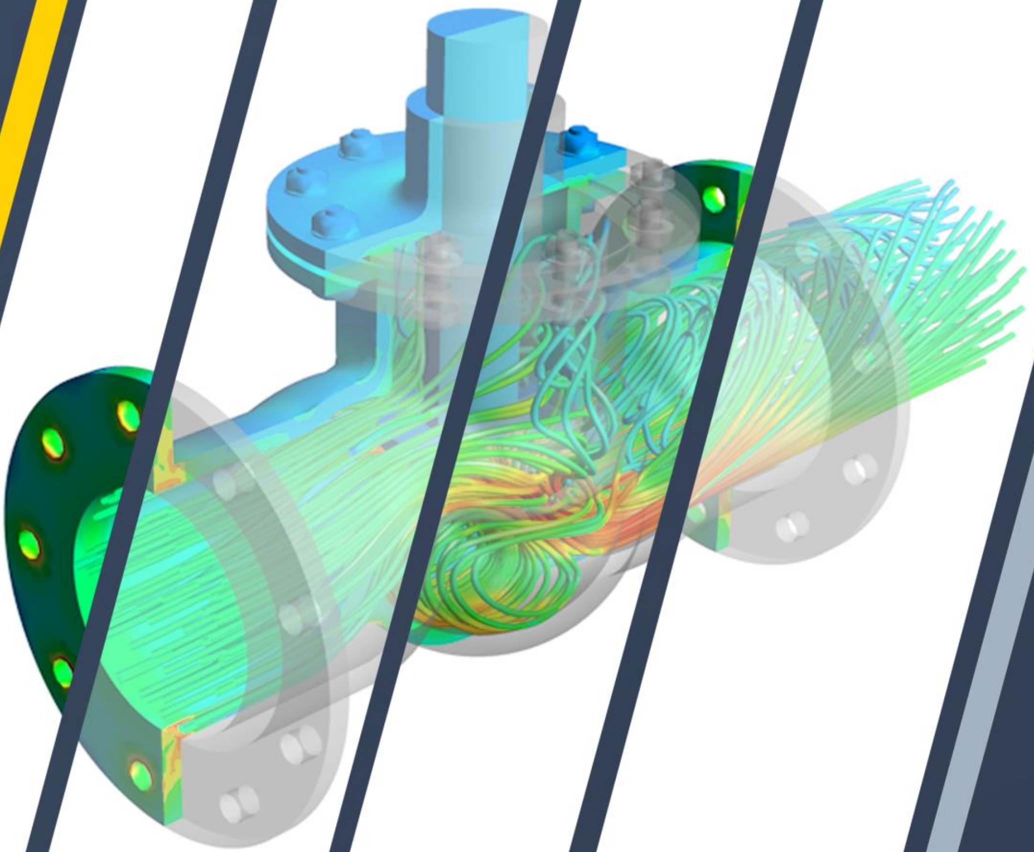
Lecture 04: Multi-Component Analysis - Steady

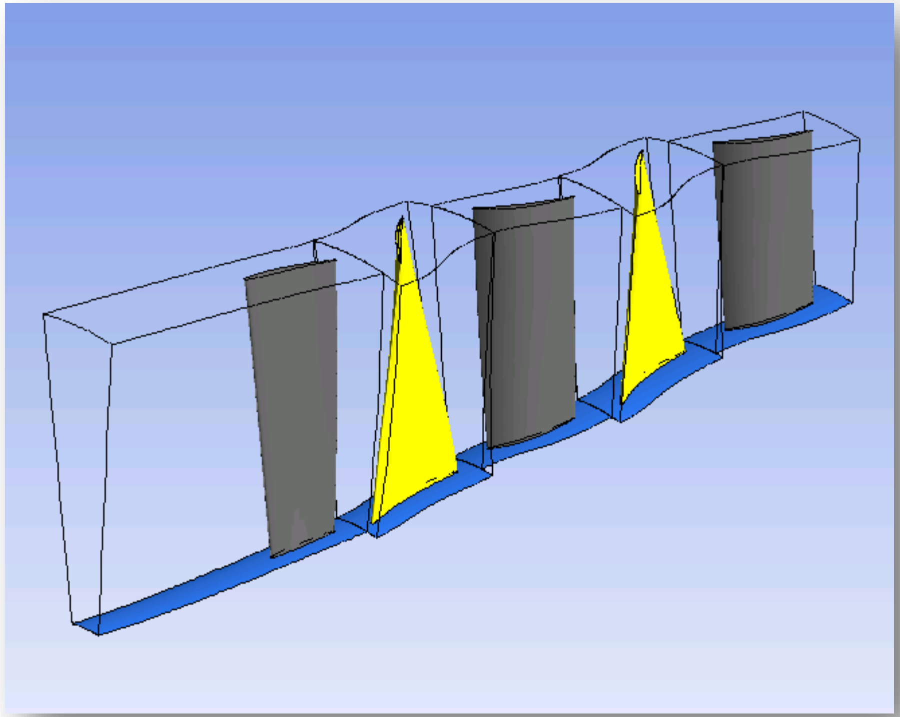


ANSYS CFX Rotating Machinery Modeling

Release 2019 R3

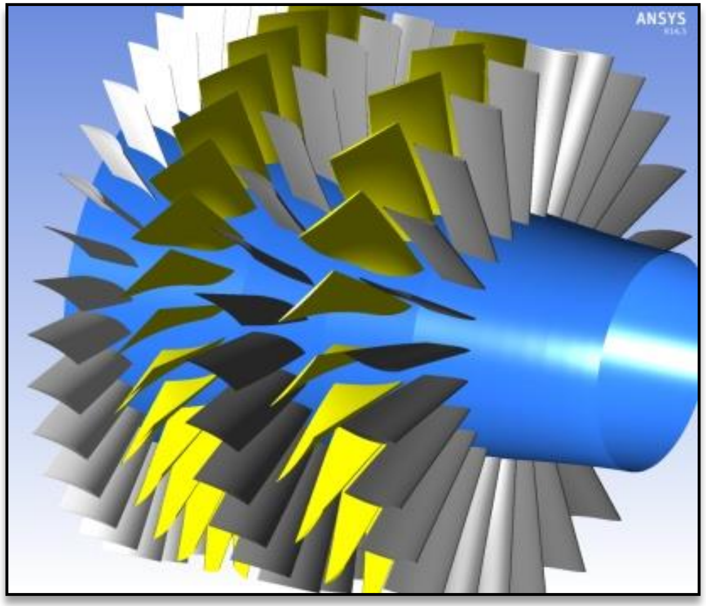
Outline

- Introduction to Multi-Component Analysis
- Multiple Frames of Reference
- Mixing Plane Model
- Frozen Rotor Model
- Multiple Frames of Reference Interfaces
- Summary



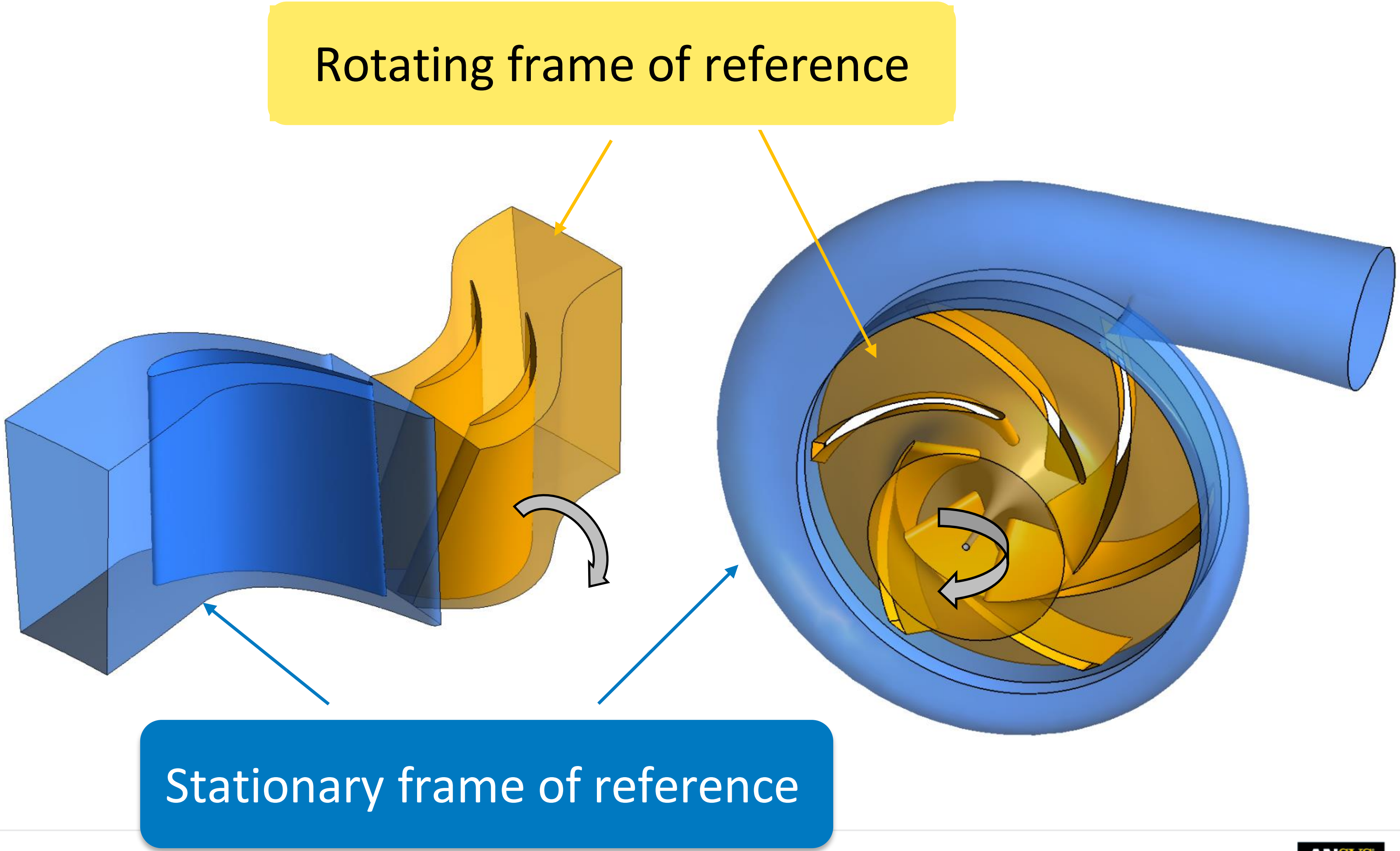
Introduction to Multi-Component Analysis

- Many rotating machines contain multiple components (Multi-stage machines)
  - A stage consists of stator blade row (to turn the flow appropriately) and a rotor blade row (to add to or extract energy from the flow)
- Some contain stationary surfaces which are not surfaces of revolution about the axis of rotation
  - Example: The volute surfaces of a pump
- Single rotating component analysis could still be used for simplified single rotating parts
  - Example: pump impeller rotor domain (see workshop 1 of this course)
- Most useful to examine component interactions
  - Match components to achieve desired performance over operating range



