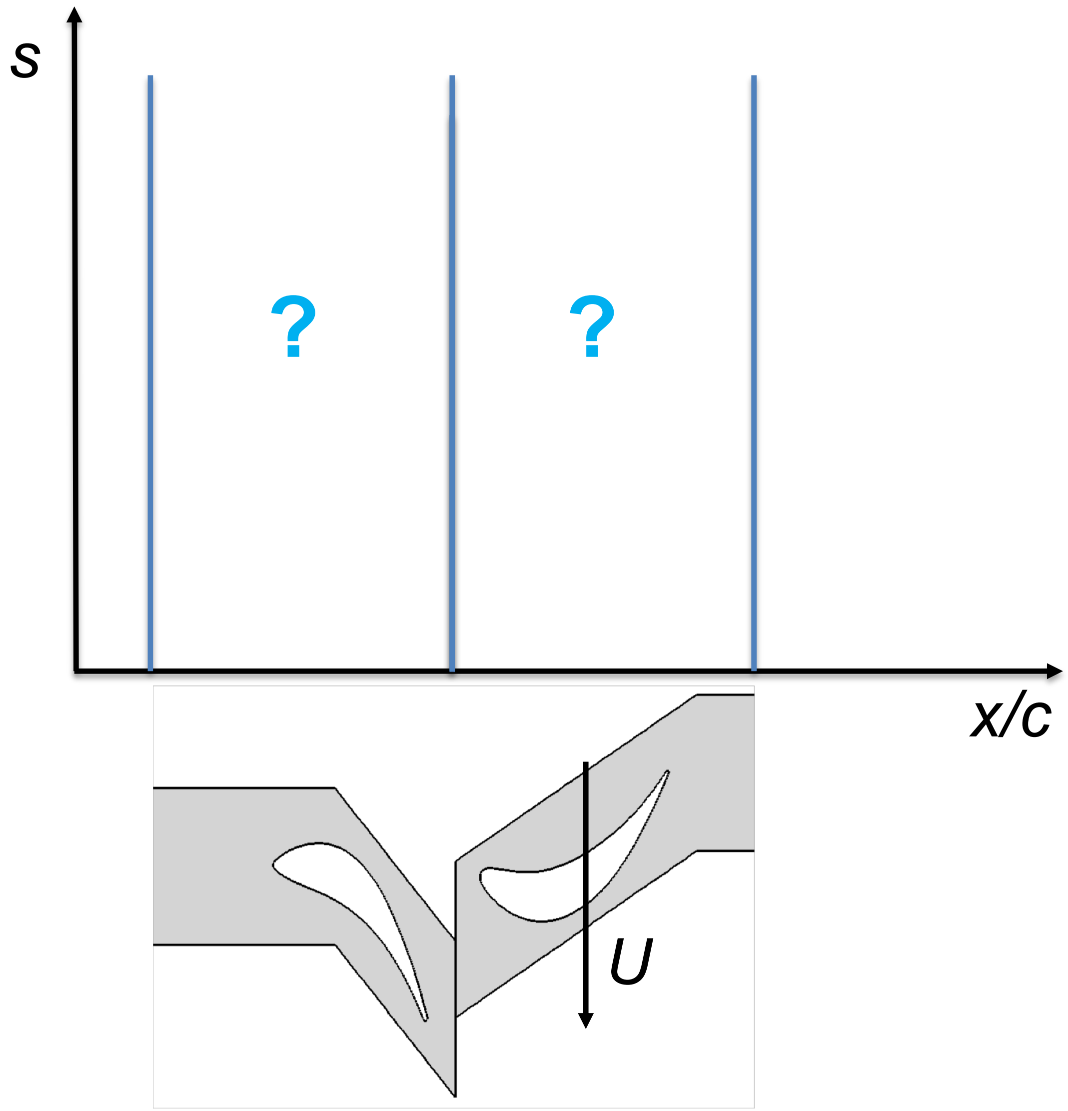
RANS vs. URANS for Supersonic Turbine





Either methods provide comparable efficiency

EXERCISE: plot entropy in turbine stage



Summary

- For industry practices, URANS is the most accurate method for blade row calculations

- Cost and memory requirement (also I/O) still an issue, especially for multi-stage turbomachinery → not applicable for design optimization

- Good practice to accelerate convergence of URANS methods is to initialize using a steady solution obtained by using the mixing-plane

Reduced Order Models for Unsteady Simulations: Harmonic Balance

What is Harmonic Balance (HB)?

