CFD for Wind Turbine Aerodynamics

TWIND Summer School

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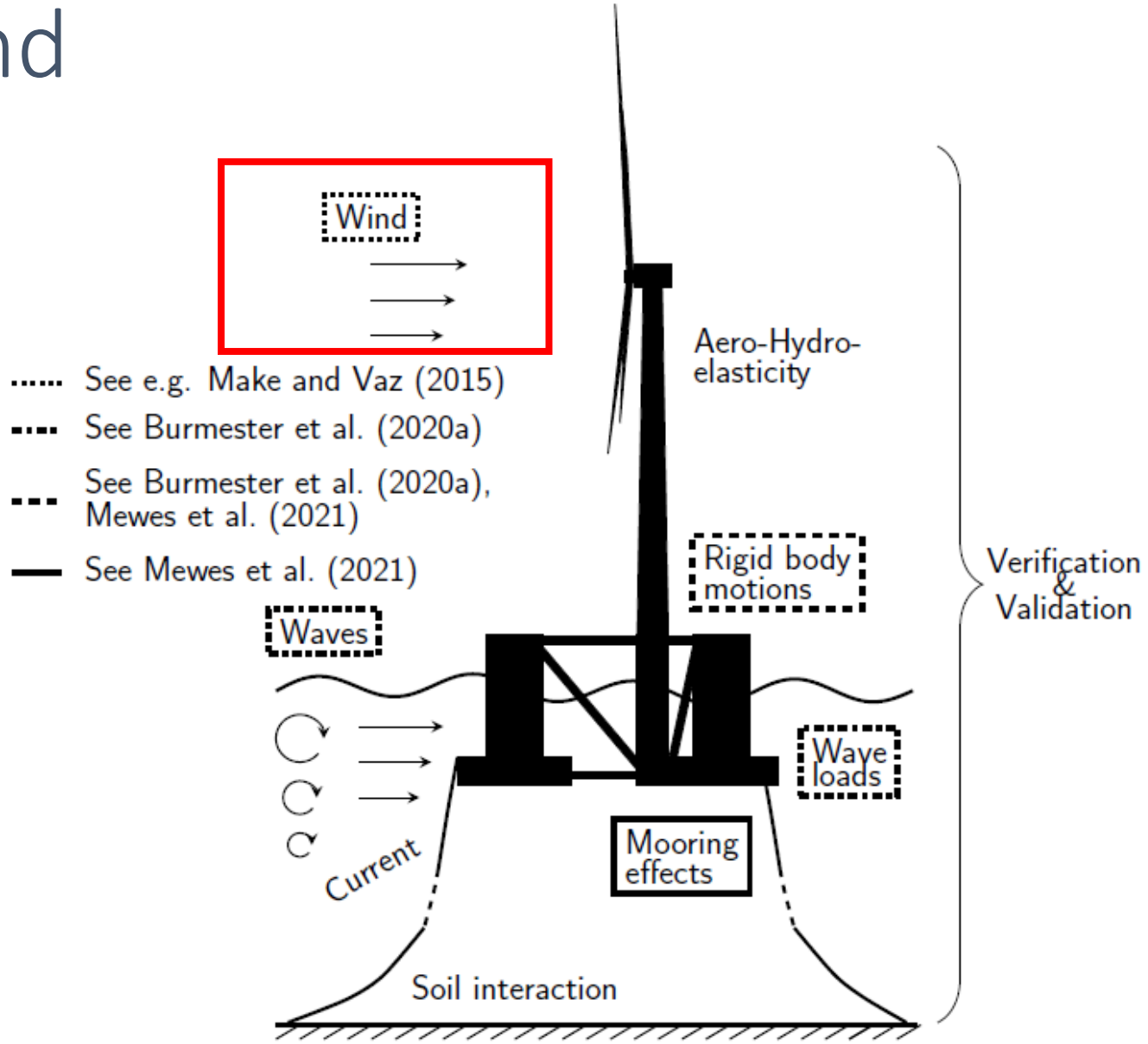
Background


Wind
See e.g. Make and Vaz (2015)
See Burmester et al. (2020a)
See Burmester et al. (2020a), Mewes et al. (2021)
See Mewes et al. (2021)
Aero-Hydro-elasticity
Rigid body motions
Verification & Validation
Waves
Wave loads
Current
Mooring effects
Soil interaction

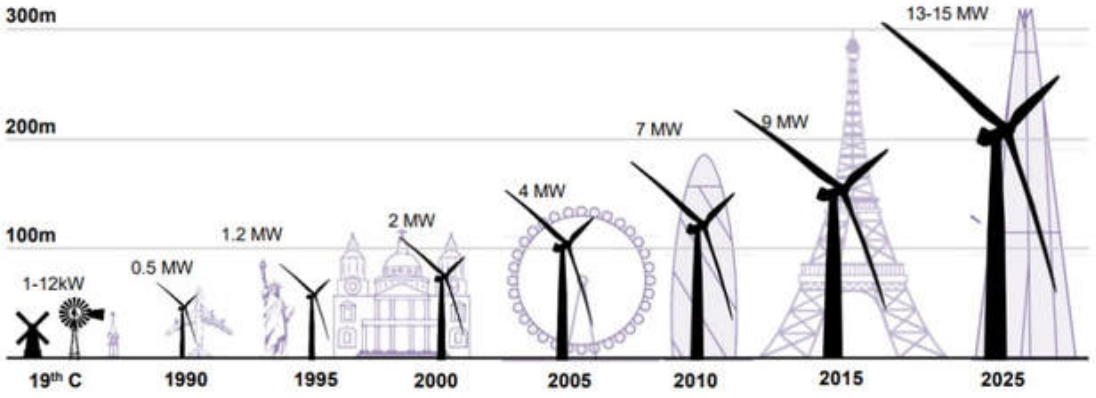
Background

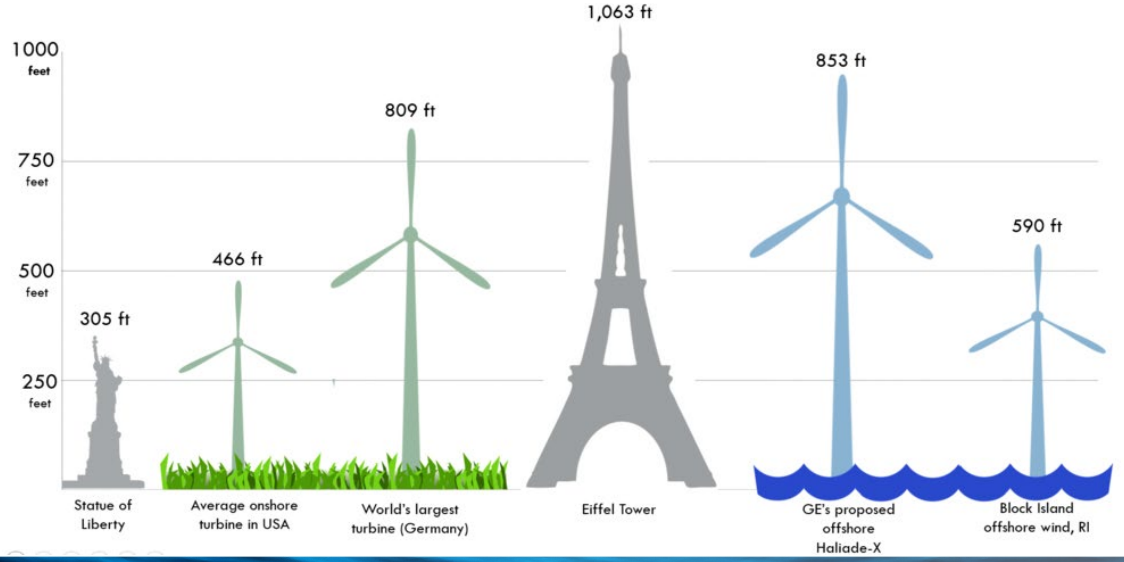
- Wind turbines work at high loadings.
- Wind turbine flows are *quite* quasi rotating bi-dimensional (high AR).
- Similarities between propellers, current turbines and wind turbines. Experiences can be shared.
- One should master CFD for **flat-plate, foils, wings, rotating blades** before tackling **wind turbines.**
- Moderate-High Reynolds: between 1E6-1E8.
- Mach numbers: lower than 0.3 (for 15MW turbines around it…).
- There are several super-tuned classical low-fidelity tools for wind turbine design and analysis. That explains the *late* application of CFD methods to these devices.

- *Disclaimer: lots of highly-expert people on this topic…*

Background

- Bigger is better?!



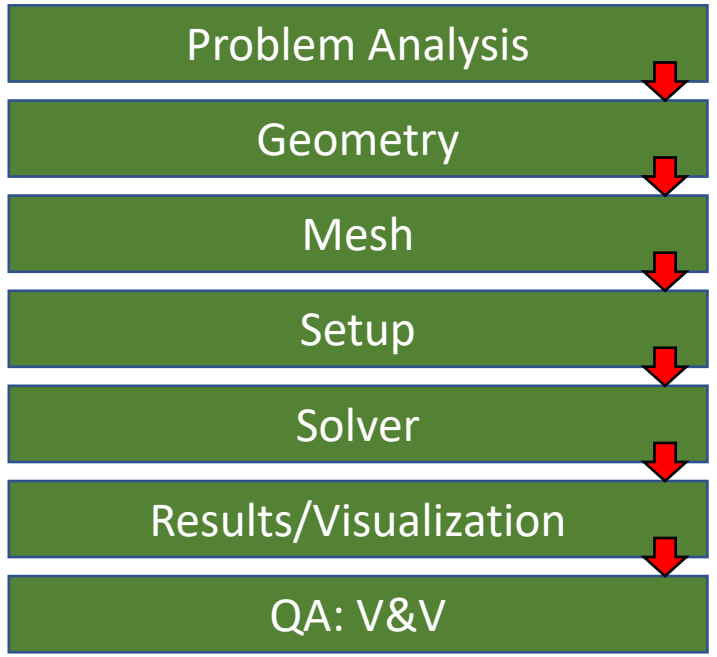


CFD Recipe

- Geometry
- Grids
  - Type
  - Cell size
  - Boundary Layer
- Domain
- Equations
  - Reference frames
  - Laminar vs Turbulent Flow
  - Transition Models
  - Turbulence Models
  - Boundary Conditions

- Control settings
  - Convection, Diffusion, DT, Limiters, Solvers, Relaxation, Source terms, extras
- Monitoring
  - Residuals
  - Forces, Moments
- Results
- Visualization
- Post-processing

- V&V: quality assessment!

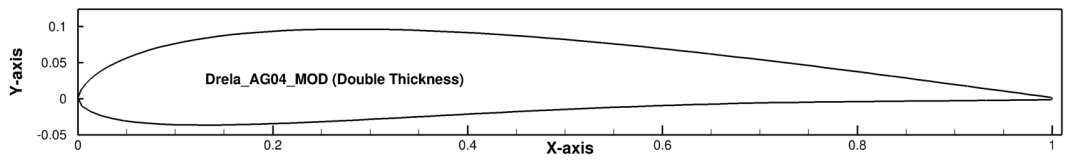


CFD Recipe - **Geometry**

- Water-tight geometrical description!
- Normal surface CAD description does not suffice (SolidWorks, Rhino, etc)!
- Laborious part… depending on the CAD and grid generator package.