Introduction to Multi-Component Analysis (2)

- Multi-Component Analysis is best performed using the Multiple Frames of Reference (MFR) ANSYS CFX capability
- Flow domain is split to stationary and rotating domains meshed independently
  - Each domain in its respective frame
    - ➢ Rotating domains in Rotating Frames of Reference (RFR)
    - ➢ Stationary domains in Stationary Frames of Reference (SFR)

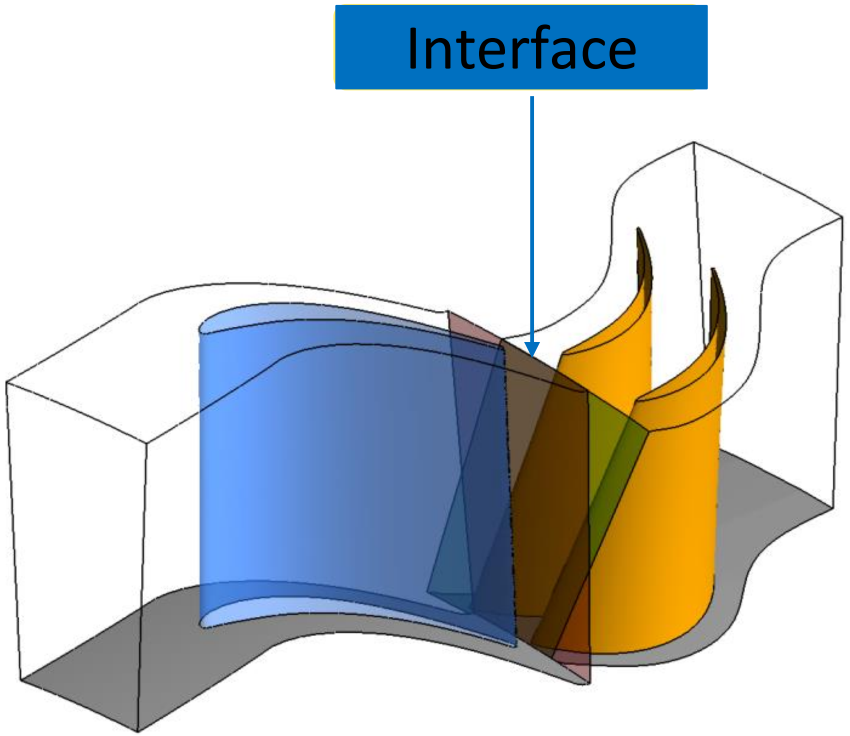


Introduction to Multi-Component Analysis (3)

- MFR method simultaneously solves a series of rotating and stationary components
  - Two-way fully-coupled interactions
- Interfaces between rotating and stationary components handled by flow solver
  - Approaches available:
    - Steady pitch change (pitch change illustrated in next slide)
      - **Mixing Plane Model (MPM)**
      - **Frozen Rotor Model (FRM**)

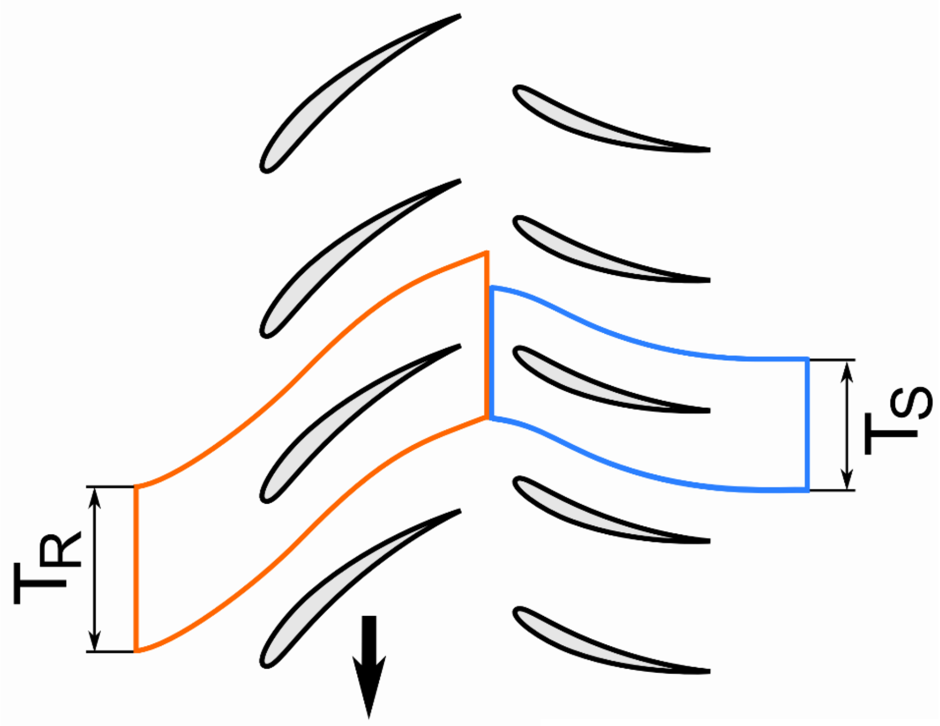
      Covered in this lecture
    - Transient full-annulus
      - Transient Rotor Stator (TRS)
    - Transient pitch change
      - Blade Row (TBR)

      Covered in following lecture
- General combination of components:
  - Any combination of RFR and SFR
  - RFR to RFR: different rotational speeds
  - RFR to RFR: counter-rotating



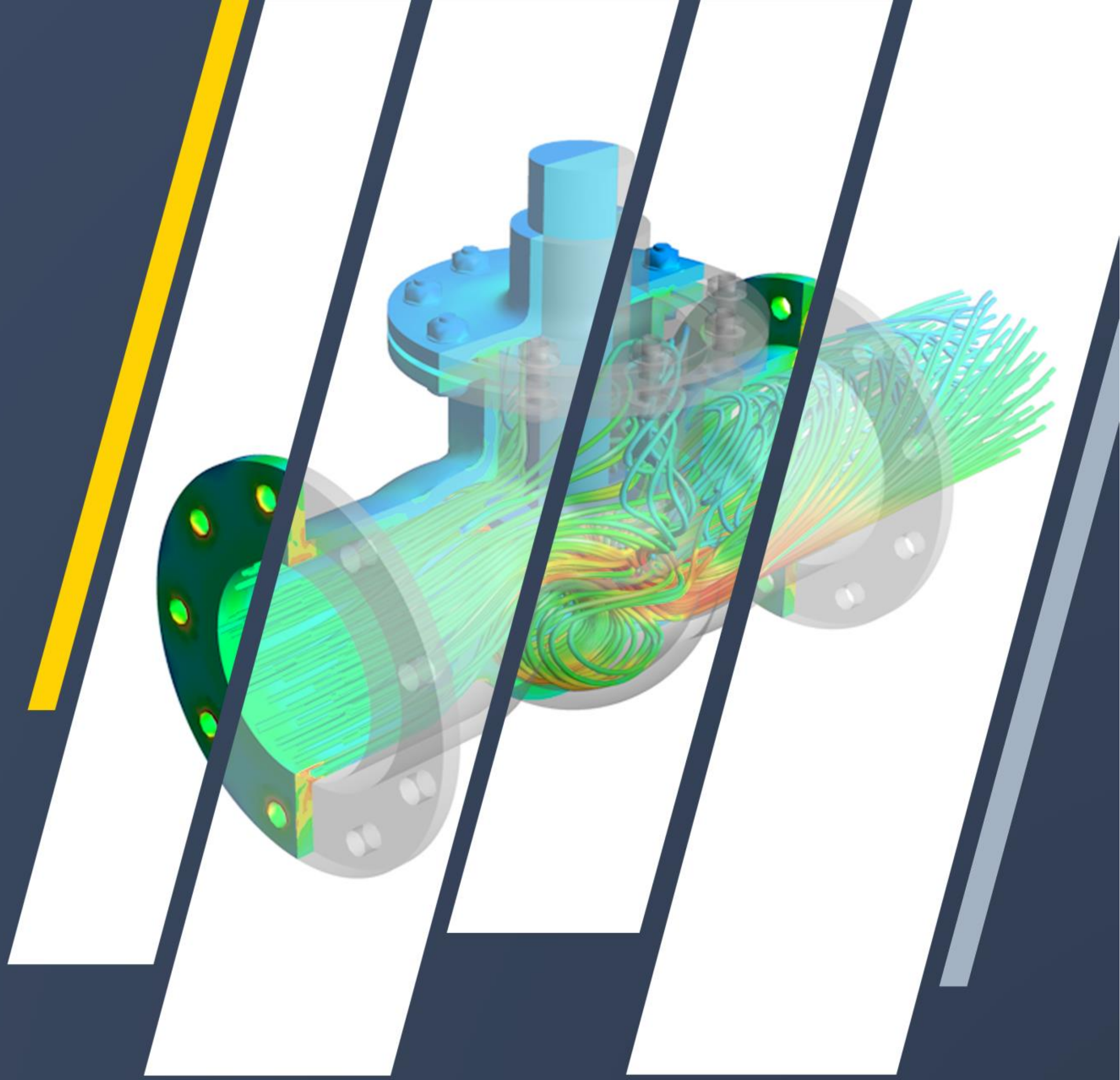
Pitch Change Illustration

- Taking advantage of rotational periodicity in MFR method is especially desirable
  - Solve for one passage per component, where possible
    - ➢ Reduce computation cost
  - Different blade counts in rotor and stator full-wheels result in non-matching pitches between rotor and stator single-passage domains
    - ➢ In the example on the right, 4-blade rotor pitch T_R is larger than 5-blade stator T_S
  - Methods that can account for non-matching pitches are called **pitch change** methods
  - Mixing Plane Model and Frozen Rotor Model are both pitch change methods



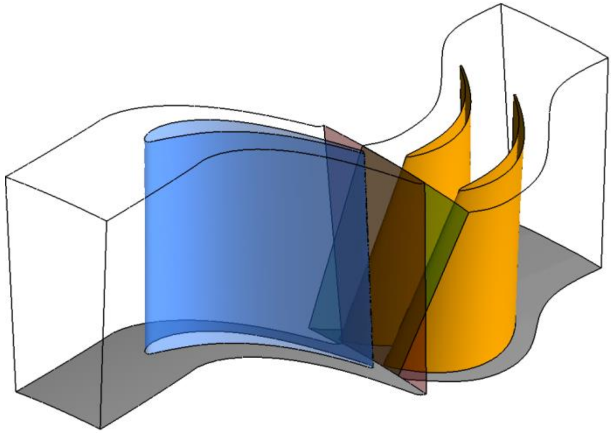
Courtesy Marc Kainz

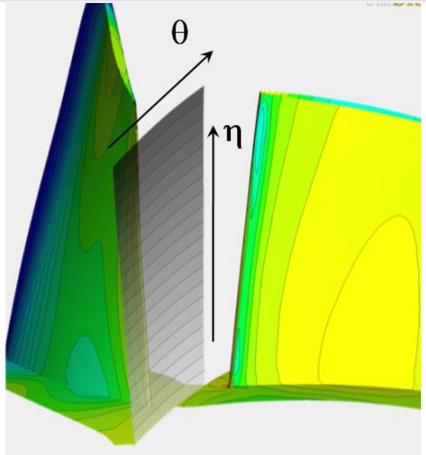
Mixing Plane Model (MPM)