A **Reduced Order Model** to solve for **unsteady** effects characterized by a **known** discrete set of **frequencies**

Question: which of the following problems cannot be tackled by HB?

a) Noise landing gear

b) Unsteady load on isolated wind turbine blade

c) Stator-rotor wake interaction of a multi-stage turbine

d) Pulsing inlet flow in turbochargers

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a) **Noise landing gear**

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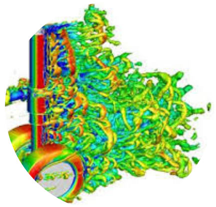
Where Can It be Applied?

Unsteady Phenomena

Tonal

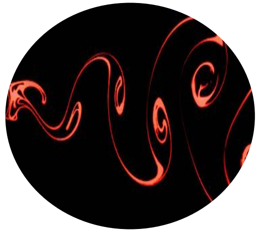
Known $\{\omega_1, \omega_2, \dots, \omega_K\}$



Unknown $\{\omega_1, \omega_2, \dots, \omega_K\}$

Periodic

Known T



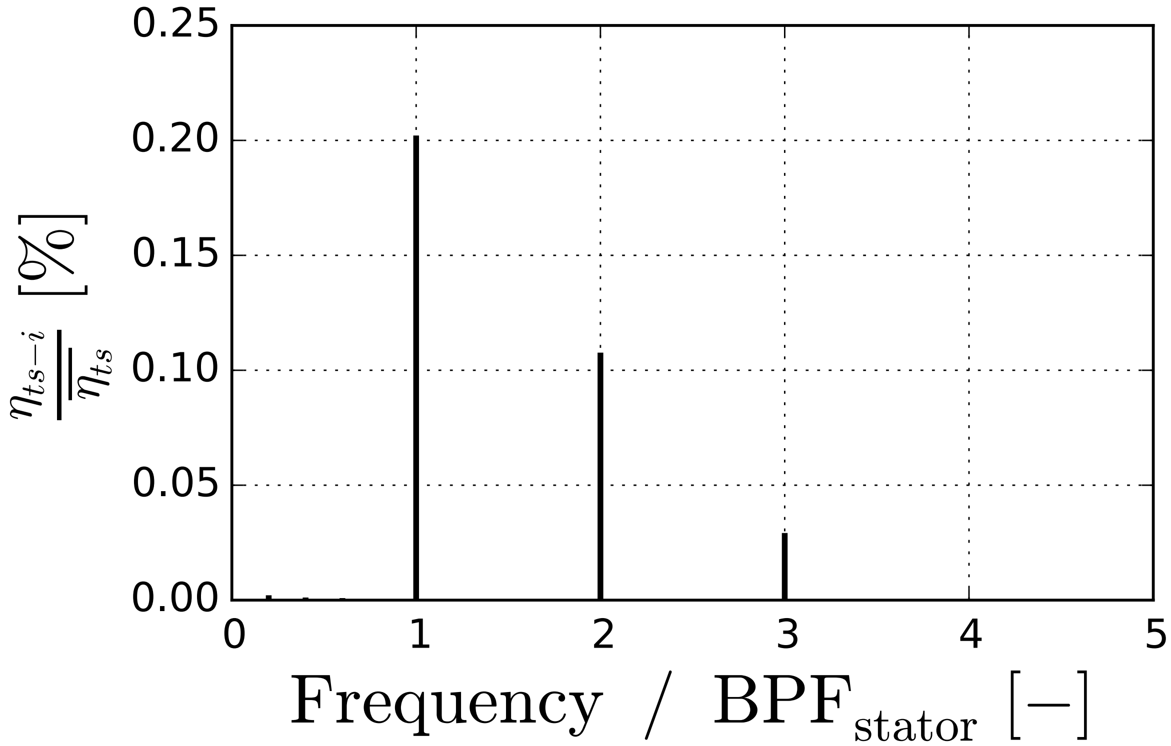
Unknown T

HB in a nutshell

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

An example of periodic signal

Frequency Spectrum of a Typical Turbomachinery Stage (URANS)



BPF = blade passing frequency

Typically, 3 harmonics are enough to estimate performance with engineering accuracy. The harmonics are here normalized by the BPF of the stator.