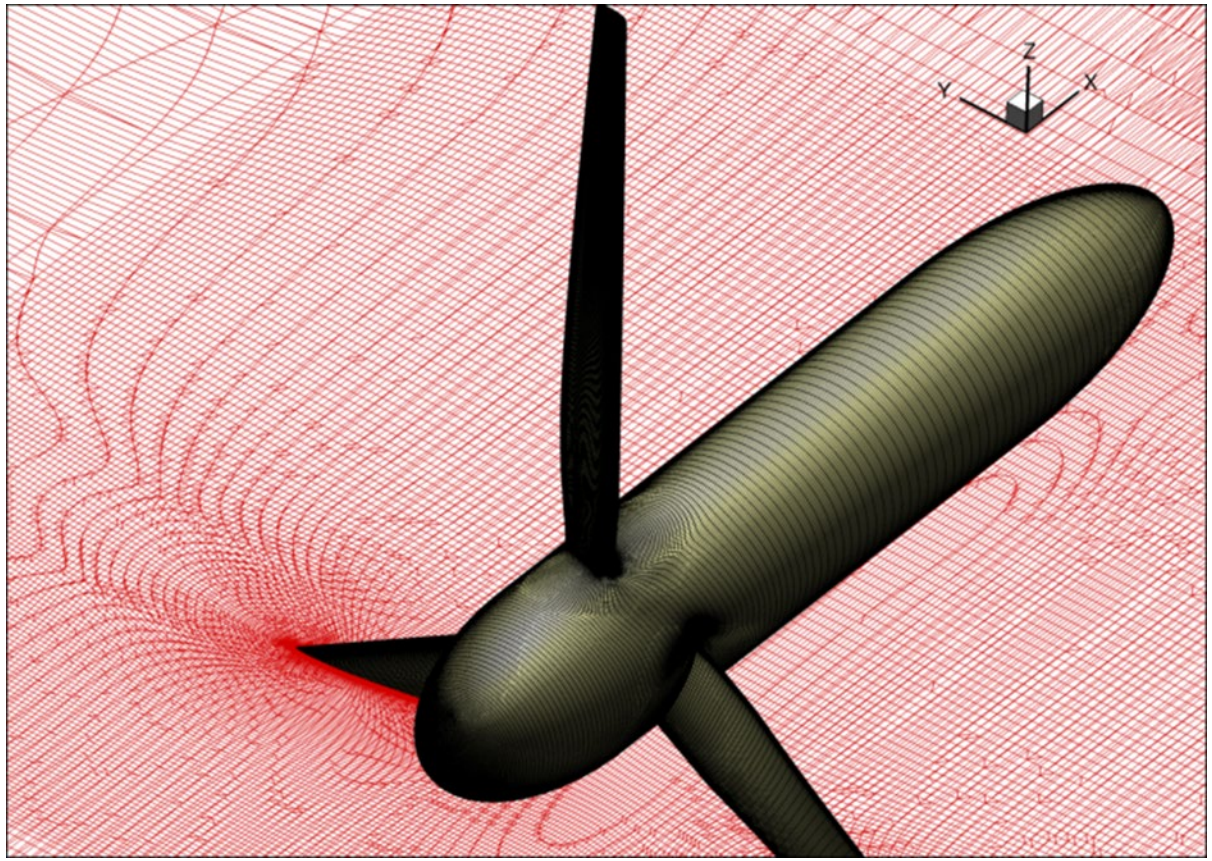
Table 2-1: Properties of the full scale and model scale ($\lambda = 50$ + Froude scaling) NREL 5MW Baseline Wind Turbine [24].

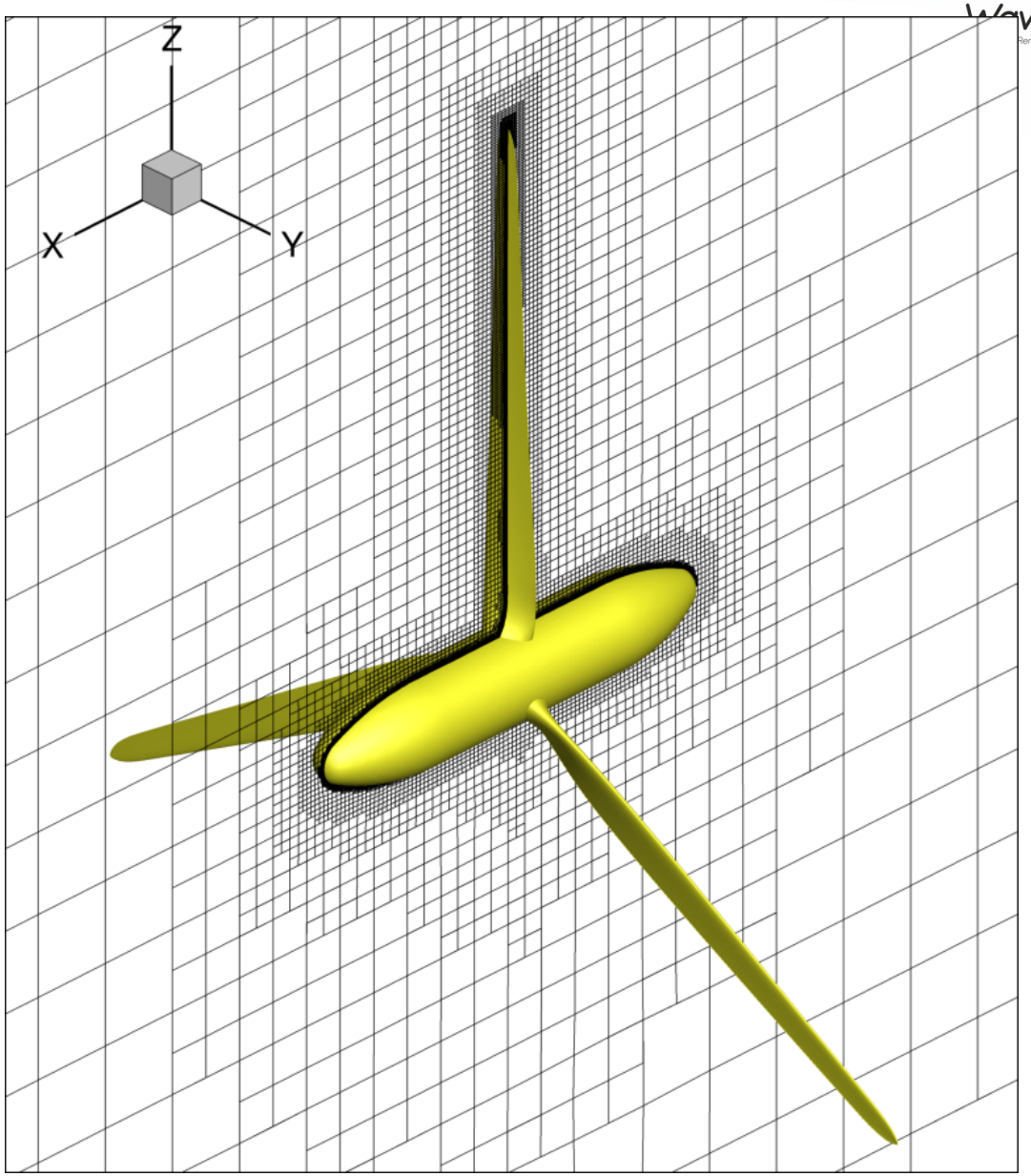
Property	Full Scale	Model Scale	Units
Rated Power	5	5.7	$[MW]/[W]$
Rotor Diameter	126	2.52	$[m]$
Hub Diameter	3	-	$[m]$
Hub Height (above sea level)	90	1.80	$[m]$
Cut-In Rotor Speed	6.9	48.81	$[RPM]$
Rated Rotor Speed	12.1	85.6	$[RPM]$
Cut-In Wind Velocity	3	0.42	$[m/s]$
Rated Wind Velocity	11.4	1.6	$[m/s]$
Cut-Out Wind Velocity	25	3.54	$[m/s]$
Rated Tip Speed	80	11.31	$[m/s]$
Reynolds no. @ 0.7 Radius	11.5×10^6	35.7×10^3	$[-]$



CFD Recipe - **Grid**

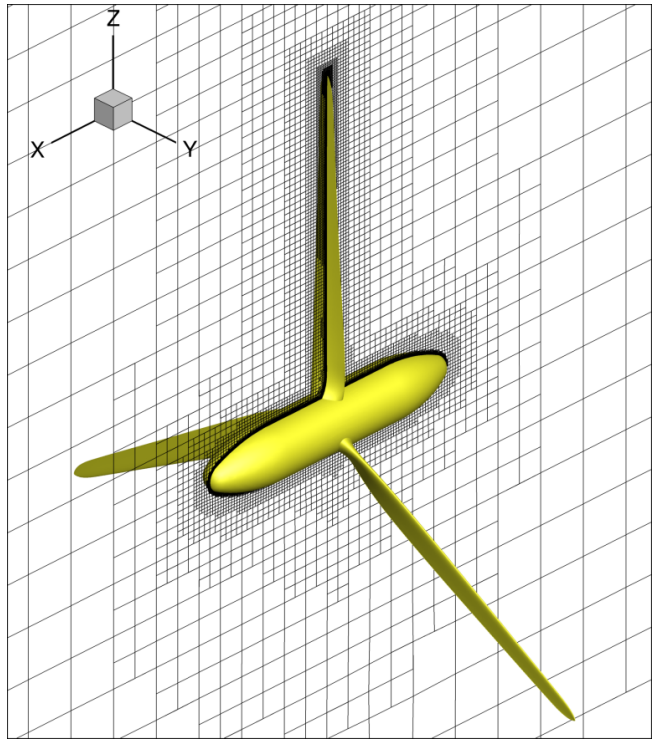
- Structured vs unstructured

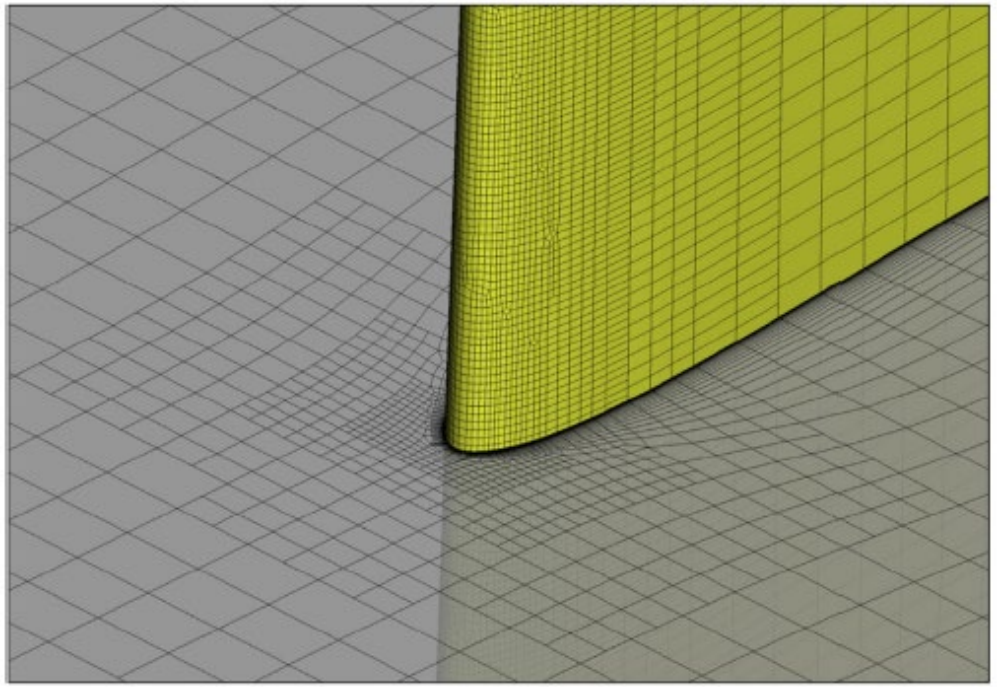


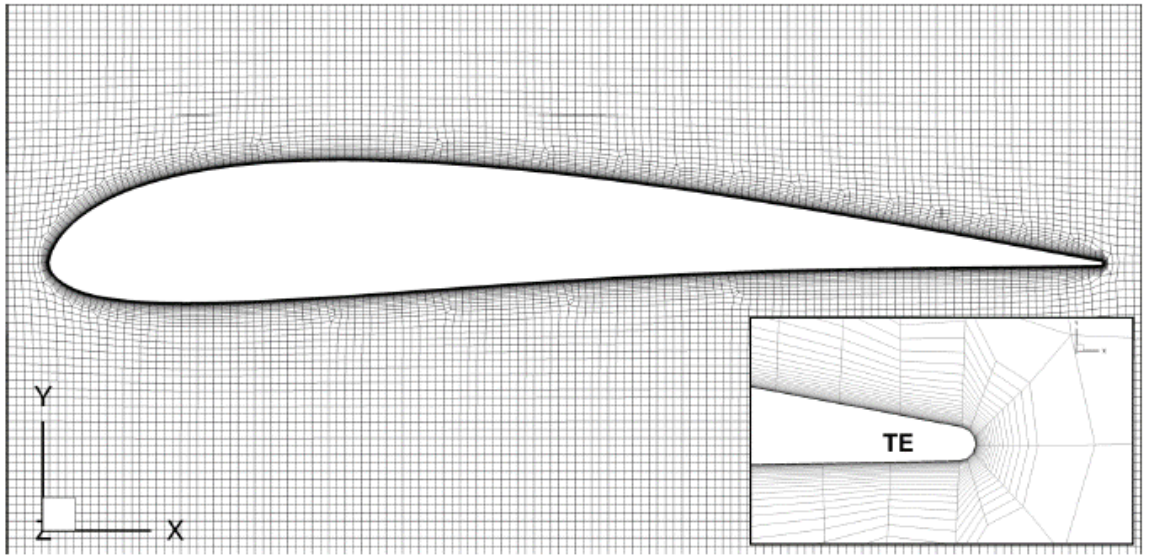


CFD Recipe - **Grid**

- Where to refine?
- How many cells?
- Boundary layer description? Y+?