Mixing Plane Model

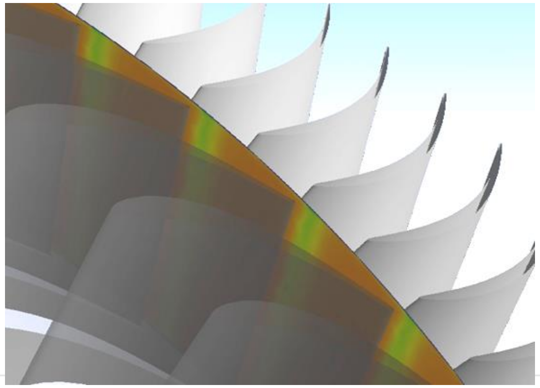
Blade pitch change via conservative "mixing" process in circumferential direction



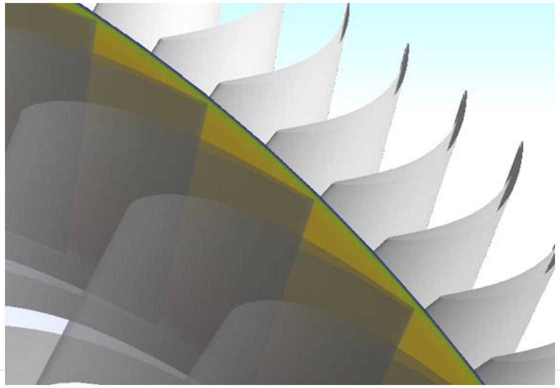


Upstream interface side

Downstream interface side



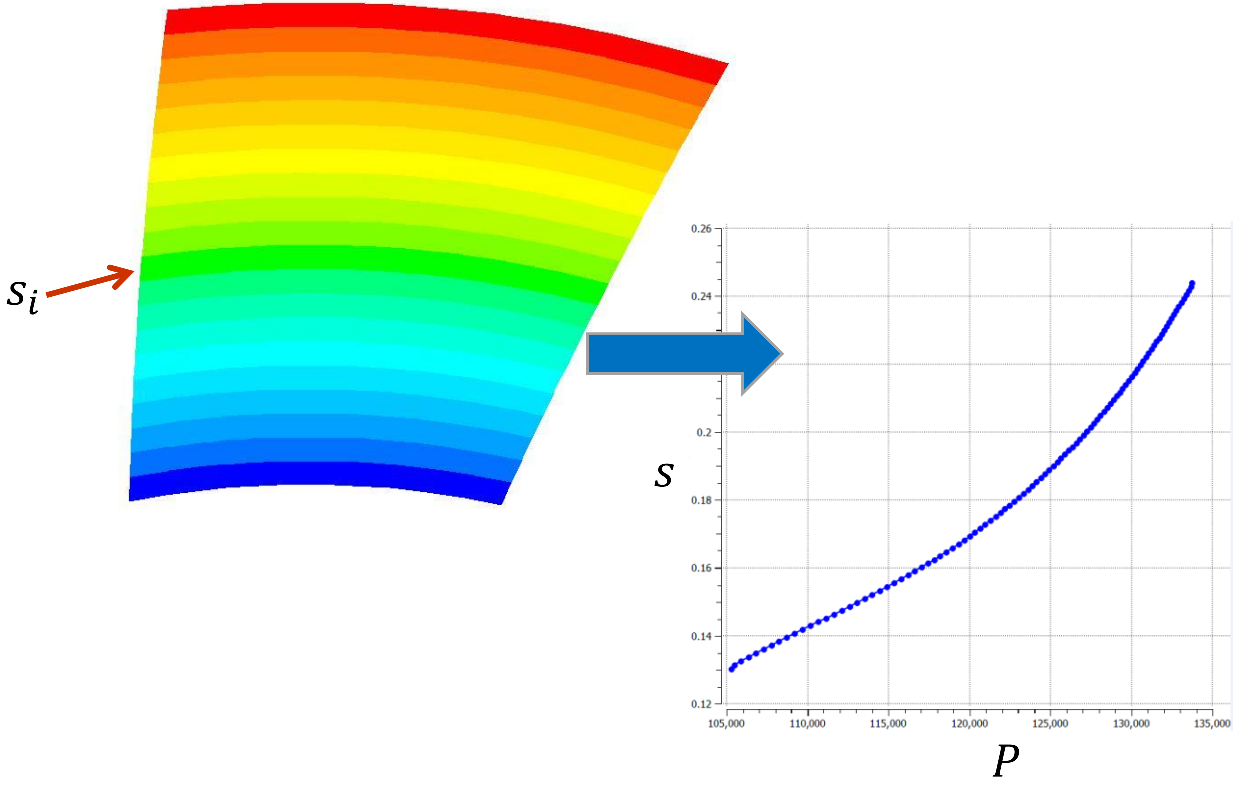
Mixing



Mixing Plane Interpolation

- The mixing plane model uses a circumferential averaging technique
  - Any flow variable distribution $\phi(s,\theta)$ on the upstream side of the interface is transformed to an averaged spanwise profile → used in the downstream side of the interface
    - ➢ The spanwise direction s can be any coordinate in the direction from hub to shroud
  - Variation in the spanwise direction is preserved
  - Blade pitch change via conservative “mixing” process in circumferential direction

In CFX the Mixing Plane Model is known as the **Stage Interface Model**

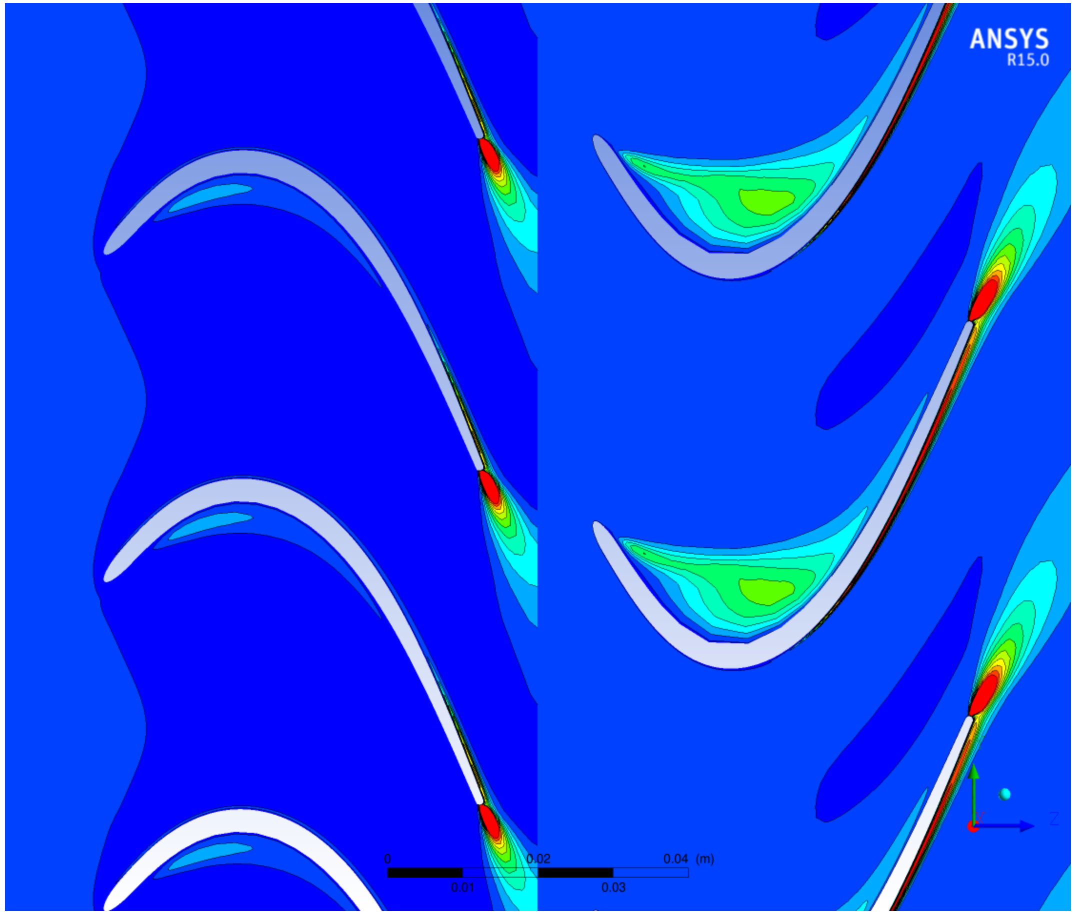


$$\bar{\varphi}(s) = \frac{1}{\Delta\theta_p}\int_{\Delta\theta_p} \varphi(s,\theta)d\theta \approx \bar{\varphi}(s_i) = \frac{\sum_j \varphi_{i,j} A_{i,j}}{\sum_j A_{i,j}}$$

j = index of cell faces whose centroids are close to s within band i

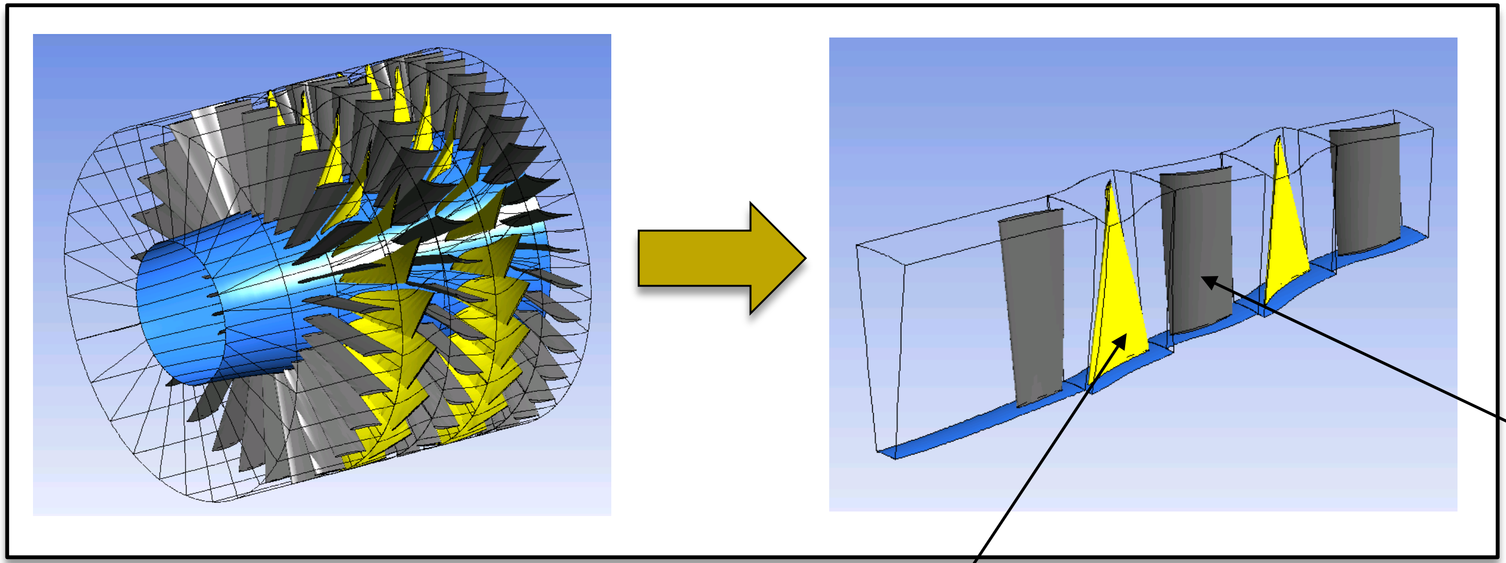
Mixing Plane Model Contours Example

No transient interaction between blade rows (wakes, vortices)