Pros & Cons

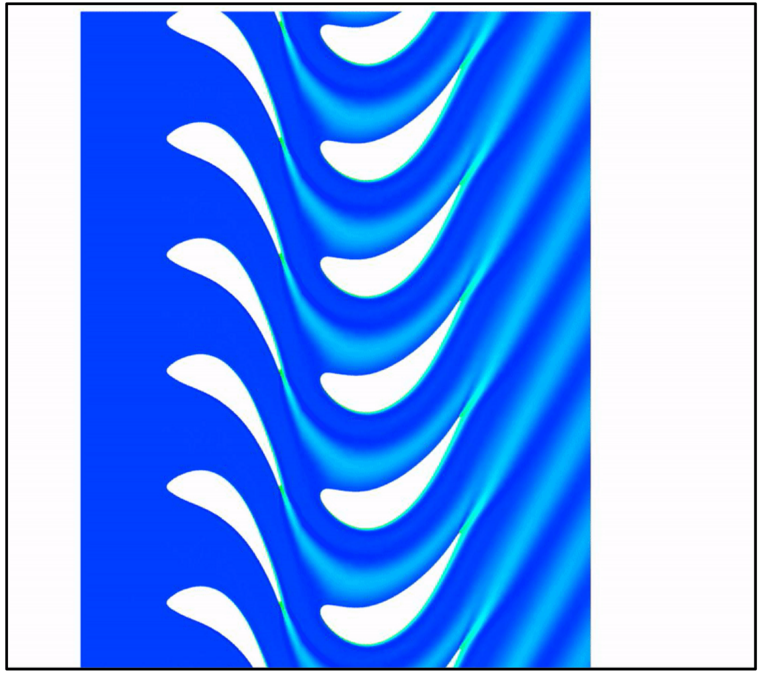
PROS :

- Analogy with steady-state
- Faster compared to time-accurate
- Very suitable for unsteady optimization
- Low I/O CPU overhead

CONS :

- Memory (compared to steady-state)
- Trade-off performance vs accuracy
- Numerical stability

Methods Comparison



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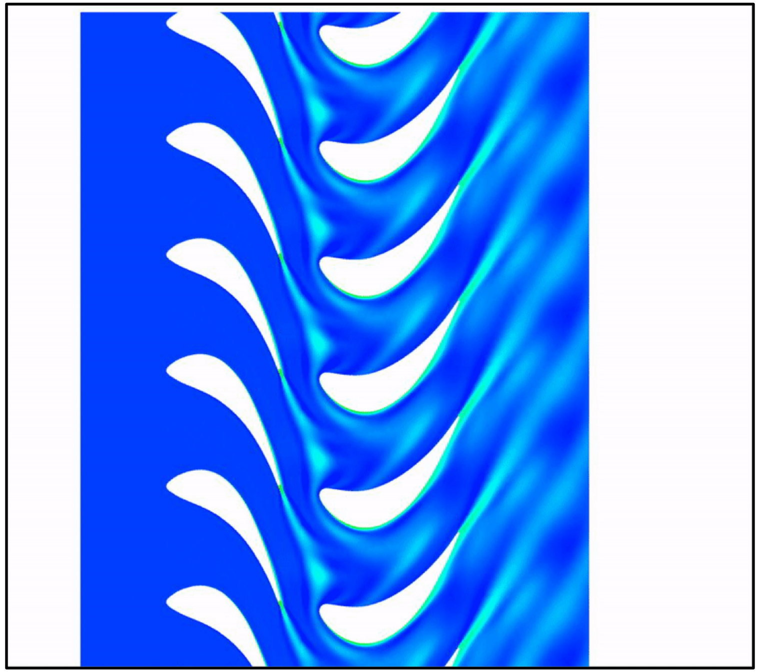