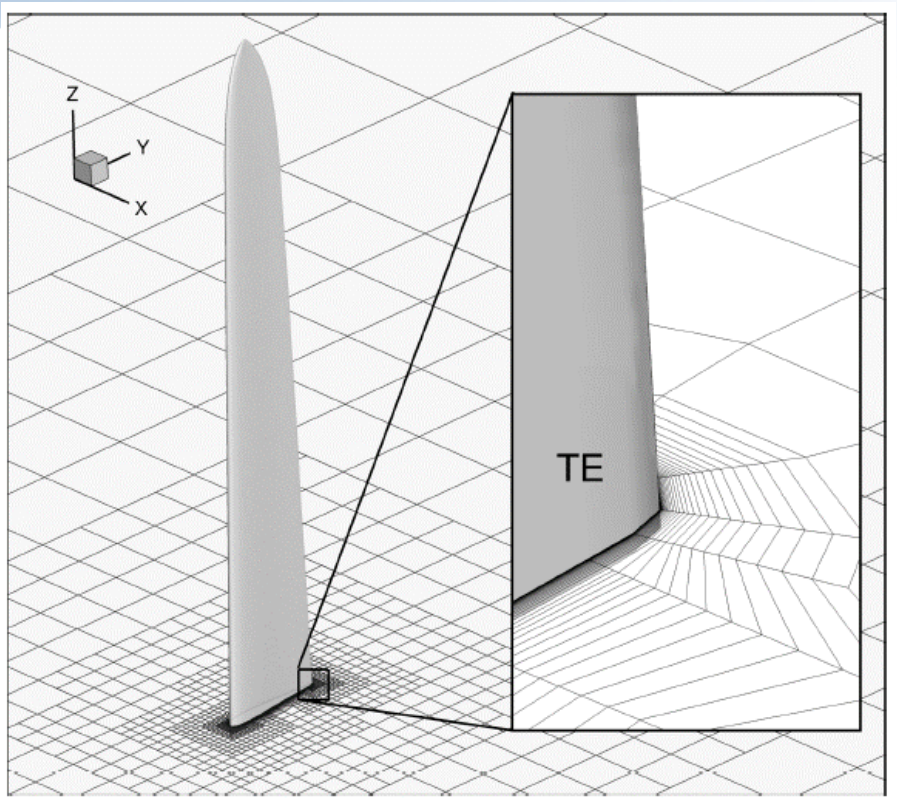


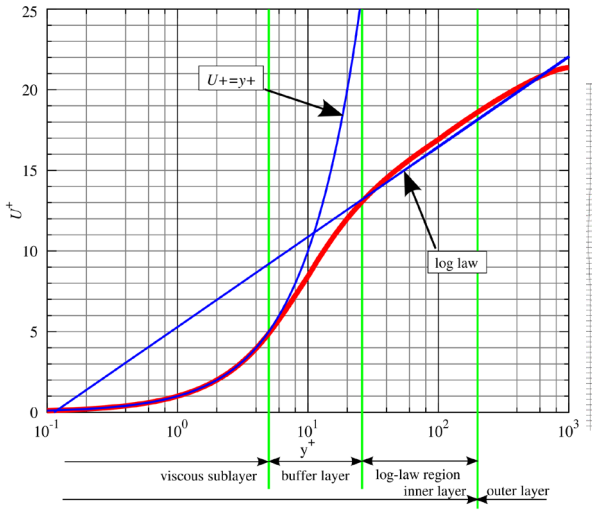


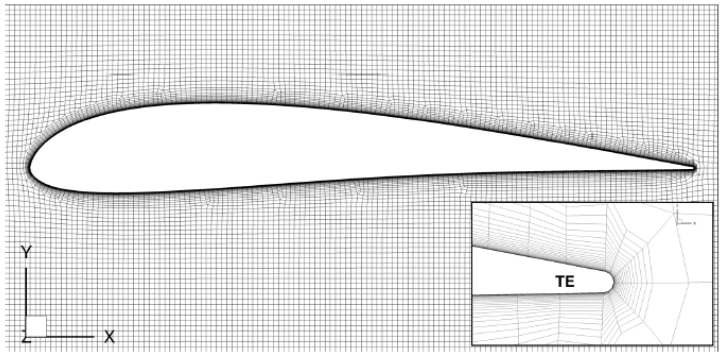


CFD Recipe - **Grid**

- Where to refine?
  - Curvature areas
  - Leading Edge
  - Trailing Edge
  - Tip
  - Wake
  - Boundary Layer
- How many cells?
  - Good questions?! Don't know; need V&V study. Start as small as possible. But around 1MCell per blade seems a good number to start!
- Boundary layer description? Y+?
  - Never, never use Wall-Functions!
  - Try grids with y+ <= 1.

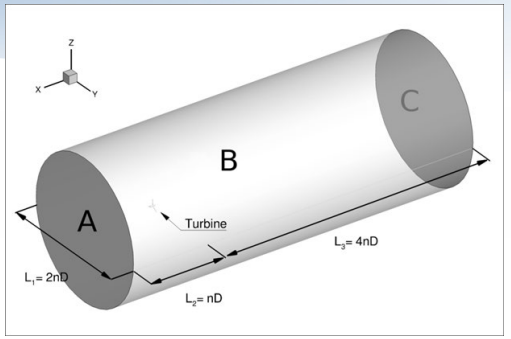


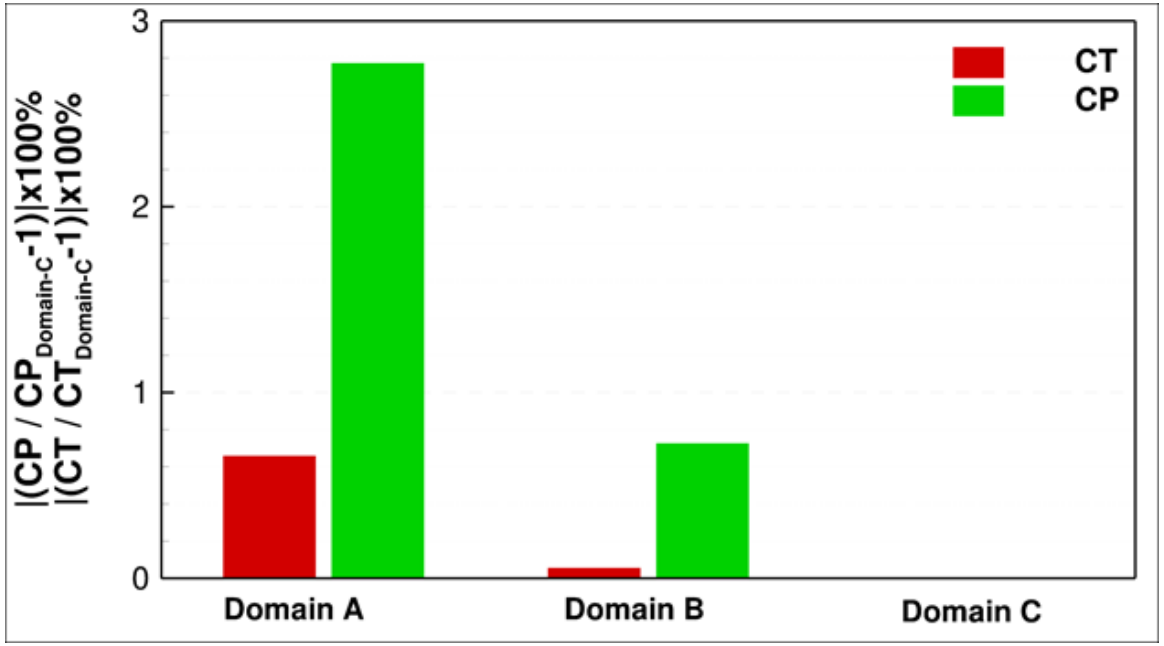


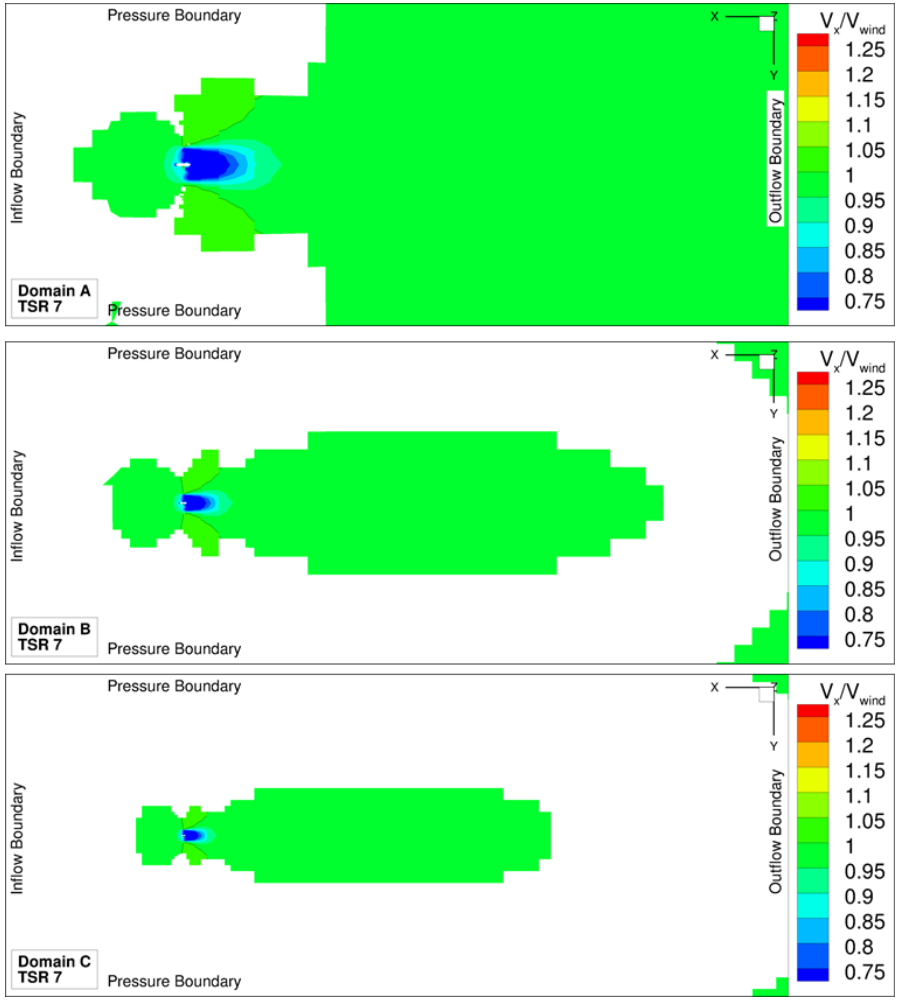


CFD Recipe - **Domain**

- Which type? Depends on the motion model.
- How big? Depends on the boundary conditions and case. Please study this beforehand!!!