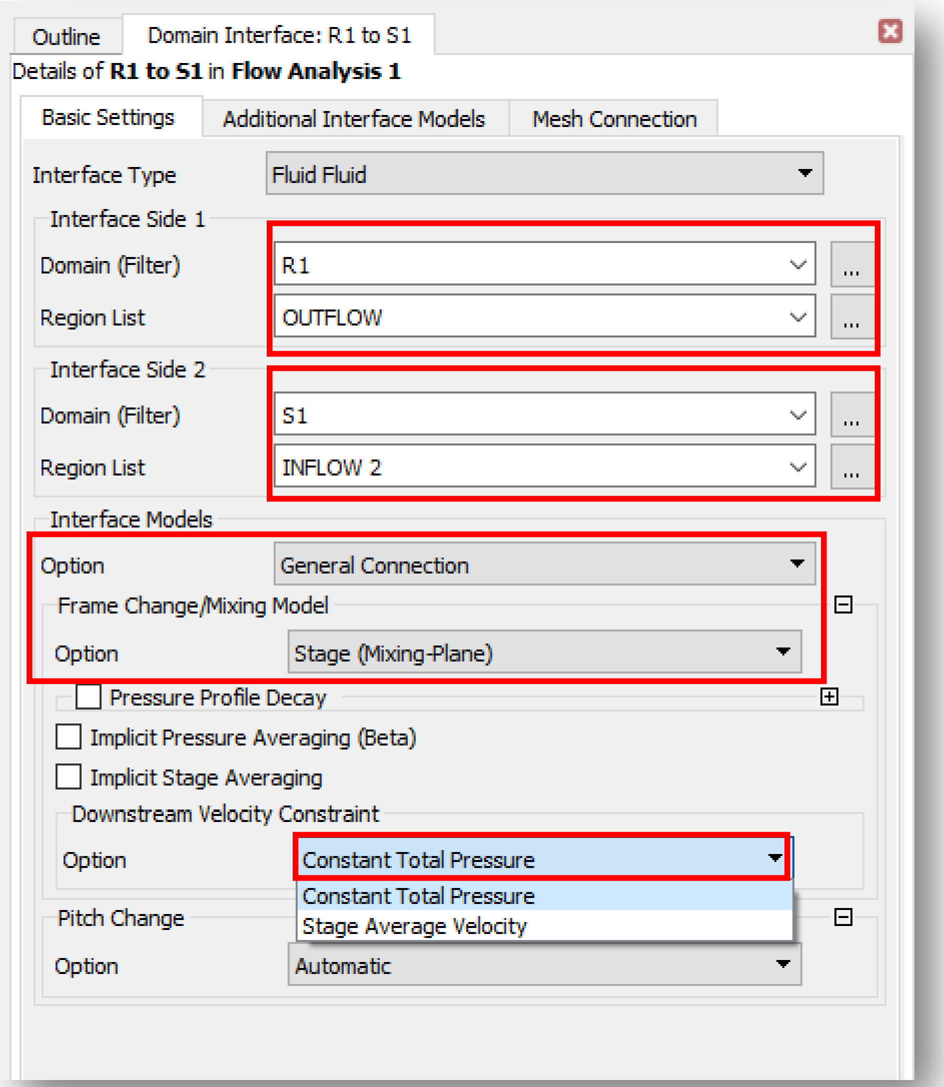
Mixing Plane Characteristics

- Simulation is run as steady state
- Usable when circumferential variation at interface is small or not important
  - Axial compressor, axial turbine, radial impeller with vaned diffuser…
- Only one passage in each component is modeled using periodic rotational boundary condition
- Mixing losses occur at Stage interface



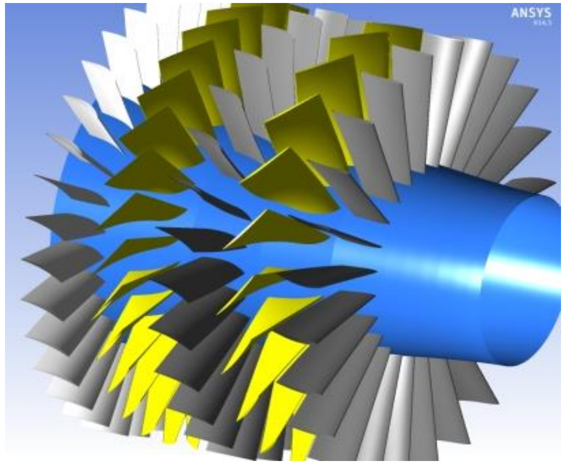
Mixing Plane Model Setup (CFX-Pre)

- Create a Domain Interface
- Define the interface boundaries to connect (Domain, Region List)
- Select “General Connection”
- Select “Stage (Mixing-Plane)” Option for “Frame Change/Mixing Model”
  - Downstream Velocity Constraint:
    - ➢ Stage Average Velocity
    - ➢ **Constant Total Pressure** (default)
      - Gives better results if distance between upstream row TE and downstream row LE is small



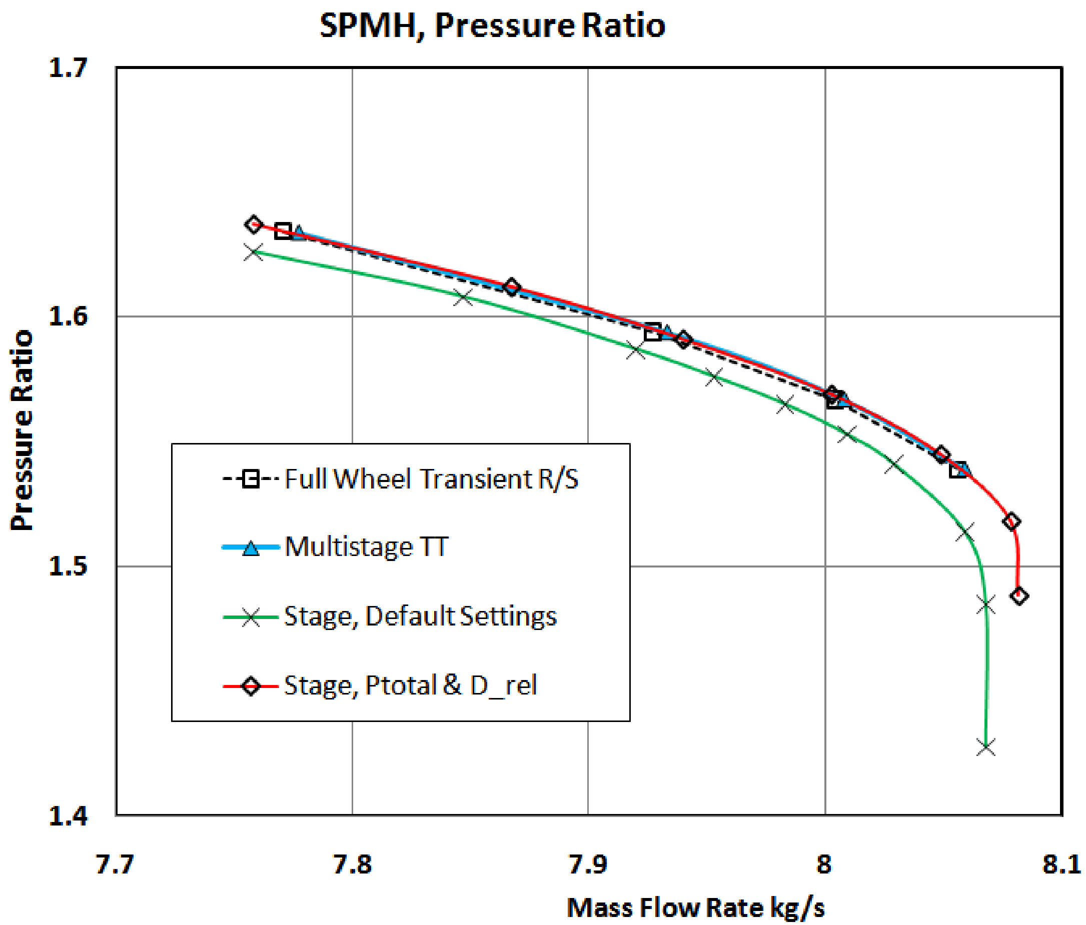
Mixing Plane Example – 2.5 Stage Axial Compressor

Hannover compressor with modified blade counts



Design rotational speed	17100 rpm
Mass flow rate	7.82 kg/s
Total pressure ratio	2.7
Isentropic efficiency	89.8%
Inlet total pressure	60 kPa
Inlet Mach number	0.5