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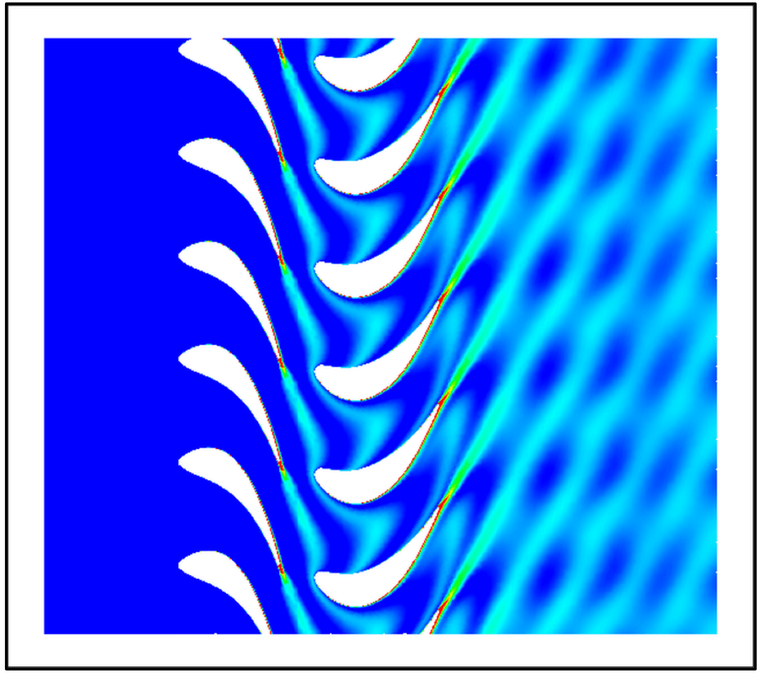