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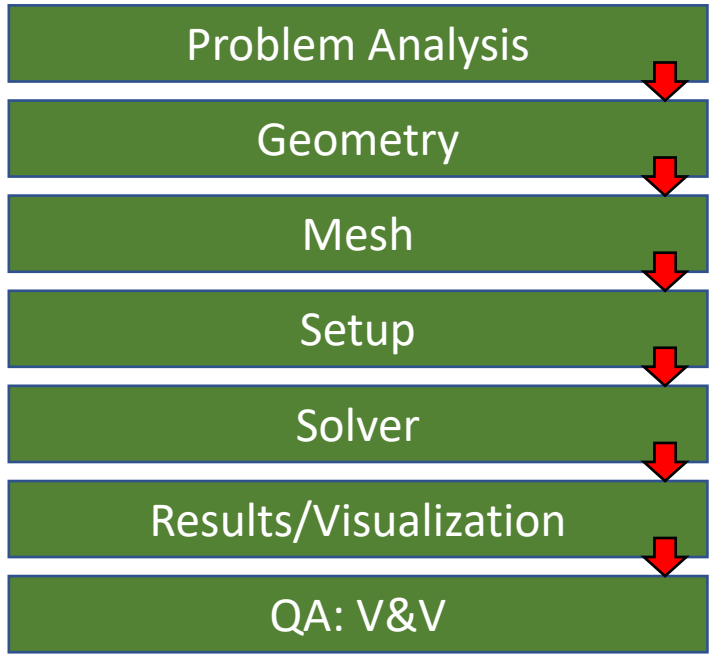
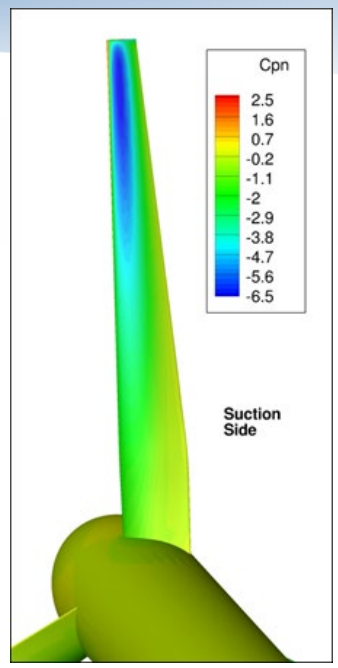
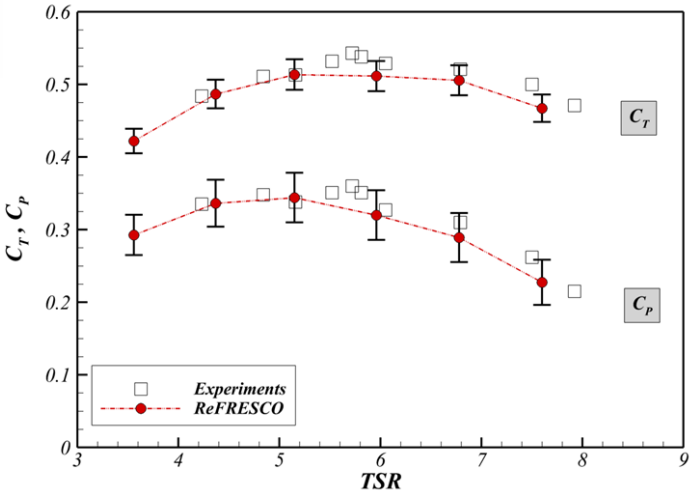
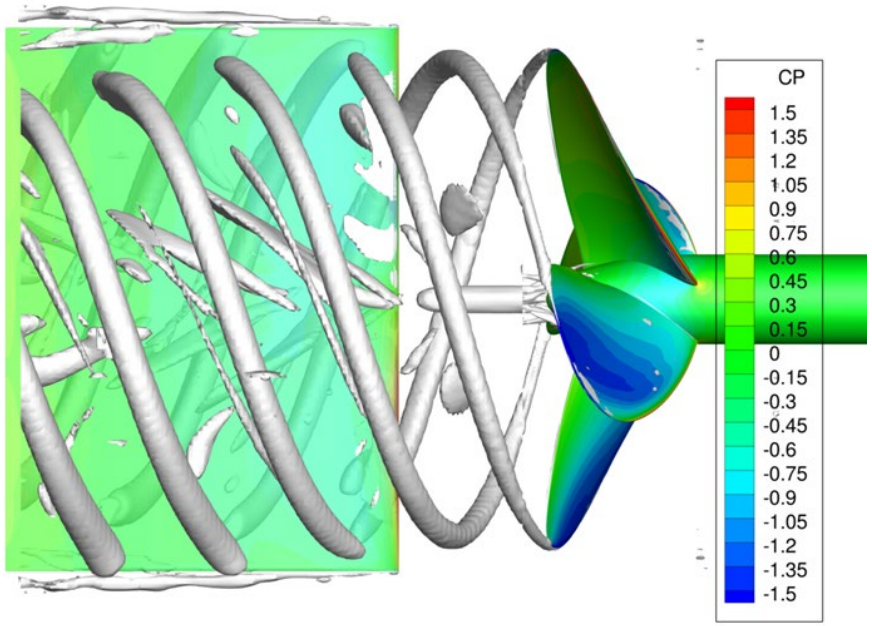


CFD Recipe - **Equations**

- Navier-Stokes or RANS
- Depending on Reynolds and Objective:
  - RANS-Turb Models: forces & moments, boundary-layer bahviour!
  - SRS Approaches: for wake!
- Transition Models => If Reynolds below 1E6!
- (if Flexible then FSI, then Structural Eqs of Motion. *Next time*…)
- Motion & Reference system
- $V_x, V_y, V_z, p, k, \omega, \gamma$ (7 equations)

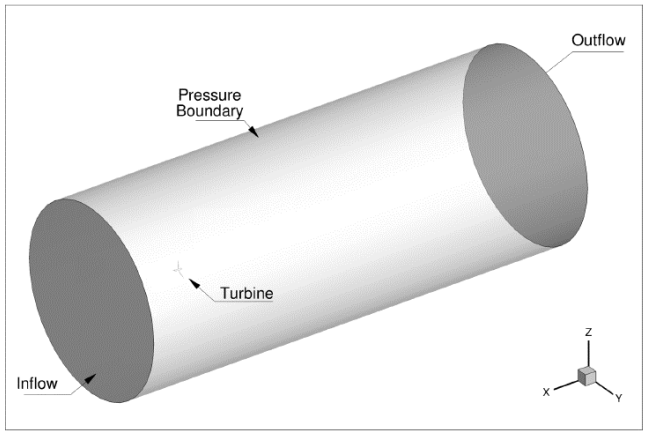


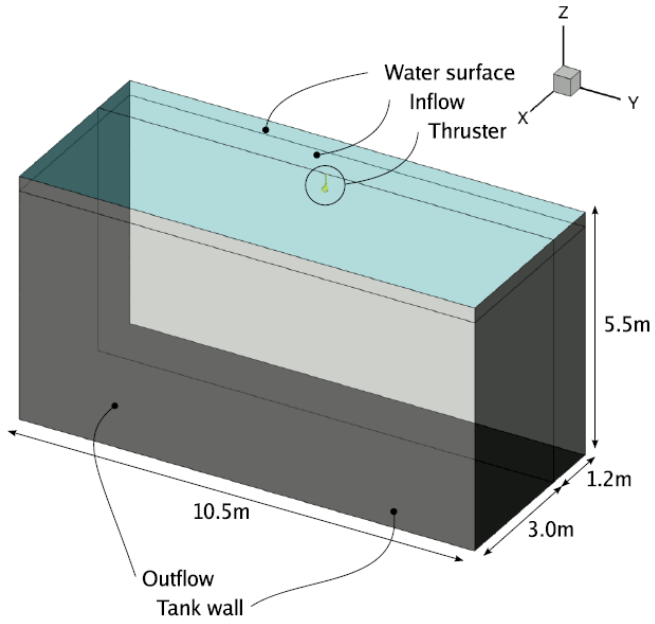




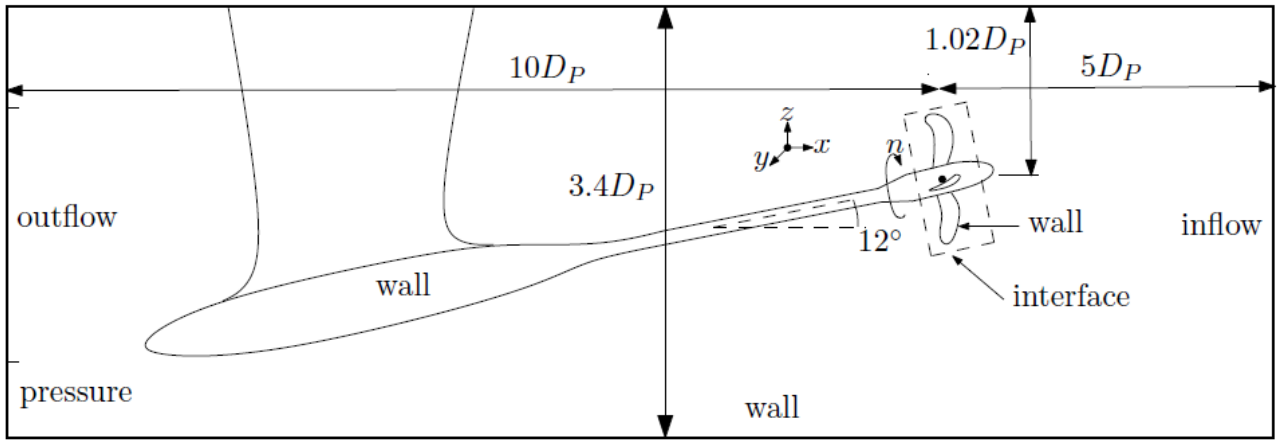
CFD Recipe – **Boundary Conditions**

- Depending on the case, grid layout and grid motion.
- Wall for rotating object.
- Hub?
- Inflow-Outflow
- External, Pressure, or Wall.





- If domain is big enough than external boundary BC is less problematic



CFD Recipe - **RefSys**

- **Moving Reference Systems**
  - **RFM** (relative formulation)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

$$\frac{\partial}{\partial t}[\rho \mathbf{U}] + \nabla \cdot \{\rho \mathbf{U}\mathbf{U}\} = -\nabla p + \nabla \cdot \left\{\mu \left[\nabla \mathbf{U} + \nabla \mathbf{U}^T\right]\right\} + \nabla (\lambda \nabla \cdot \mathbf{U}) + \mathbf{f_b} + \mathbf{f_{bo}}$$

$$\mathbf{f_{bo}} = \frac{d^2 \mathbf{x}_o}{dt^2} + \frac{\boldsymbol{\Omega}}{dt} \times \mathbf{x} + 2\boldsymbol{\Omega} \times \mathbf{U} + \boldsymbol{\Omega} \times (\boldsymbol{\Omega} \times \mathbf{x})$$

$$\frac{\partial}{\partial t}(\rho \phi) + \nabla \cdot (\rho \phi \mathbf{U}) = \nabla \cdot (\Gamma_\phi \nabla \phi) + Q_\phi$$

  - Variables and eqs on relative/moving reference frame. Imagine a propeller?
  - Permits steady calculations of rotating objects;
  - Unsteady calculations (not due to the motion) are possible.
  - Easier to define boundary conditions (no-slip wall of a moving object);
  - Attention:
    - Initialization might be an issue and lots of extra terms…
    - Careful with turbulence models. And btw is vorticity conserved or not?