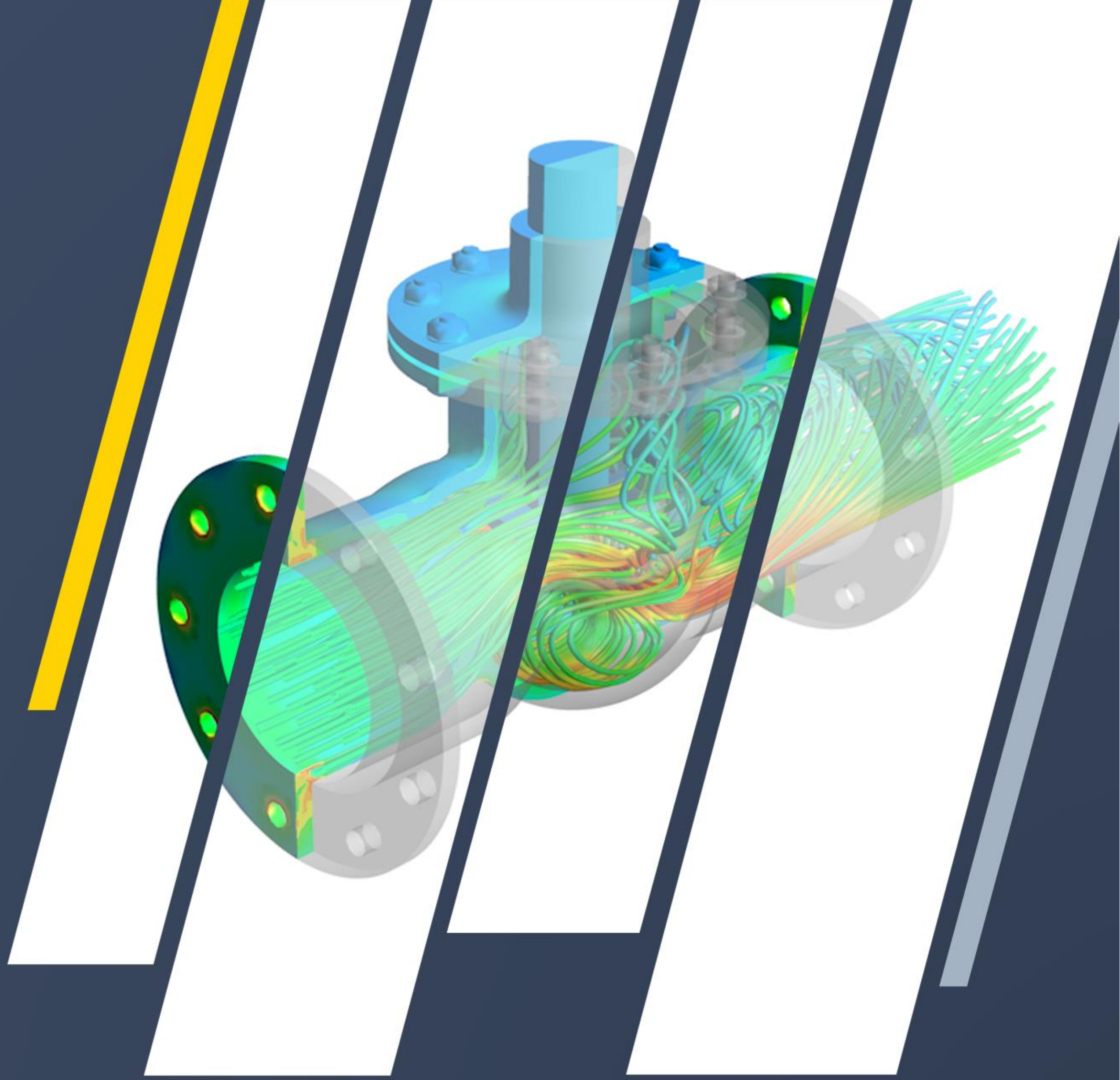
Ref. 1/3 wheel	11.6 mil nodes
TT, PT, mixing-plane	1.3 mil nodes



Mixing Plane Model Limitations

- Interpolation process can introduce errors at the mixing plane interface
- Mixing plane can handle some backflow, but you should avoid using the mixing plane if a large amount of backflow is present (leads to poor convergence)
  - Robustness issues with bidirectional flow within a circumferential band
  - Backflow direction, total temperature, scalars will be computed from downstream profiles
- Mixing process resulting from the averaging will introduce additional (usually small) loss to the stage calculation
- Wake effects, shock wave interactions will not be predicted
  - Modeling these effects requires a transient rotor stator model
- Errors in the mixing plane model increase as the spacing between the stages decreases (stronger interaction)

Frozen Rotor Model (FRM)

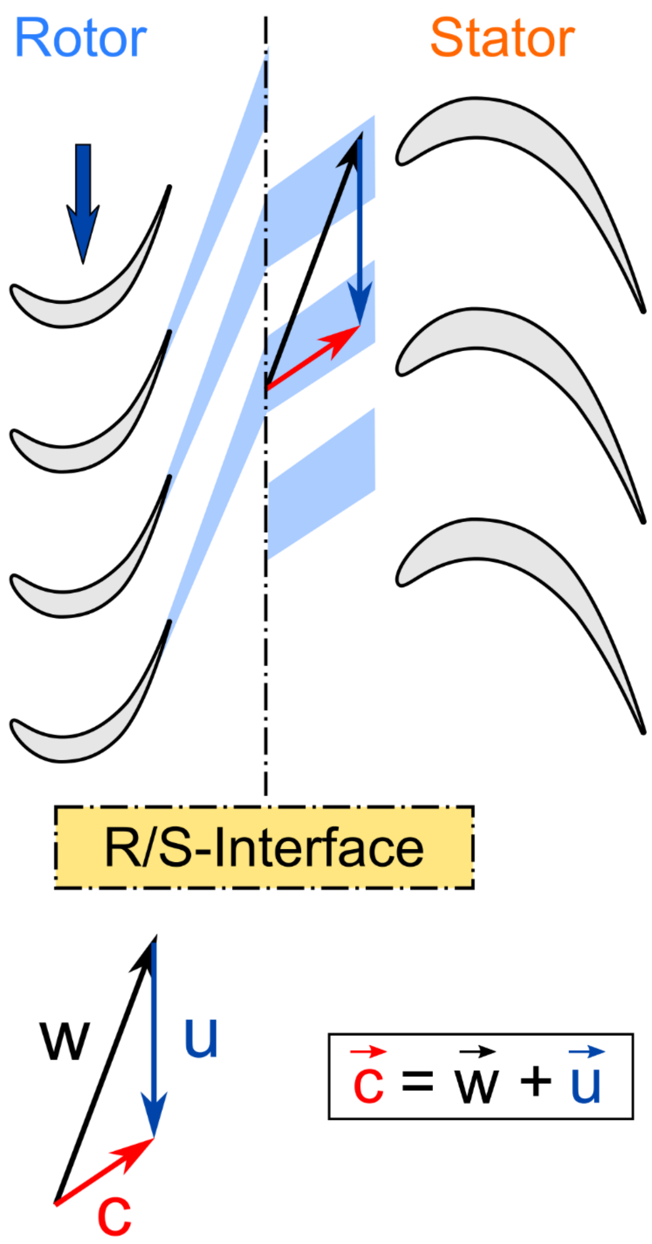


Frozen Rotor Model

Frame change at interface w/o averaging

Sensitive to relative component position

Blade pitch change via conservative interface flux scaling

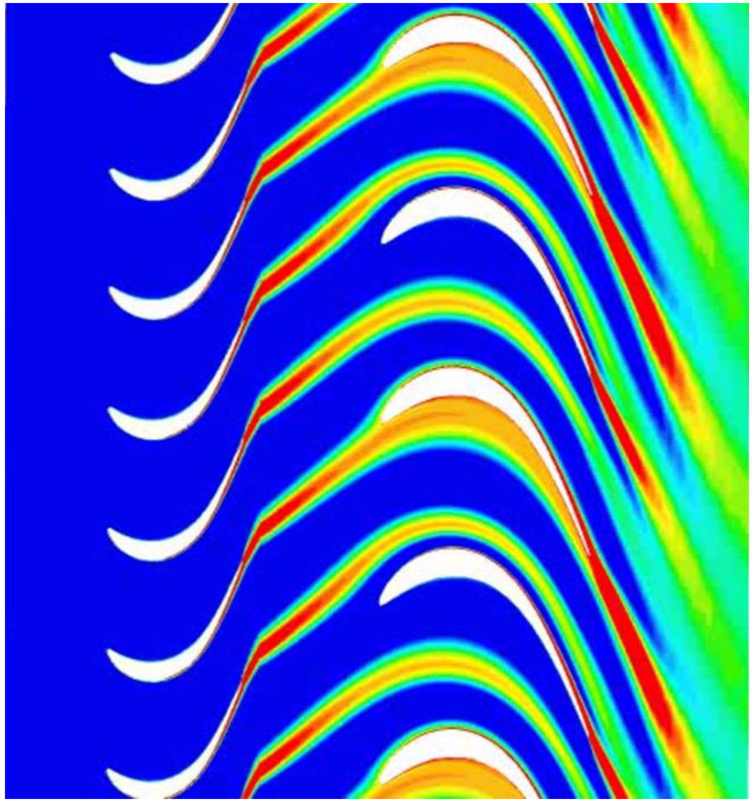


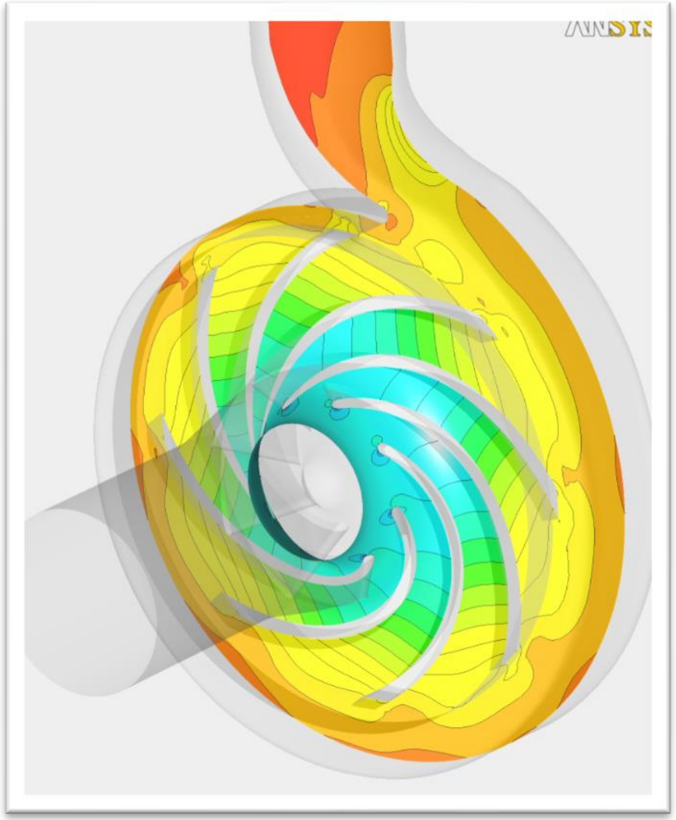
Frozen Rotor Model

- At the interfaces, appropriate transformations of the velocity vectors and velocity gradients are performed, and local fluxes of mass, momentum, energy, and other scalars are determined
- No account is taken for the relative motion of one domain with respect to the other!
  - Meshes do not move with time
  - For this reason FRM is often referred to as the “frozen rotor” approach
  - Result is sensitive to relative position of components
    - Try different rotor angular positions
- More robust and requires less intensive computing resources than Mixing Plane Model

Frozen Rotor Model Contours Examples

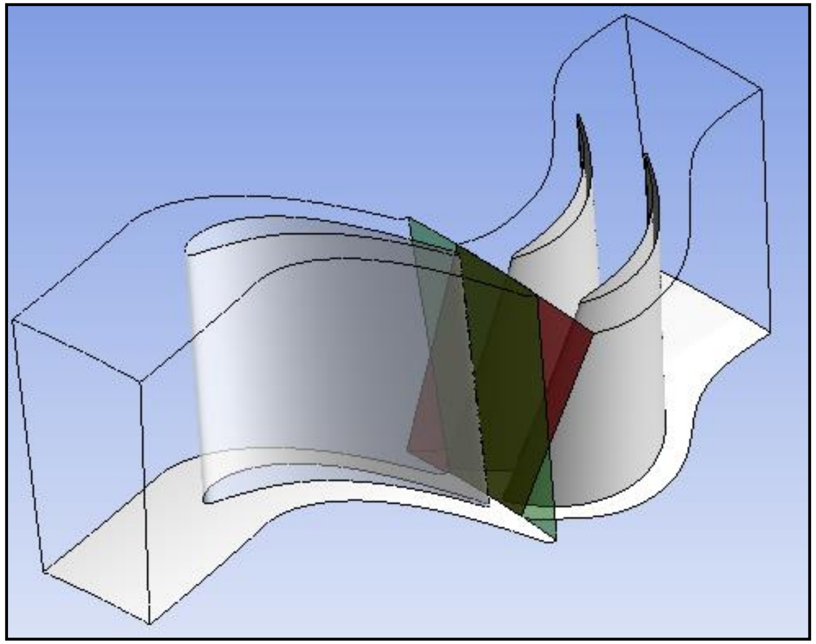
Blade wakes are fixed to a specific angular position