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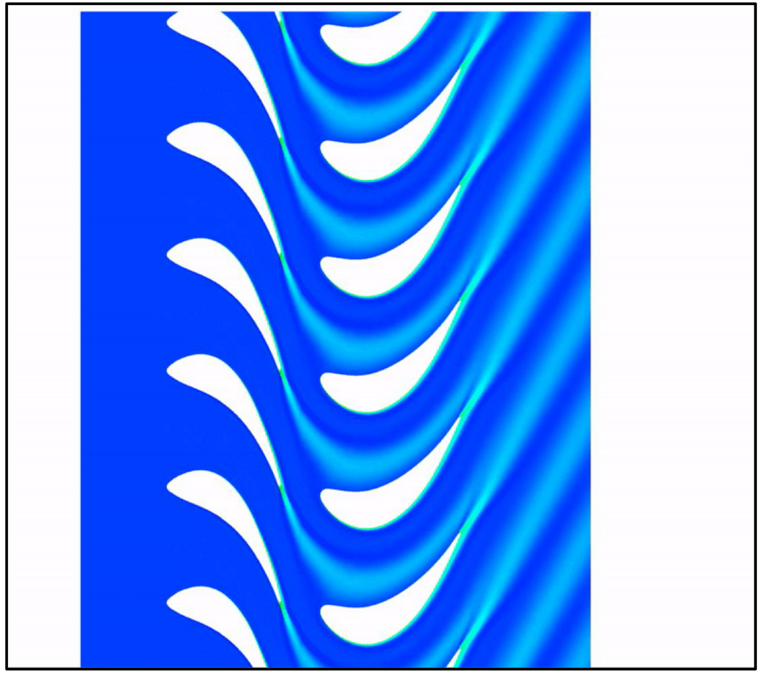
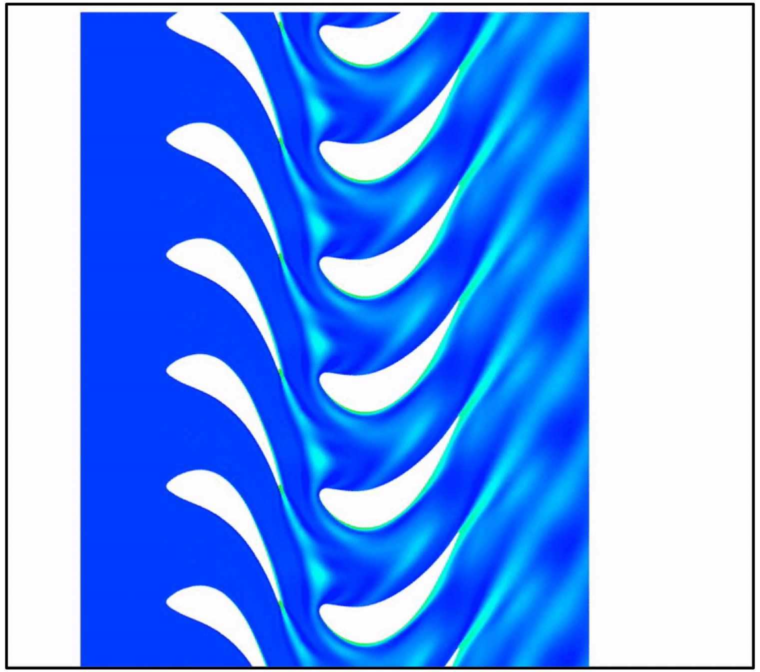
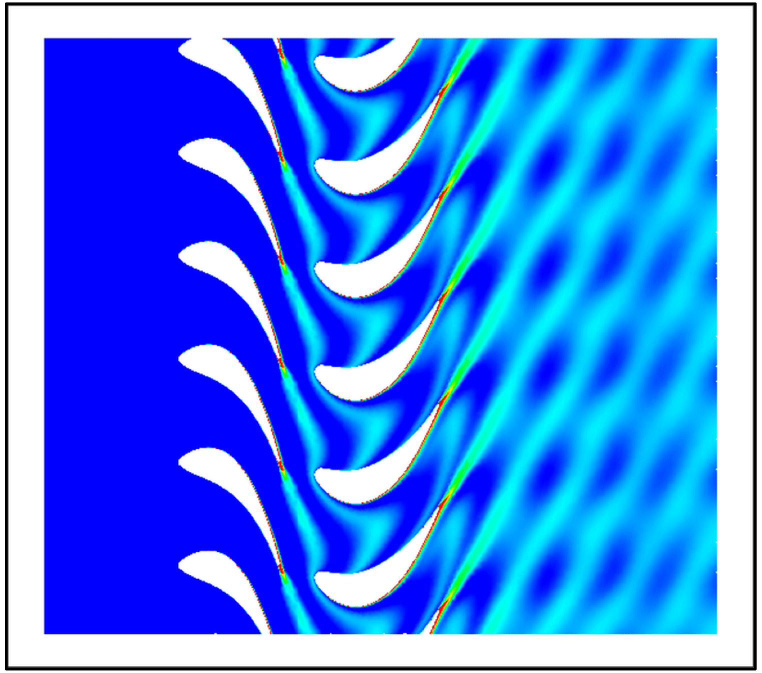