CFD Recipe - **RefSys**

- **Moving Reference Systems**
  - **MRF/ABF** (moving reference-frame/absolute formulation)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho (\mathbf{v} - \mathbf{v_g})] = 0$$

$$\frac{\partial}{\partial t}[\rho \mathbf{v}] + \nabla \cdot \{\rho \mathbf{v}\mathbf{v}\} = -\nabla p + \nabla \cdot \left\{\mu \left[\nabla \mathbf{v} + \nabla \mathbf{v}^T\right]\right\} + \nabla (\lambda \nabla \cdot \mathbf{v}) + \mathbf{f_b} + \mathbf{f_{b_1}}$$

$$\mathbf{f_{b_1}} = \boldsymbol{\Omega} \times \mathbf{v}$$

$$\frac{\partial}{\partial t}(\rho \phi) + \nabla \cdot [\rho \phi (\mathbf{v} - \mathbf{v_g})] = \nabla \cdot (\Gamma_\phi \nabla \phi) + Q_\phi$$

  - Variables on earth-fixed reference frame and eqs on relative ref system.
  - Steady (due to motion) and Unsteady calculations (not due to the motion) are possible.
  - Attention:
    - There are some approximations here to get the simplified fb1!
    - Easier to continue to define boundary conditions in RFM (no-slip wall of a moving object); propeller vs a duct.
    - Note that $\nabla \cdot \mathbf{v_g} = 0$ due to the rigid-body motion assumption.
    - Initialization in the earth-fixed ref sys

CFD Recipe - **RefSys**

- **Moving Reference Systems**
  - **MVG** (moving grid)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot [\rho (\mathbf{v} - \mathbf{v_g})] = 0$$

$$\frac{\partial}{\partial t}[\rho \mathbf{v}] + \nabla \cdot \{\rho \mathbf{v} (\mathbf{v} - \mathbf{v_g})\} = -\nabla p + \nabla \cdot \{\mu [\nabla \mathbf{v} + \nabla \mathbf{v}^T]\} + \nabla (\lambda \nabla \cdot \mathbf{v}) + \mathbf{f_b}$$

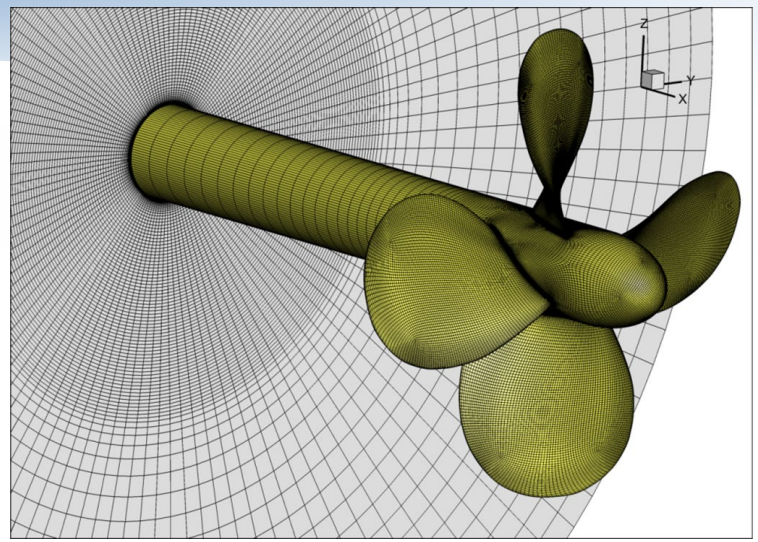
$$\frac{\partial}{\partial t}(\rho \phi) + \nabla \cdot [\rho \phi (\mathbf{v} - \mathbf{v_g})] = \nabla \cdot (\Gamma_\phi \nabla \phi) + Q_\phi$$

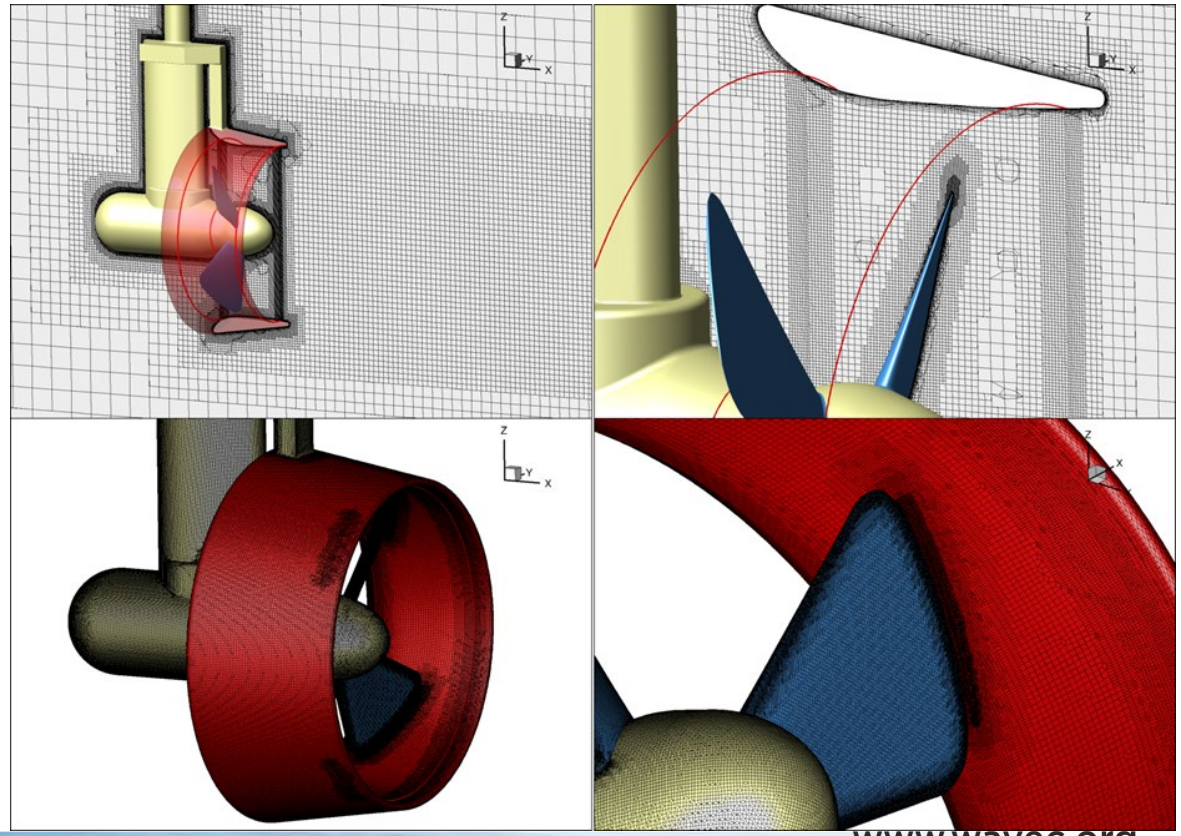
  - Variables and equations on earth-fixed reference frame.
  - Unsteady calculations always!
  - Attention:
    - No extra body forces.
    - Easier to continue to define boundary conditions in RFM (no-slip wall of a moving object); propeller vs a duct.
    - Note that $\nabla \cdot \mathbf{v_g} = 0$ due to the rigid-body motion assumption.
    - Initialization in the earth-fixed ref sys.

CFD Recipe – **Grid&Motion**

- How to model the motion?
  - AFM, RFM, MVG

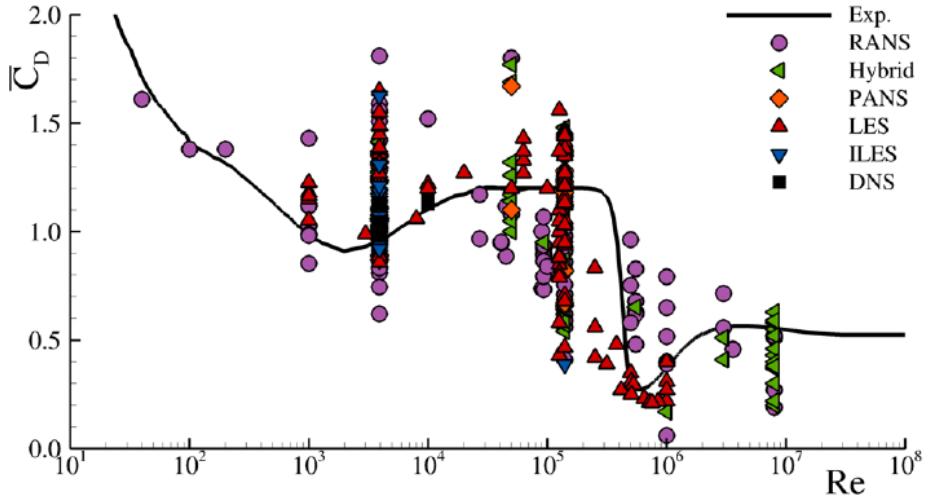
- Relation with Grid Layout
  - AFM, RFM
    - Complete domain “rotates”
    - Cylindrical domains!
    - Cheaper
    - Only for uniform inflows
  - MVG => use of Sliding-grids or Overset-grids
    - Only rotating parts “rotate”
    - Any sort of domains
    - More realistic
    - Unsteady and more expensive due to intrinsic CFD extra operations
    - For any inflow conditions

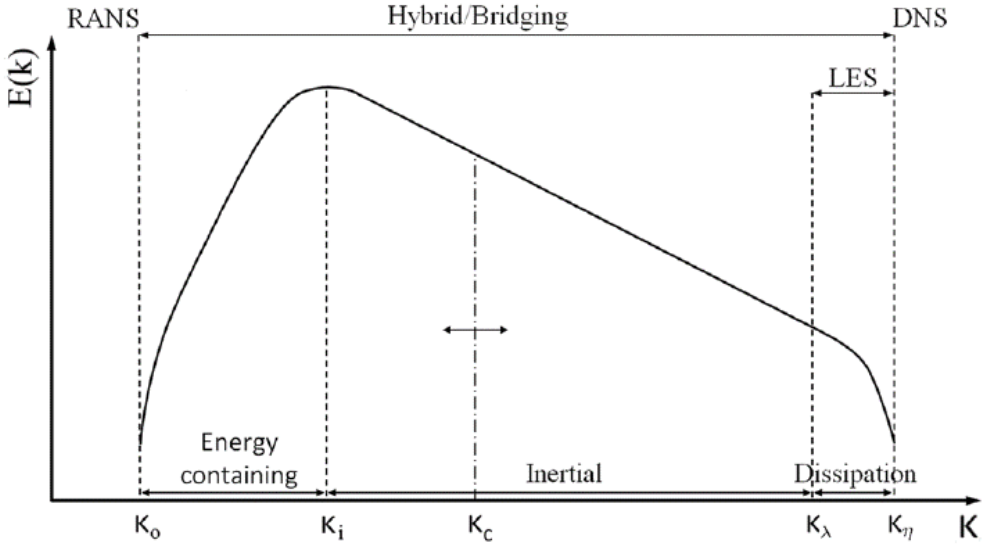




CFD Recipe - **Turbulence**

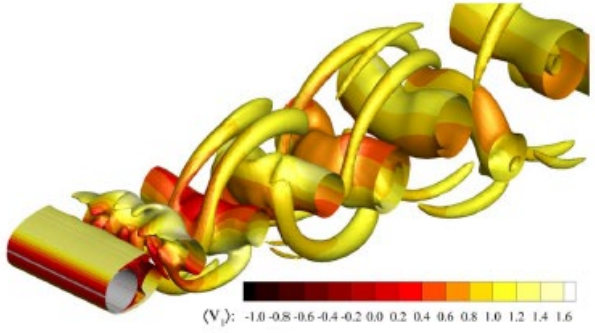
- Turbulence Modelling (uRANS)
  - Turbulence effects considered, but turbulence is not resolved.
  - Models: SST, KSKL, EARSM
- Turbulence Solving (SRS)
  - Turbulence (part of it) is resolved.
  - Approaches: (ID)DES, LES, PANS
- Transition Modelling (uRANS)
  - Since solving transition implies solving very small scales of turbulence, transition modelling is still needed for medium-high Reynolds.
  - Models: *Gamma-Re_theta, Gamma, AFT*



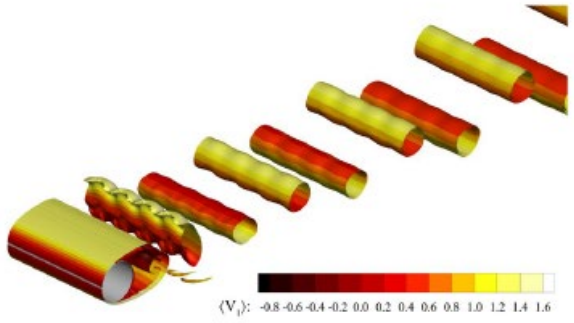


CFD Recipe - **Turbulence**

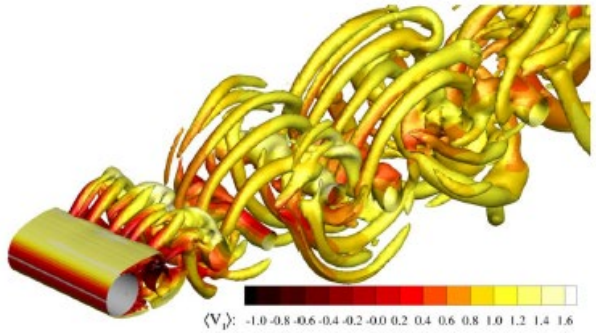
- Turbulence Modelling or Solving.