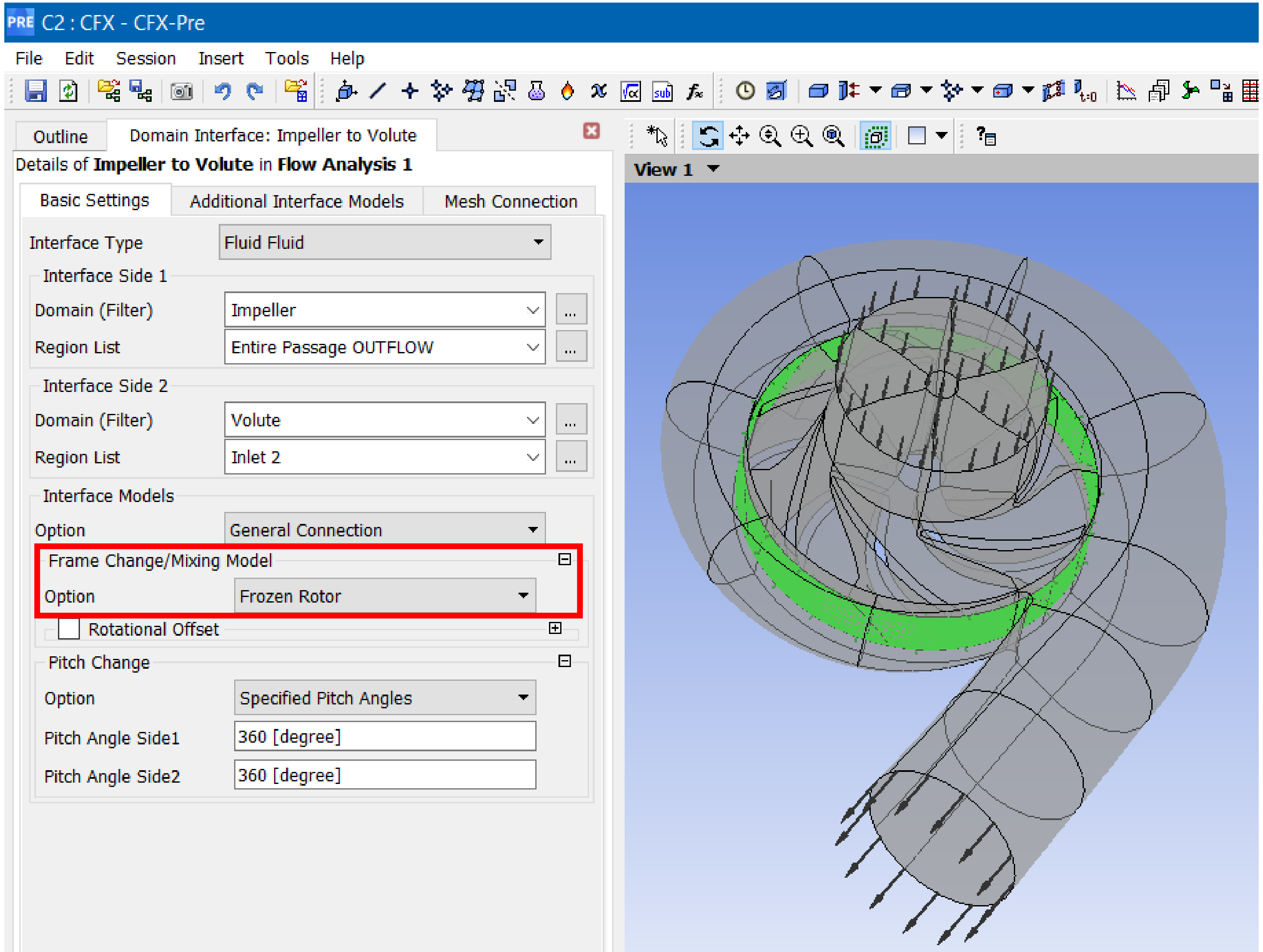
Frozen Rotor Model Characteristics

- Simulation is run as steady state
- Used when circumferential variation at interface is important, i.e. non-axisymmetric flow domains
  - impeller/volute, turbine/draft tube, propeller/ship, etc.
- Pitch change across Frozen interface is permitted
  - Flow is scaled to account for pitch change
- Errors can be significant when pitch ratio is large
  - Maintain pitch ratio near 1 to minimize errors
    - ➢ Example: Upstream blade count = 60, downstream blade count = 113
      - ▪ Pitch change of (360/113): (360/60) = 0.53
    - ➢ Use 1 upstream passage 2 downstream passages
      - ▪ Pitch change of 2*(360/113):(360/60) = 1.06



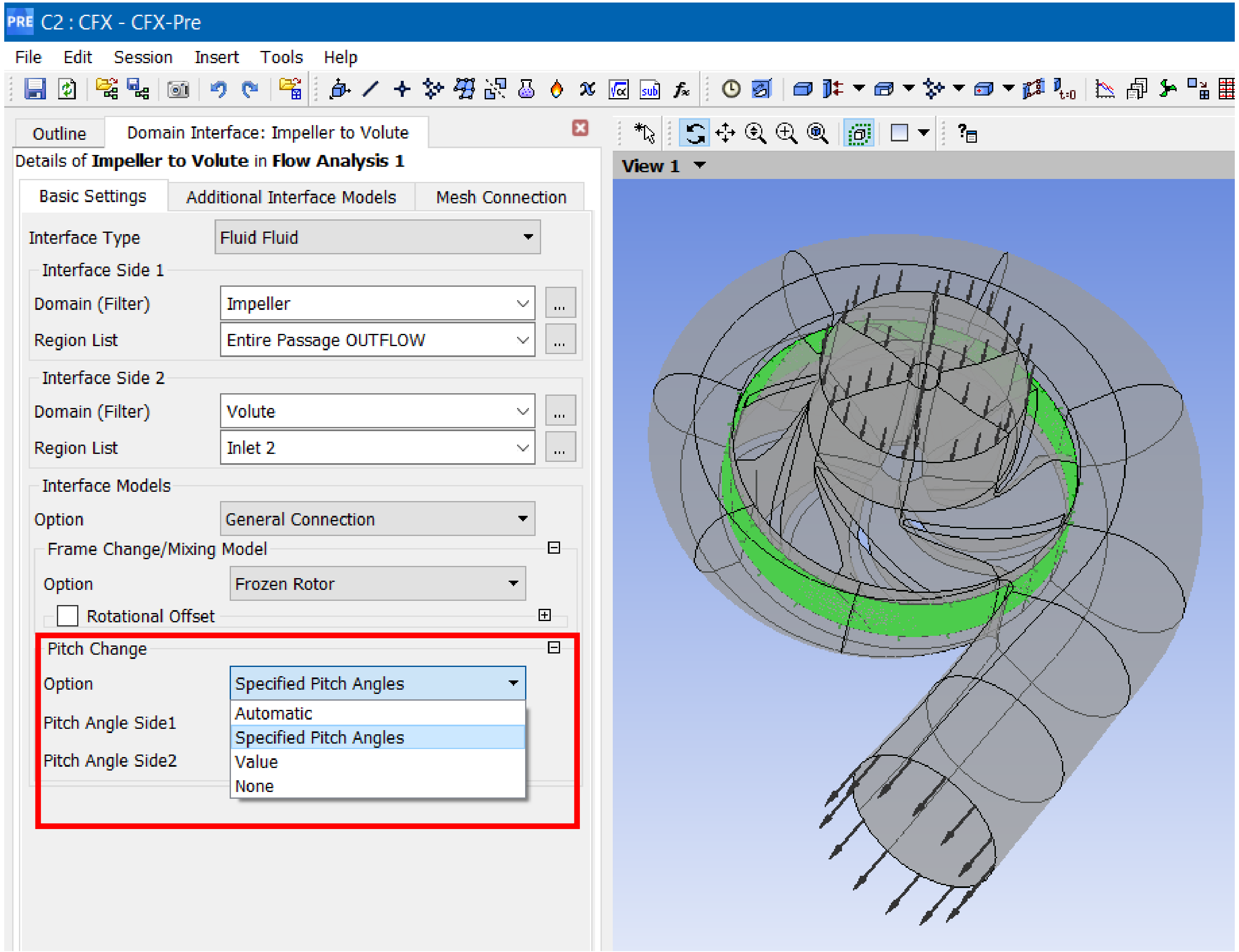
Setting Up Interfaces for FRM (CFX-Pre)

- Create a Domain Interface
- Define the interface boundaries to connect (Domain, Region List)
- Select “General Connection”
- Select “Frozen Rotor” Option for “Frame Change/Mixing Model”