Frozen-rotor

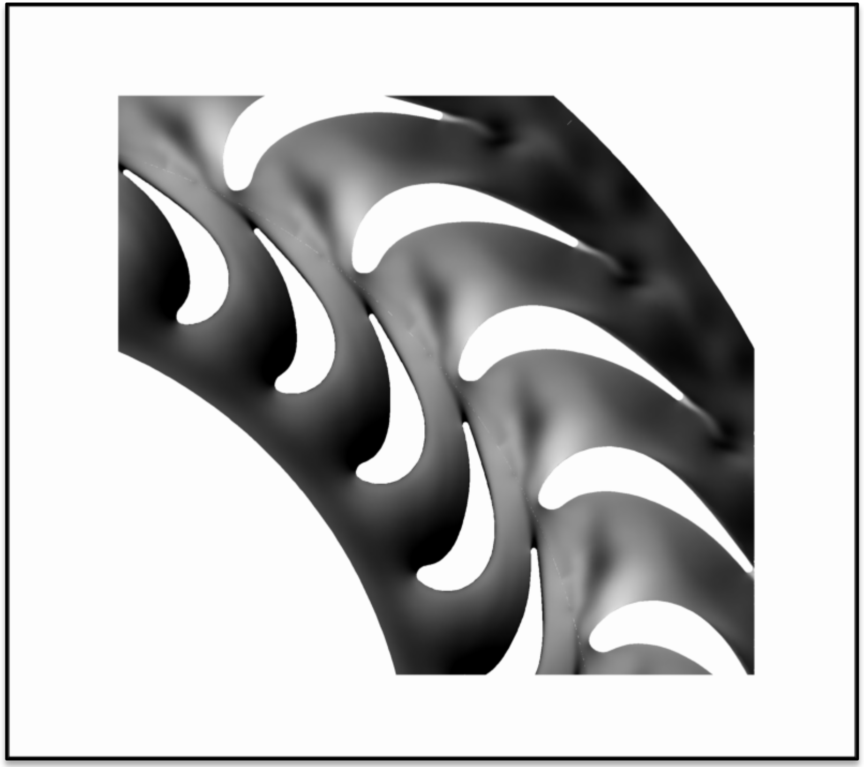


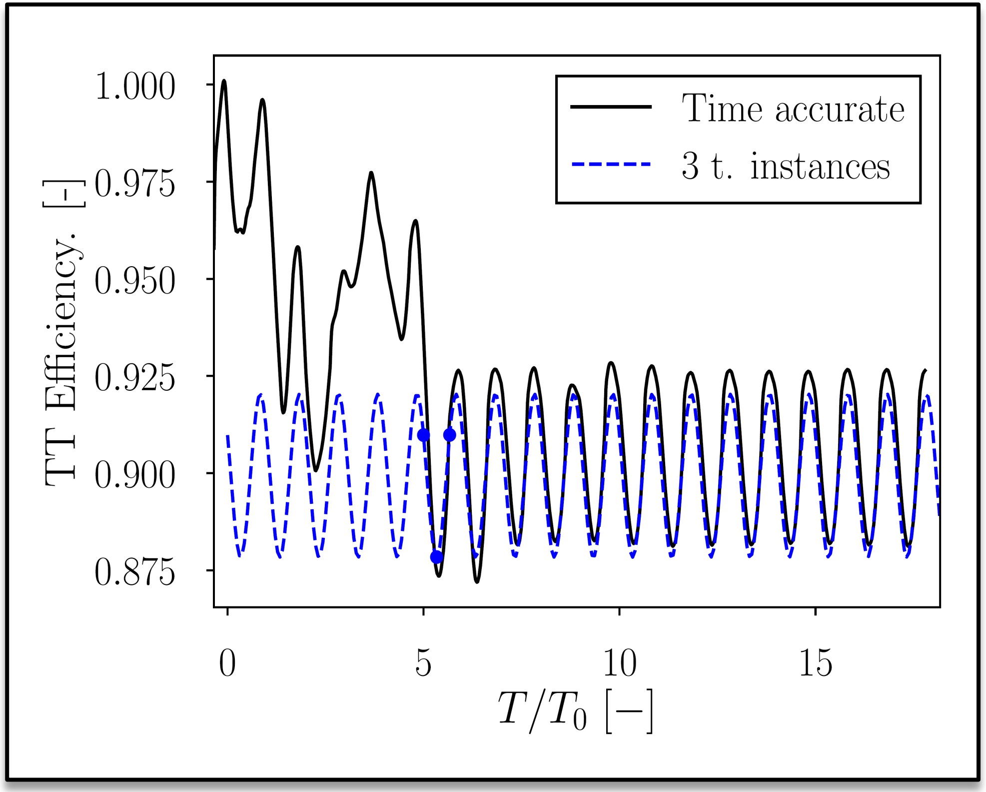
Harmonic balance



Time-accurate

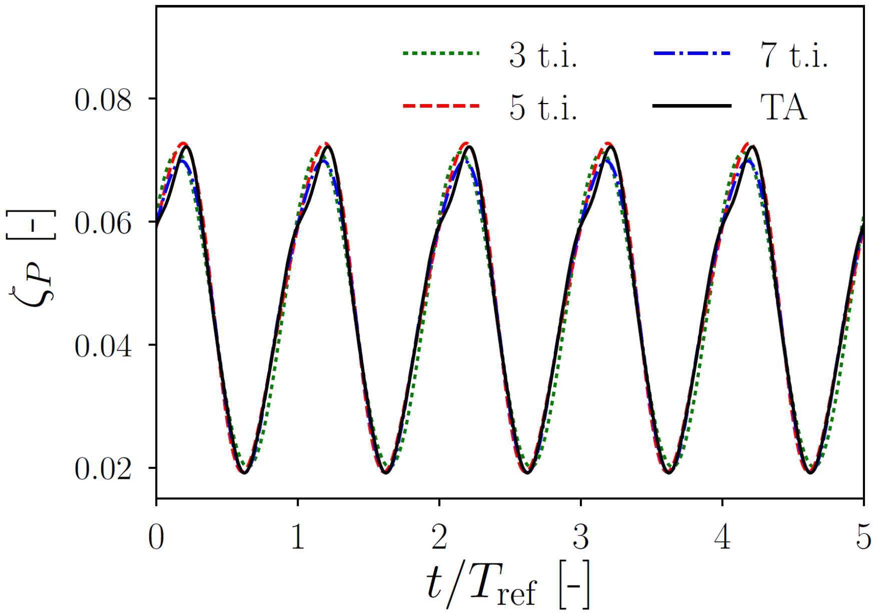
Comparison HB vs. Time-Accurate

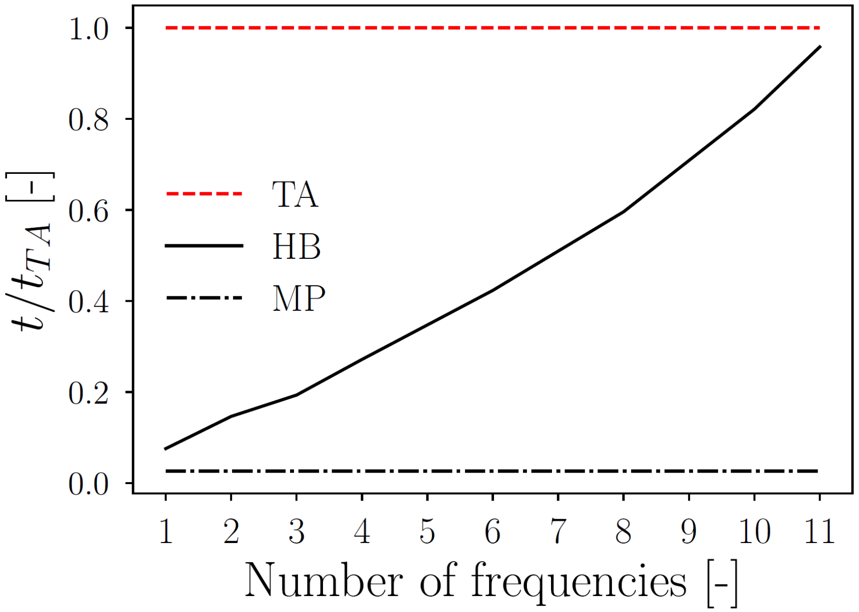




The use of HB allows to elude the calculation of the initial transient typical of time-accurate (URANS) simulations

Comparison of Computational Cost





The computational cost of HB can exceed the one of time-accurate simulations for high number of frequencies

TA = time accurate, HB = harmonic balance, MP = mixing-plane

Summary

- Harmonic balance is a reduced order model for unsteady computation of turbomachinery flows
- The method can handle a set of discrete frequencies, not necessarily multiple of each other, to be known a-priori
- Highly suited to simulate stator-rotor interaction and for all those cases where the harmonics are known.