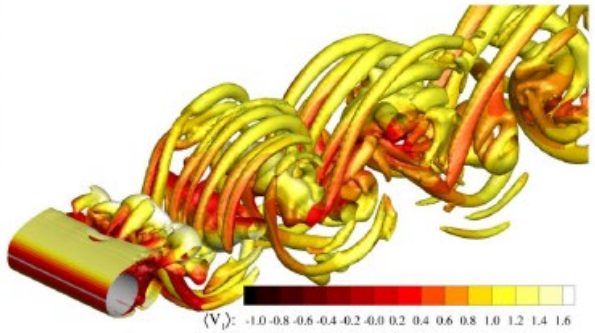
(a) SST.



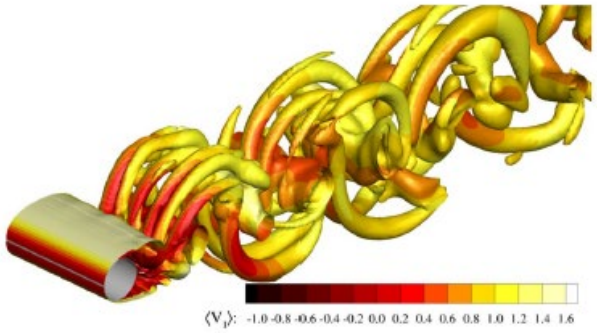
(b) RSM.



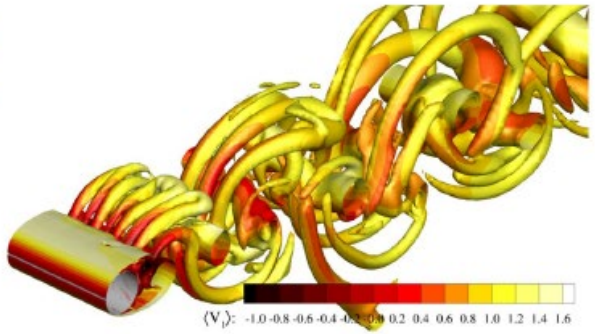
(e) DDES.



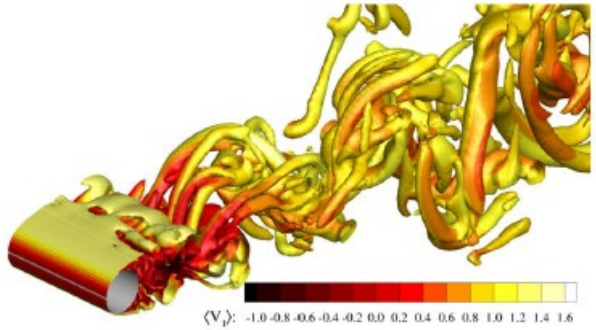
(f) IDDES.



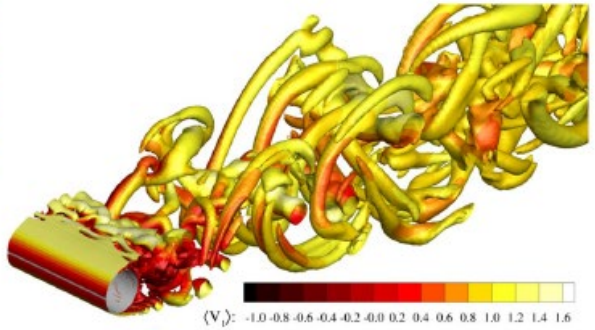
(c) EARSM.



(d) PANS - $f_k = 0.50$.



(g) XLES.



(h) PANS - $f_k = 0.25$.

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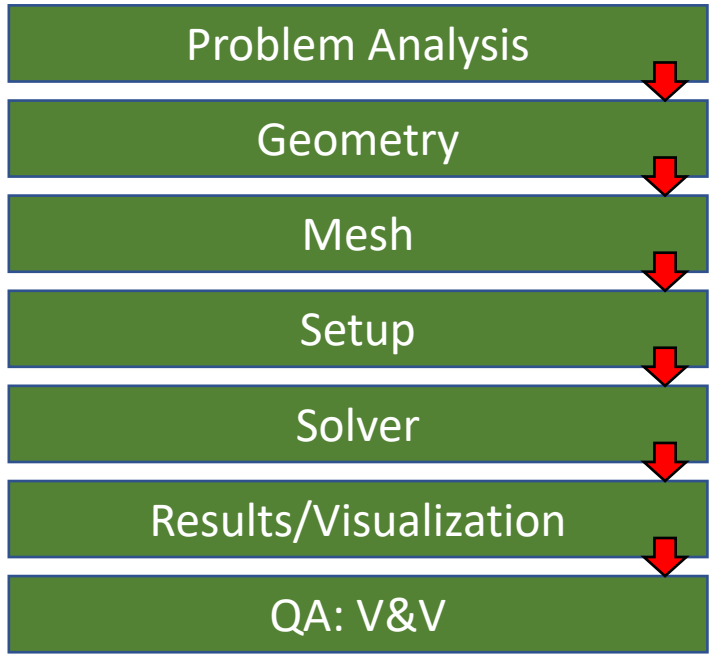

CFD Recipe – **Control Settings**

- Example: Momentum, Continuity, SST (k, ω) Turb Model
- Unsteady
  - AFM, RFM: ---
  - MVG: 1st order to start; 2nd order for accuracy
  - Time-step: 5-3deg to start with…
- Convection
  - Mom: QUICK-LIMITED
  - Press: ---
  - Turb-k : UPWIND
  - Turb-ω UPWIND
- Diffusion
  - CENTRAL for all eqs.
- Relaxation
  - Very much code, and SIMPLE-R-C-PISO specific!
  - Lower values better for robustness; Higher for speed.
  - Mom (explicit rlx): 0.5
  - Press (explicit rlx): 0.05
  - Turb-k (explicit rlx): 0.25, Turb-ω (explicit rlx): 0.25
- Extras
  - Geometrical corrections: off for robustness and on for accuracy
  - Start-up:
    - From steady (FR)
    - From large time-steps
    - Don’t forget statistical uncertainty…

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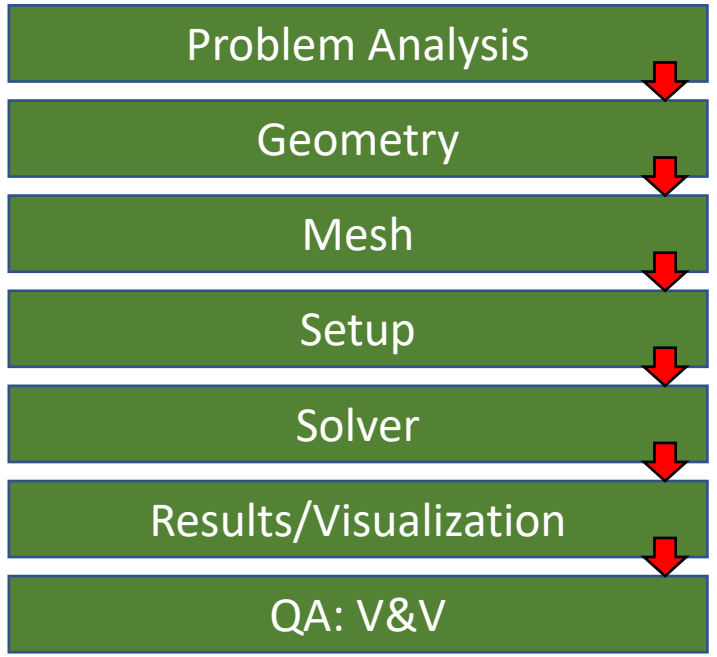
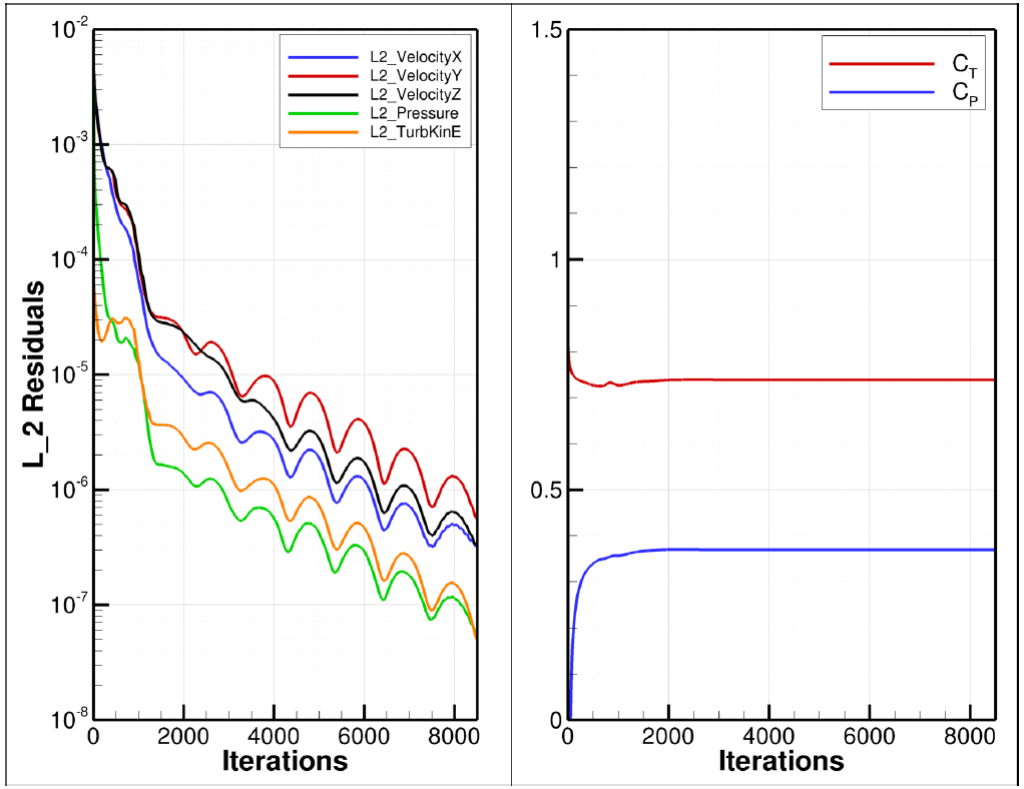
  - Convection, Diffusion, DT, Limiters, Solvers, Relaxation, Source terms, extras
- **Monitoring**
  - Residuals
  - Forces, Moments
- Results
- Visualization
- Post-processing

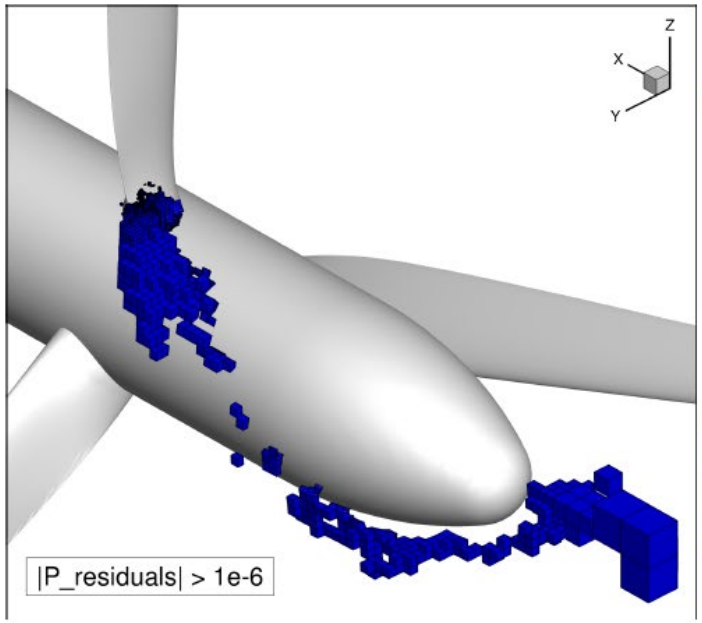
- V&V: quality assessment!