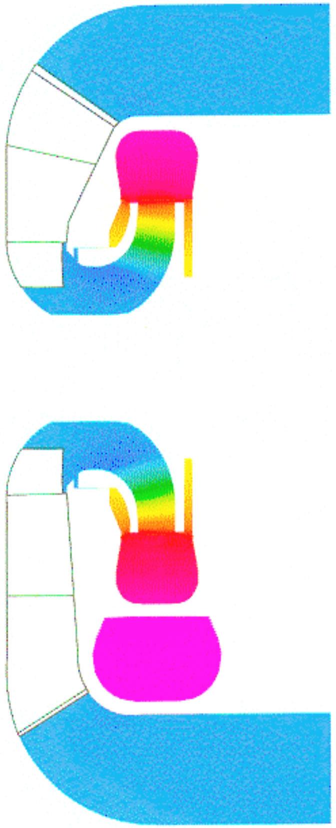


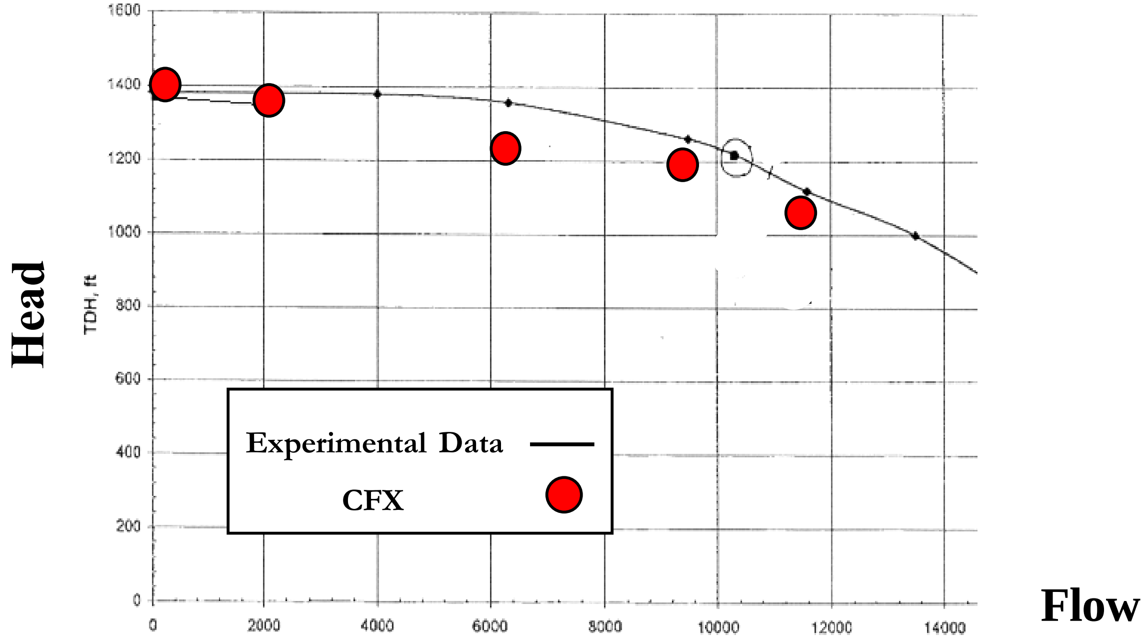
Setting Up Interfaces for FRM (CFX-Pre) 2

- Pitch Change Options
  - Automatic
    - ➢ Use with caution
  - Specified Pitch Angles
    - ➢ Always specify pitch angles when you know the blade counts
  - Value
    - ➢ Use when the precise pitch ratio is critical to the analysis
      - ▪ Example, in a closed system containing multiple pitched components
  - None
    - ➢ Use when overall extent and shape of each side of the interface perfectly match



Frozen Rotor Example Calculation

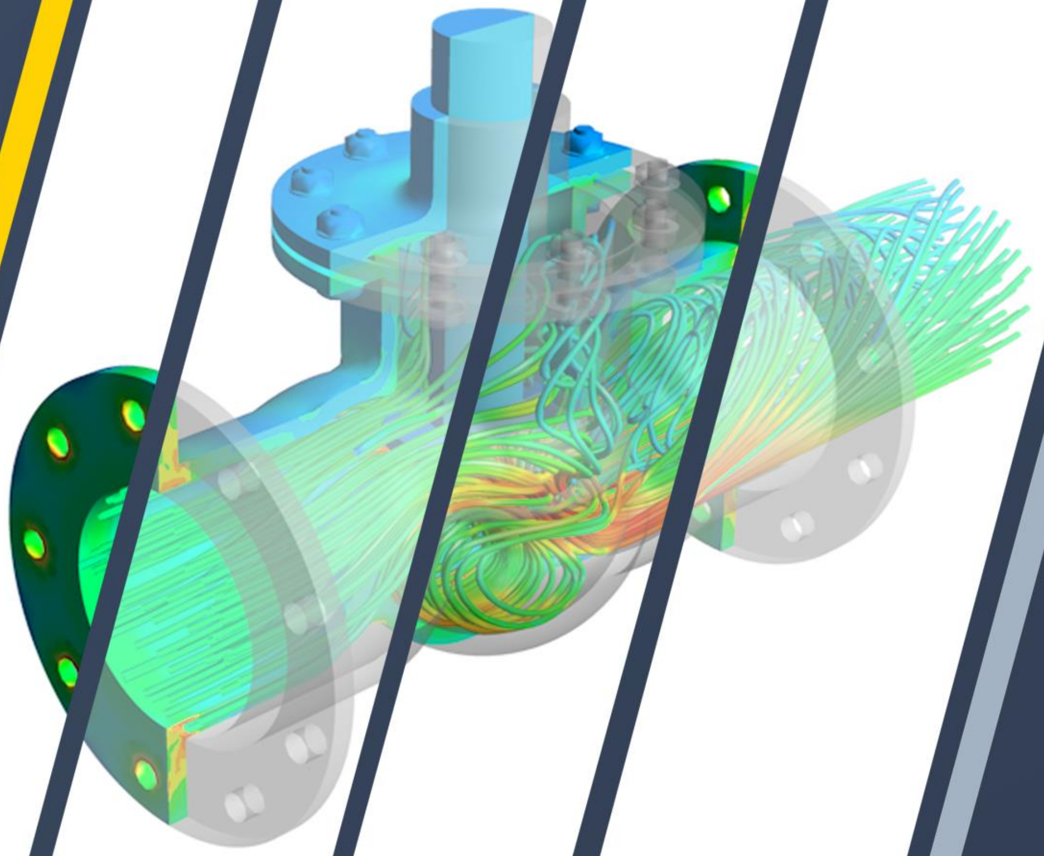




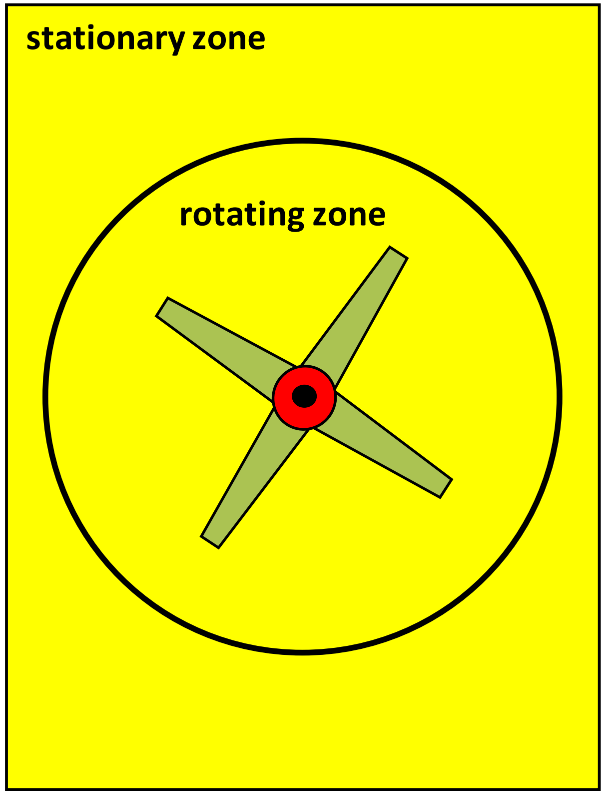
Frozen Rotor Model Limitations

- FRM models ignore the relative motions of the fluid zones with respect to each other, and thus do not account for fluid dynamic interaction between components
- Results may be dependent on the “frozen” position of the components
  - More pronounced when blade count is small
  - Try different rotor angular positions
- FRM can produce misleading results in cases where the flow passes across the rotating domain (flow enters and leaves the outer boundary of the rotating domain), or there are significant flow reversals across the interface
  - Example: crossflow fans
- For cases where the FRM approximation is not reasonable, you should use transient rotor stator instead

MFR Interface Best Practices

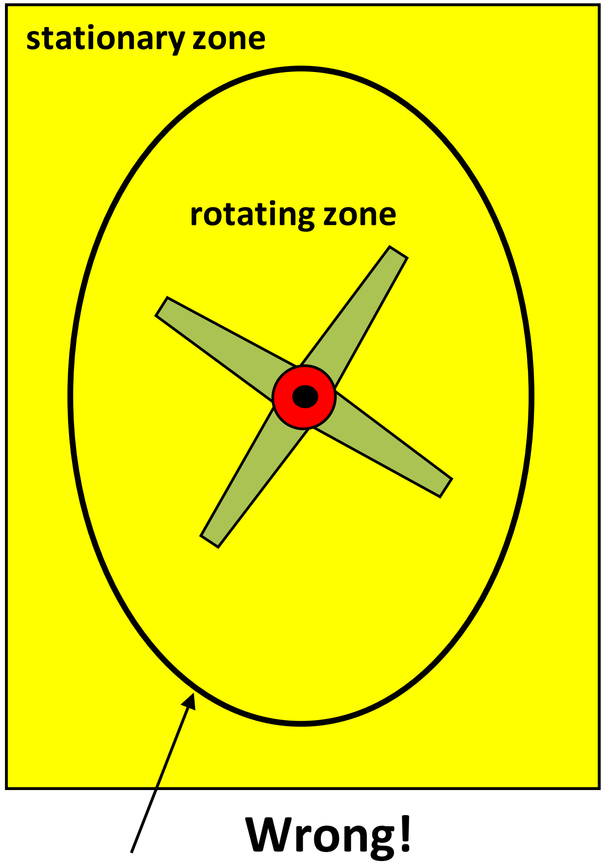


Geometric Requirement



Correct

Make sure interface is a surface
or revolution about rotational axis

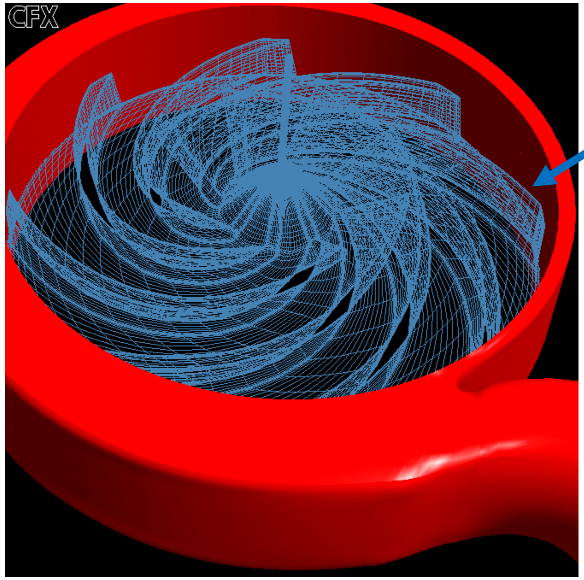


Wrong!