LIMITATIONS OF TURBOMACHINERY CFD

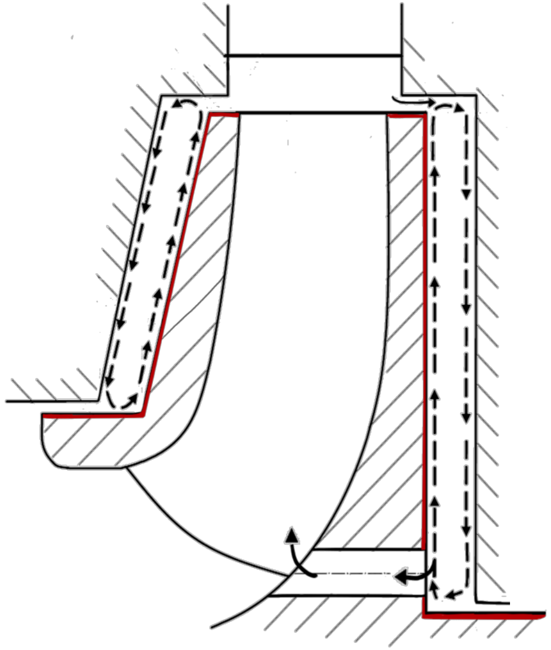
What is Still Hard to Model and Predict in Turbomachinery with CFD

- Boundary layer transition
- Turbulence effects (modeling)
- Endwall losses and leakage flows
- Leading-edge (compressors) and trailing-edge (turbine) flows

J.D. Denton, "*Some Limitations of Turbomachinery CFD*", Proceedings of ASME-Turbo Expo 2010

Because We Usually Ignore or Neglect

- Geometrical details
- Boundary conditions
- Freestream turbulence
- Endwall boundary layers



Some final tips …

- Carefully assess the **convergence** of your simulation (residuals, grid independence, conservation laws …)

- **Check** whether your results make any sense and that they are not violating any physical law!

- Focus on selecting just the **relevant** information from the output

- **Interpret** the results without forgetting the **initial goal** of your simulation!

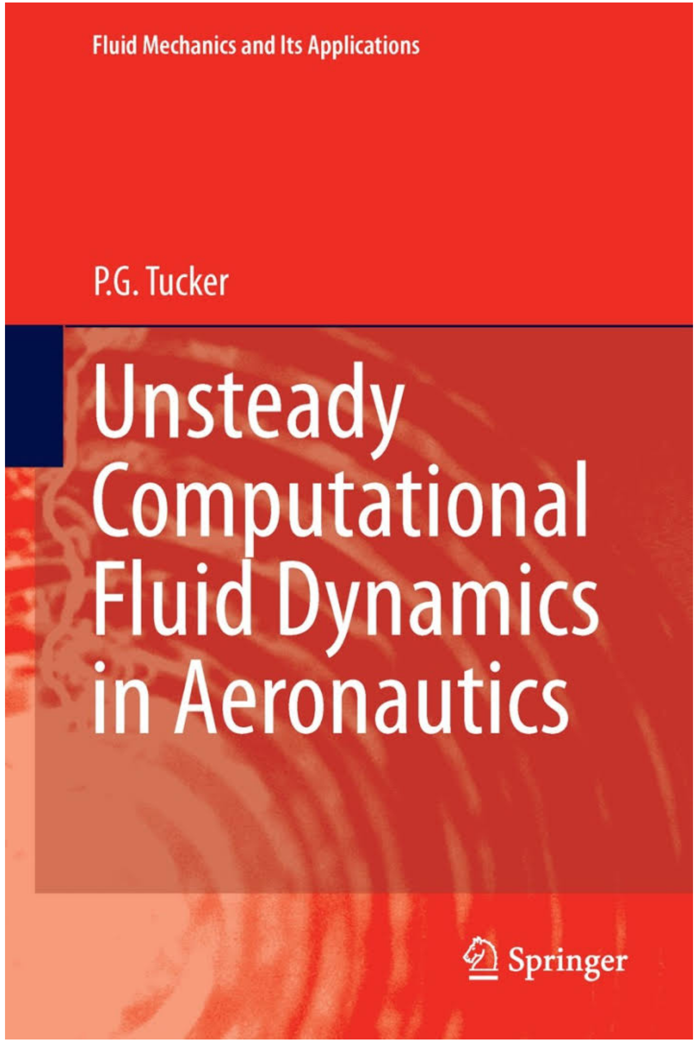
Online resources

- http://www.cfd-online.com/Wiki/Best_practice_guidelines_for_turbomachinery_CFD

- https://turbmodels.larc.nasa.gov/

Useful Reading

- P.G. Tucker, *Unsteady Computational Fluid Dynamics in Aeronautics*, Springer, 2014



Questions?