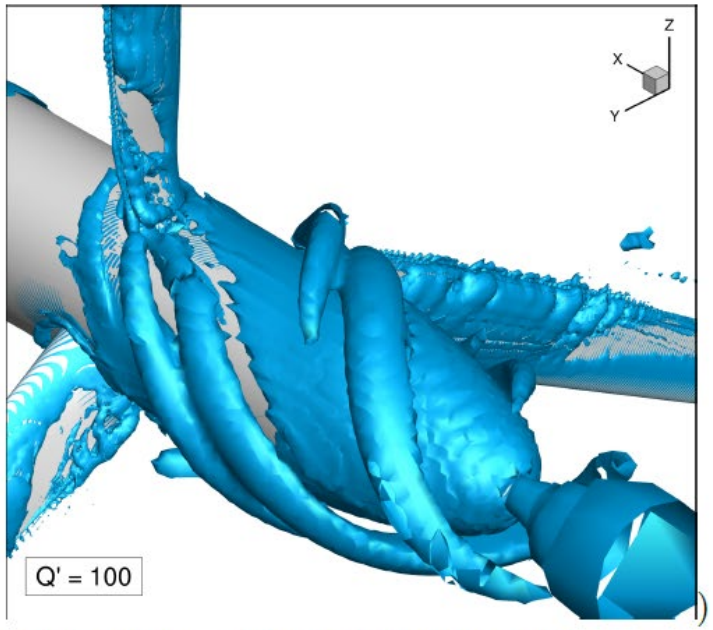
CFD Recipe – Monitoring

- Residuals, Forces, Moments





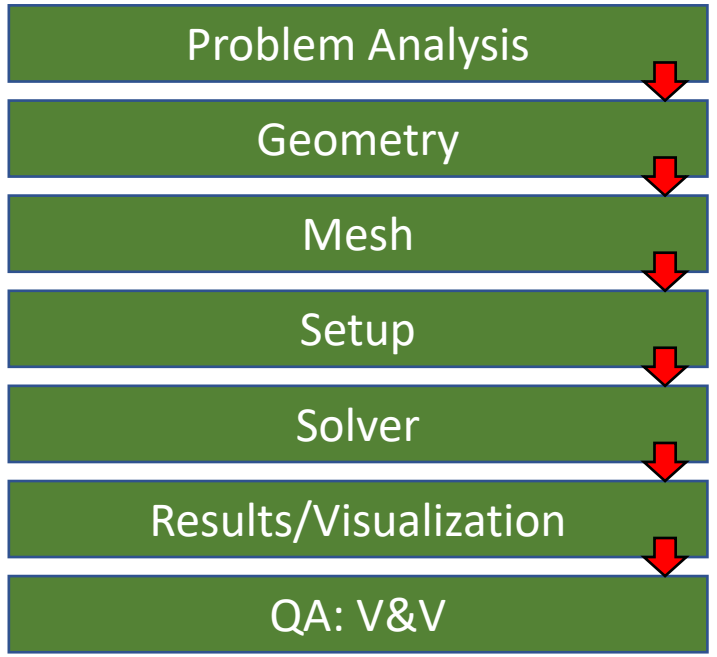
(a) Pressure residuals in the flow domain.



(b) Iso-surface of dimensionless Q factor at the blade root($\overline{Q} = 100$).

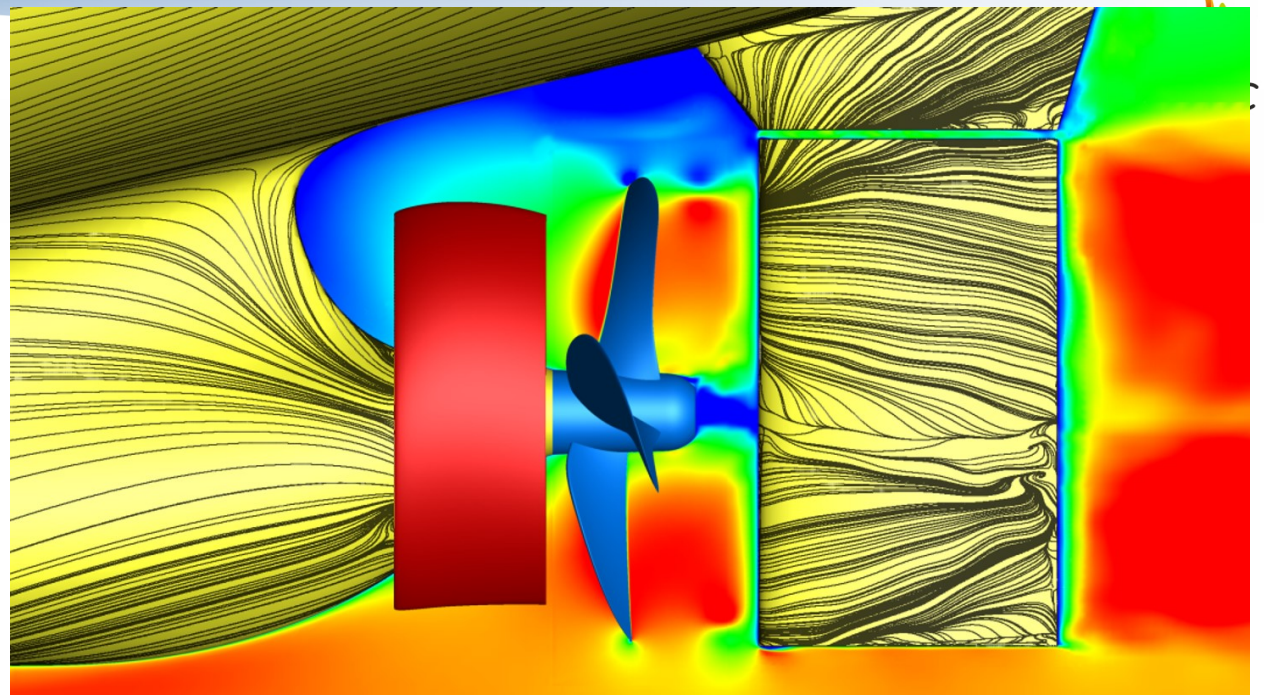
CFD Recipe

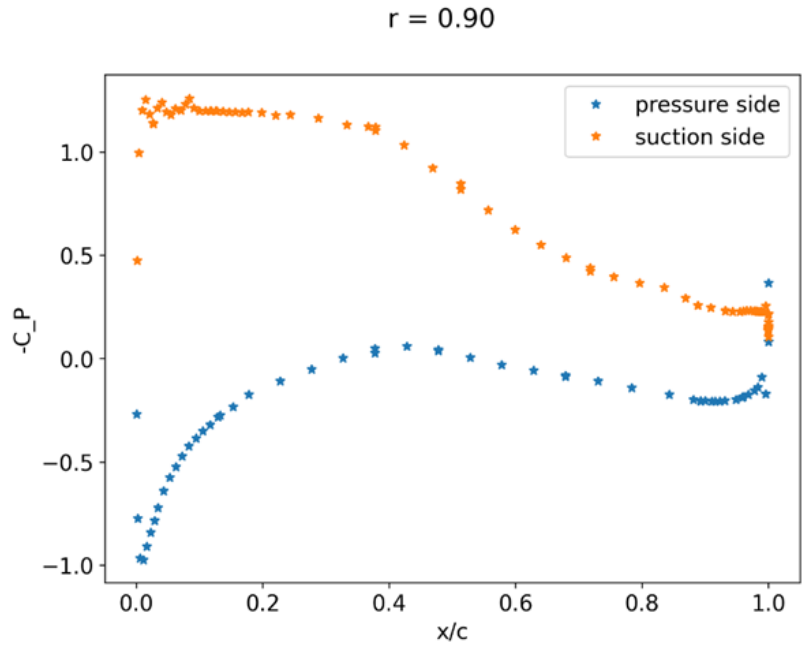
- Geometry
- Domain
- Grids
  - Type
  - Cell size
  - Boundary Layer
  - Motion
- Equations
  - Reference frames
  - Laminar vs Turbulent Flow
  - Transition Models
  - Turbulence Models
  - Boundary Conditions
- Control settings
  - Convection, Diffusion, DT, Limiters, Solvers, Relaxation, Source terms, extras
- Monitoring
  - Residuals
  - Forces, Moments
- **Results**
- **Visualization**
- **Post-processing**
- V&V: quality assessment!

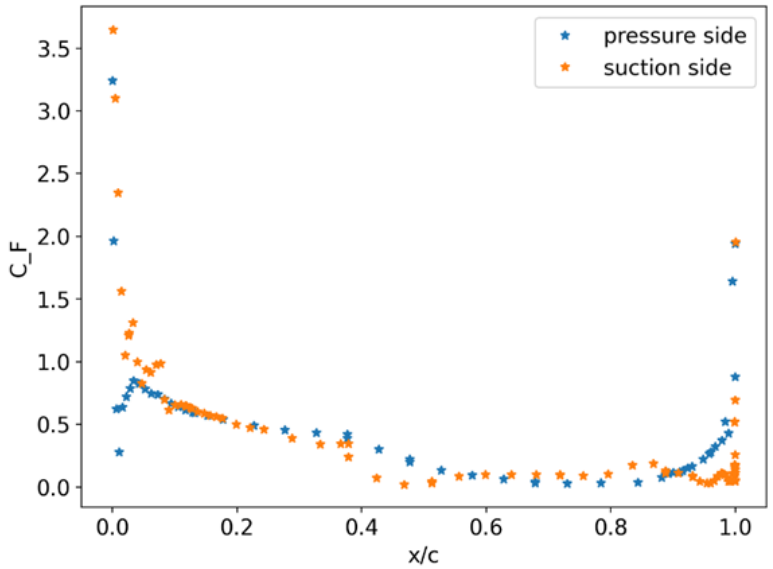


CFD Recipe - **Analysis**

- Slices
- Surface Contours
- Volume iso-surfaces
- Limiting-streamlines
- 2D Cp, Cf vs x/c plots