Interface is not a surface
or revolution

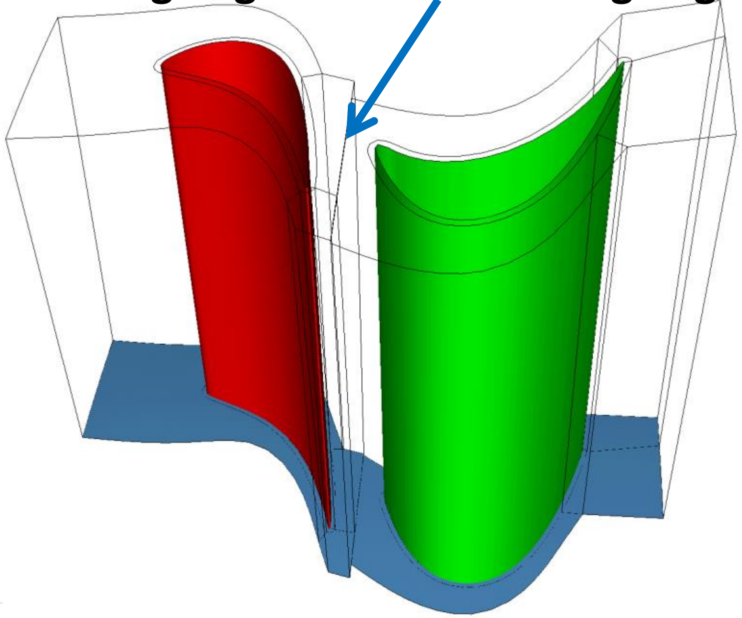
Interface Placement – General Practices

- For interfaces contained within an enclosed system (e.g. blower within a casing), choose a position midway between the outermost point on the moving zone and the closest stationary wall (e.g. tip of a pump rotor)
- For interfaces embedded in a large domain (e.g. axial fan in a room), choose a location where flow conditions are relatively uniform at the interface
  - Usually close to the rotor/impeller
  - If R*omega is supersonic in the domain, if possible, move the interface to a smaller radius



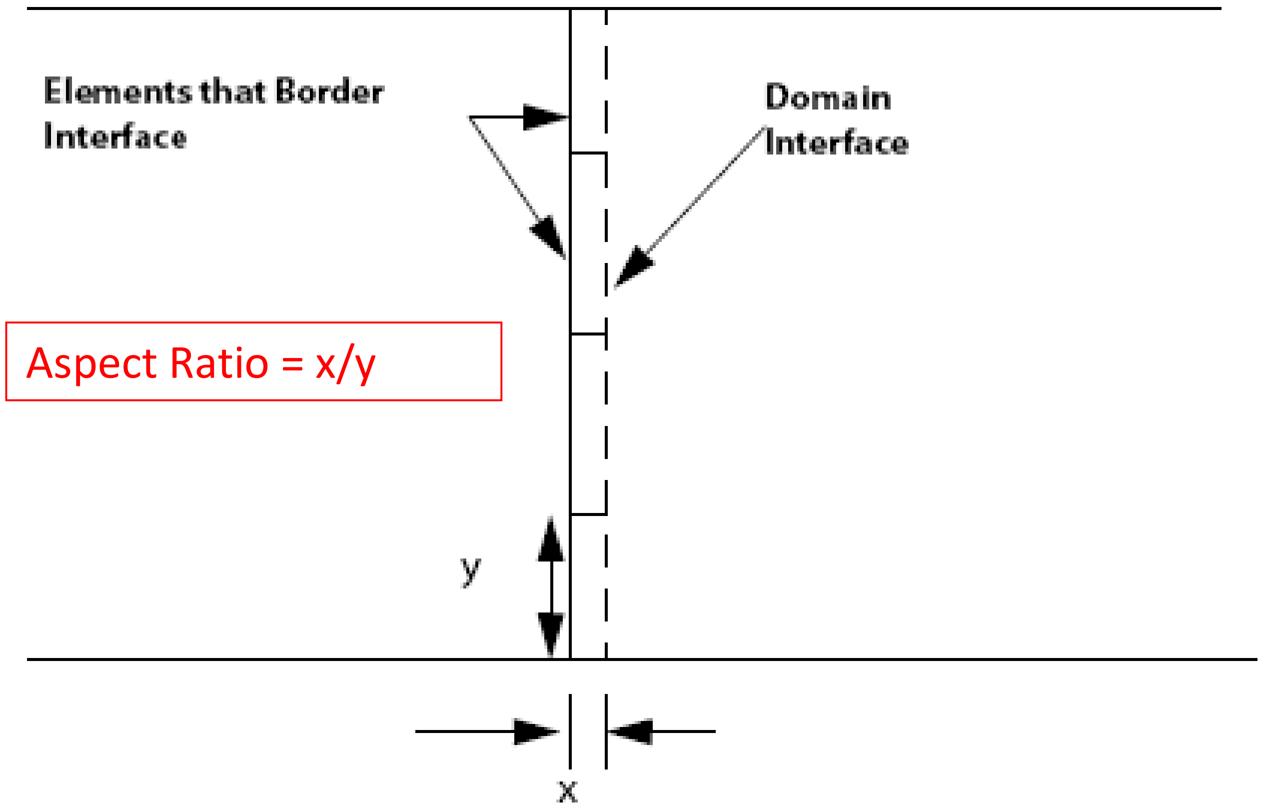
Interface midway between rotor tip and casing

Interface midway between vane trailing edge and rotor leading edge



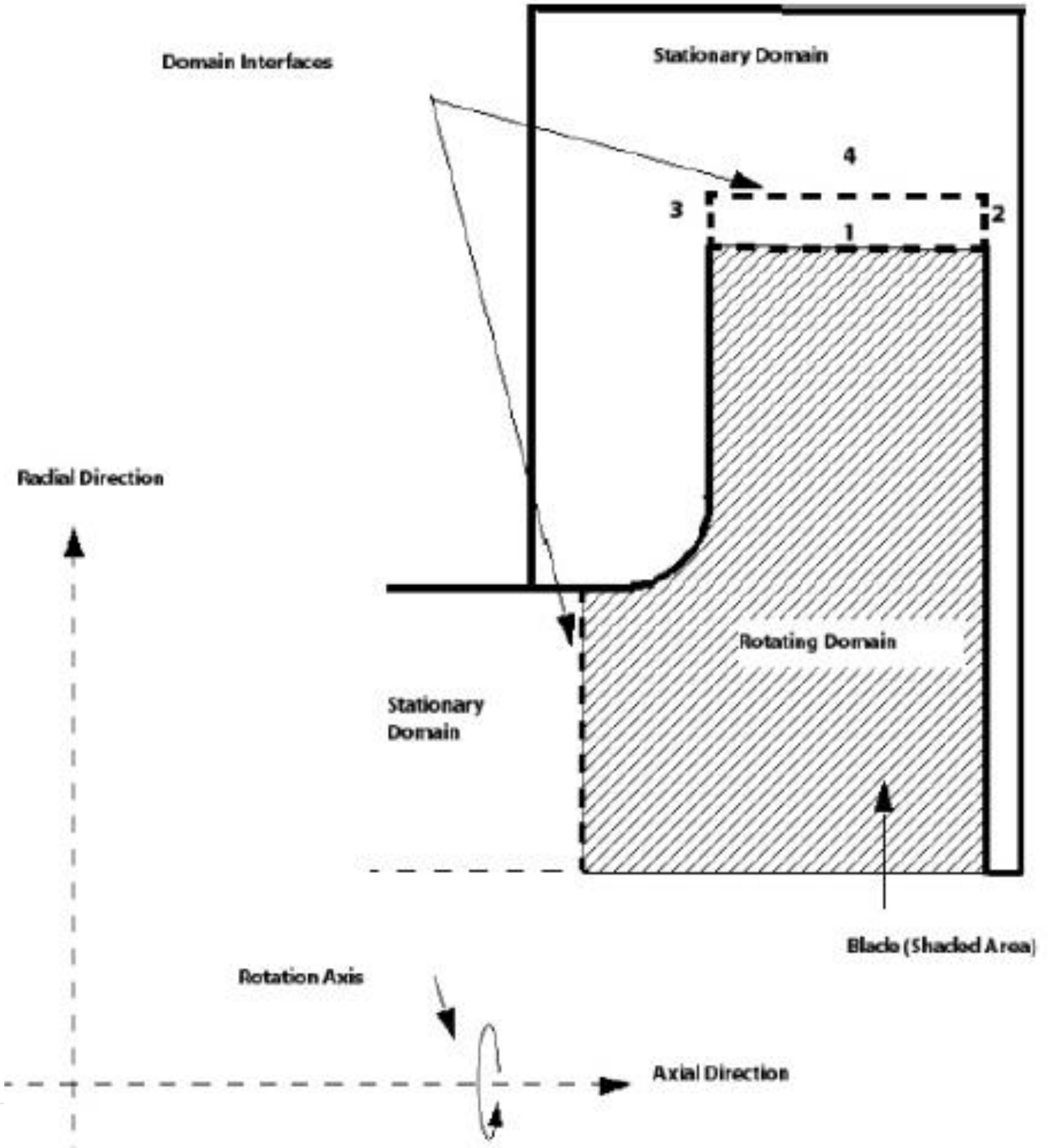
Aspect Ratio Considerations

- To minimize numerical errors, element aspect ratio at the interface should be between 0.1 and 10



Interfaces Near Blade Tip

- Although it is convenient to place a domain interface at the blade edge (1), this can result in convergence difficulties
- A better arrangement is to extend the rotating domain away from the blade edge Domain Interfaces can then be created at (2), (3), and (4)
  - Make sure (4) is not too far, to avoid supersonic relative Mach numbers
  - Create separate interfaces
    Avoid including the constant radial surface (4) in the same interface with constant axial surfaces (2) and (3)



Using Multiple Domain Interfaces

- A given simulation can make use of multiple domain interfaces. Each Fluid Fluid interface can use a different frame change model.
  - Example 1:
    - Two domains can be connected by a Fluid Fluid interface without a frame change
    - One of these domains might also contain a rotationally periodic interface to define a blade passage
    - Finally, there might be another Fluid Fluid interface between the first two domains and a third domain that uses a frame change model.
  - Example 2:
    - A four-stage axial compressor, consisting of four stators and four rotors
      - Might contain seven Fluid Fluid interfaces with a mixing plane frame change model

Using Multiple Domain Interfaces (2)

- It is possible to have a combination of frame change models within a single problem definition.
  - For example, in a stator/rotor/stator configuration, the first Fluid Fluid interface could be a Stage or Frozen Rotor interface, and the second interface could be a Transient Rotor-Stator interface.
    - This might make sense if you are only interested in accounting for the transient conditions between the rotor and the downstream stator.

Best Practices MPM and RFR

- Online documentation
  CFX Reference Guide Chapter 11
  CFX Best Practices Guide for Turbomachinery

Chapter 11: CFX Best Practices Guide for Turbomachinery

Turbomachinery applications can generally be divided into three main categories: gas compressors and turbines, liquid pumps and turbines, and fans and blowers. Each category is discussed in a separate section below.

This guide describes best practices for setting up simulations involving:

- Gas Compressors and Turbines
- Liquid Pumps and Turbines
- Fans and Blowers
- Frame Change Models
- Domain Interface Setup
- Transient Blade Row

This guide is part of a series that provides advice for using CFX in specific engineering application areas. It is aimed at users with moderate or little experience using CFX for applications involving turbomachinery.

Summary

- Multi-Component Analysis is best performed using the Multiple Frames of Reference (MFR) ANSYS CFX capability
- Two steady-state pitch change models available:
  - Mixing plane model
    - ➢ Works best for multistage problems where circumferential averaging between blade rows is a reasonable approximation
      - ▪ Axial compressor, axial turbine, etc.
    - ➢ Different pitch angles can be used, one blade row per passage is all that is needed
  - Frozen rotor model
    - ➢ Works best for cases with asymmetry in the flow
      - ▪ Pump in a volute, Fan in a volute, etc.
    - ➢ Target pitch ratio as close to 1 as possible