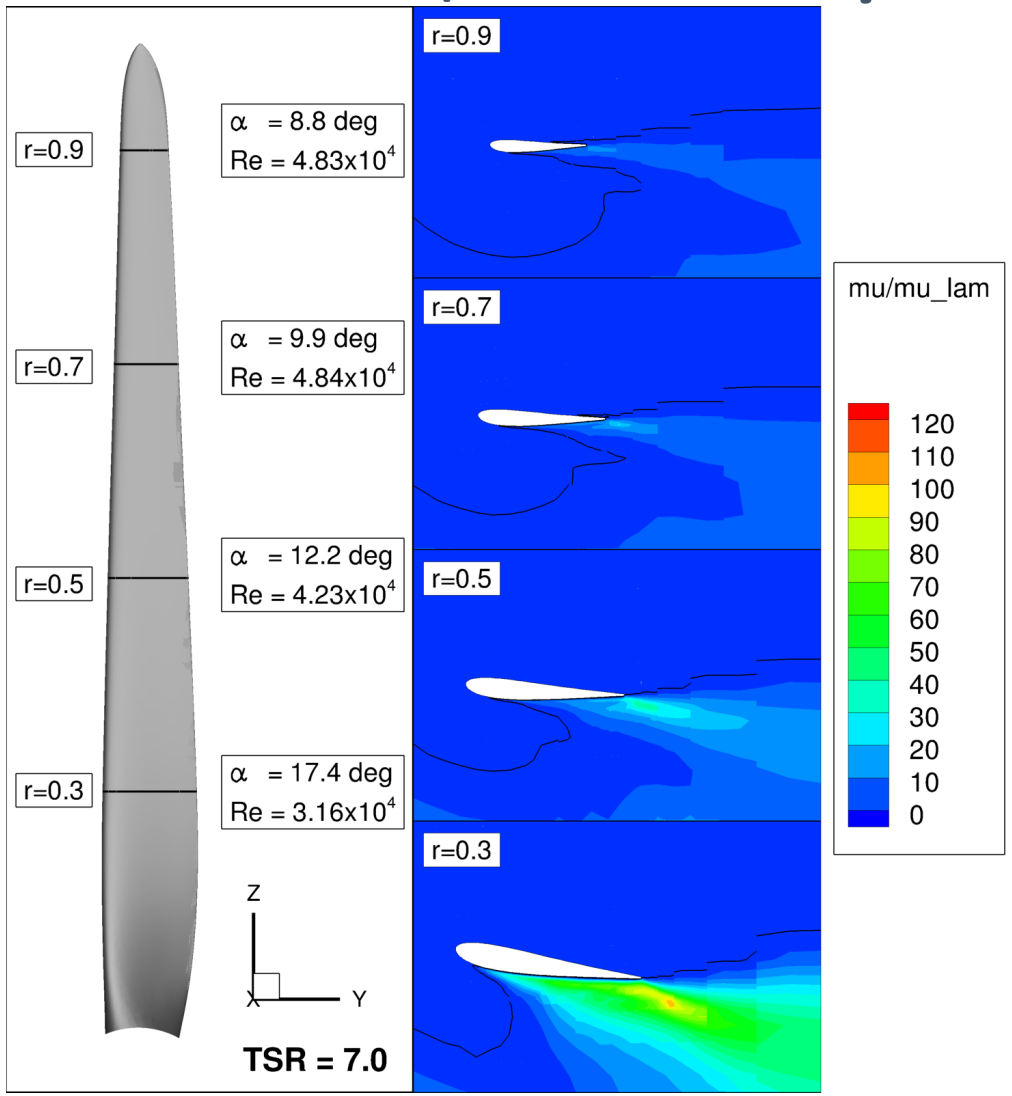


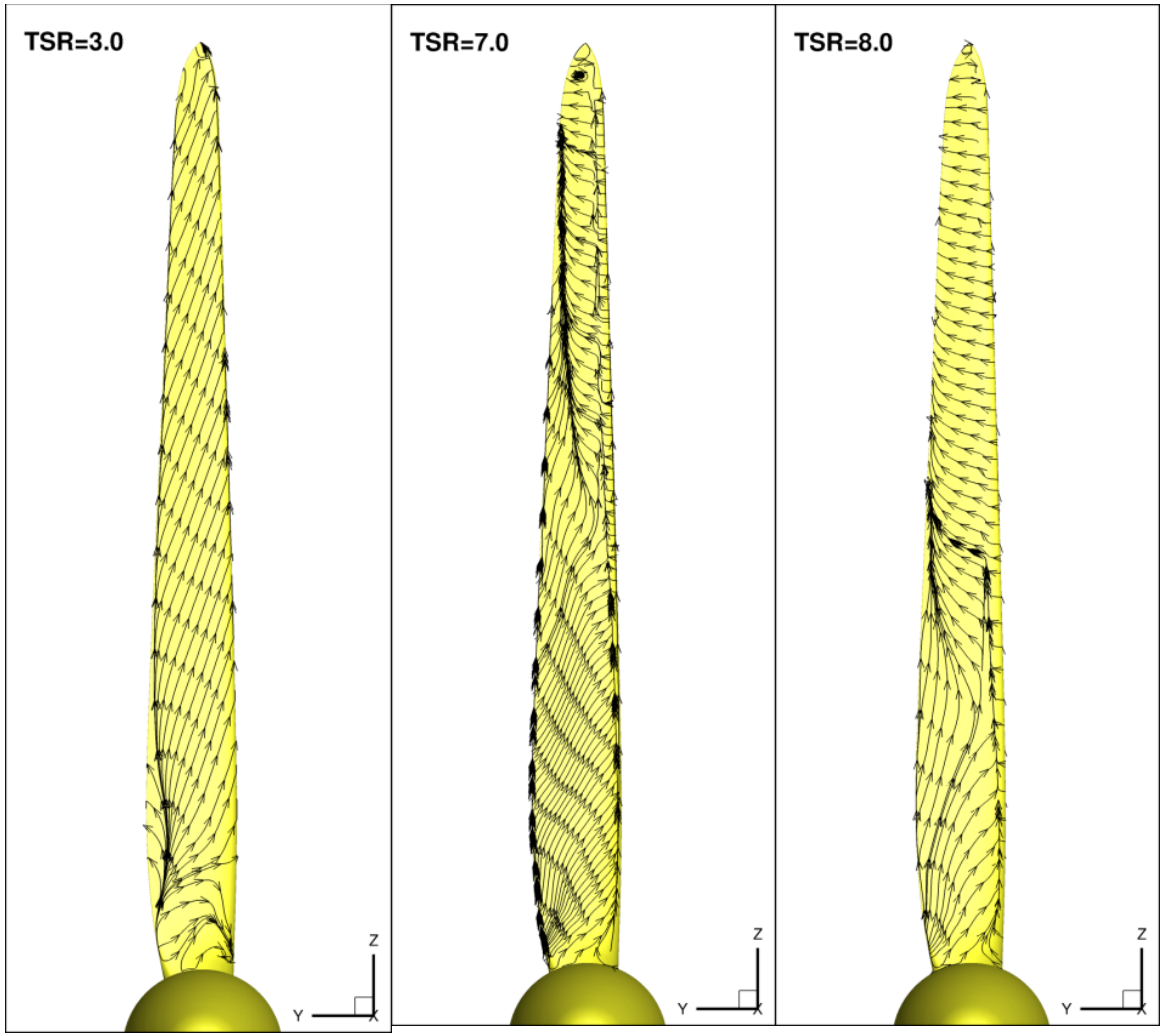




CFD Recipe - **Analysis**

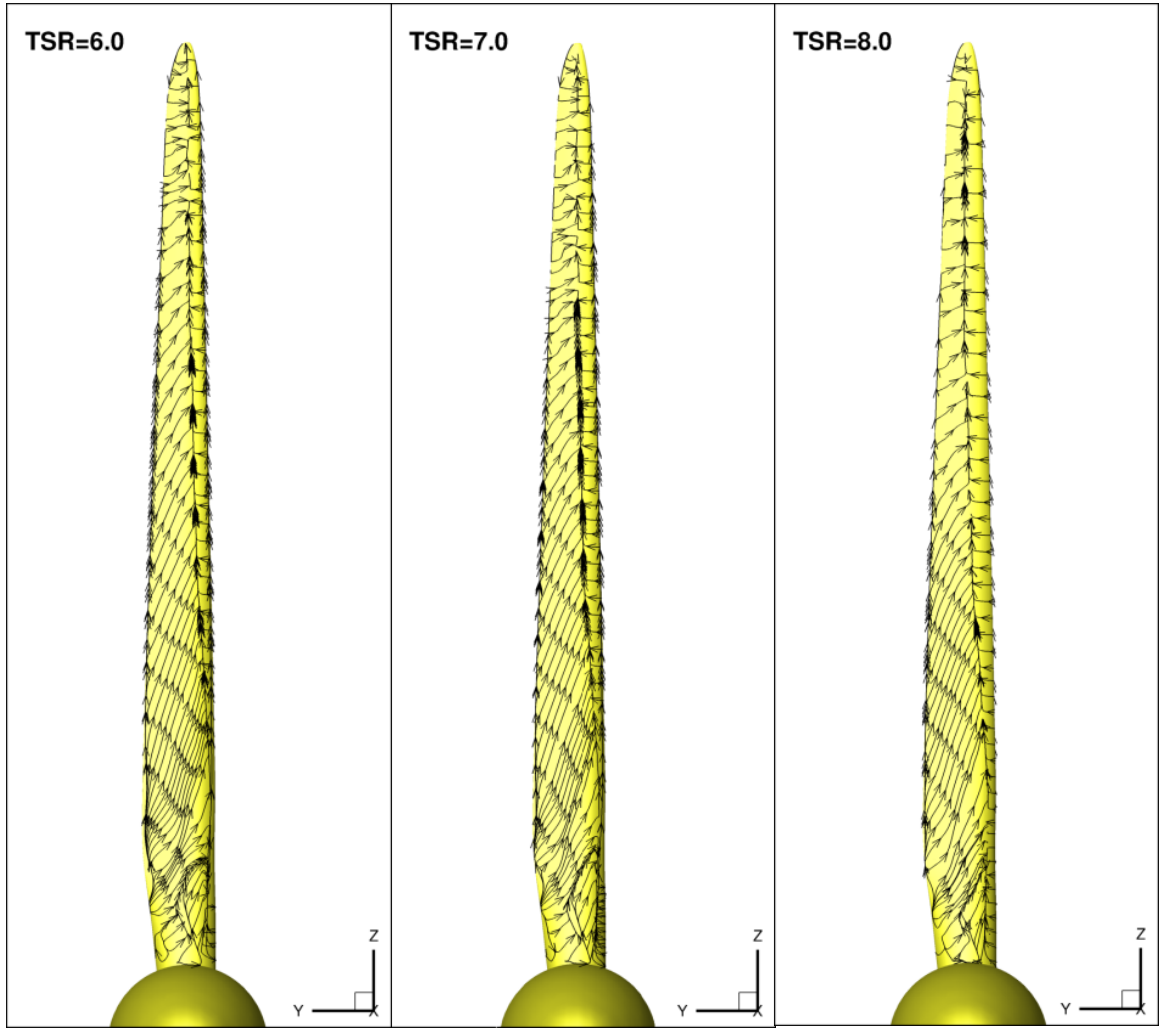
- Fully separated at low TSR
- Partially separated at operating condition



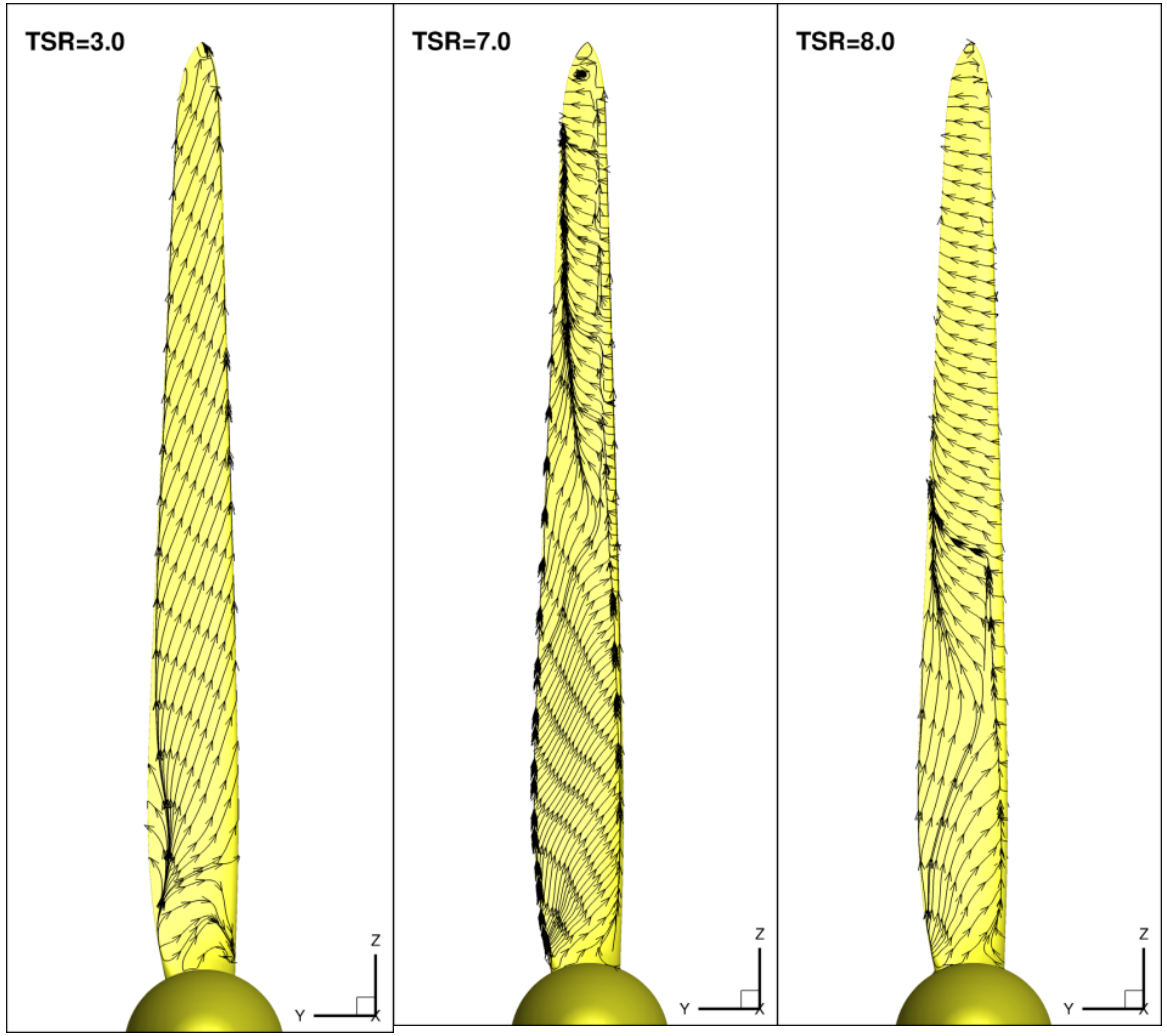


CFD Recipe - **Analysis**

NREL model-scale

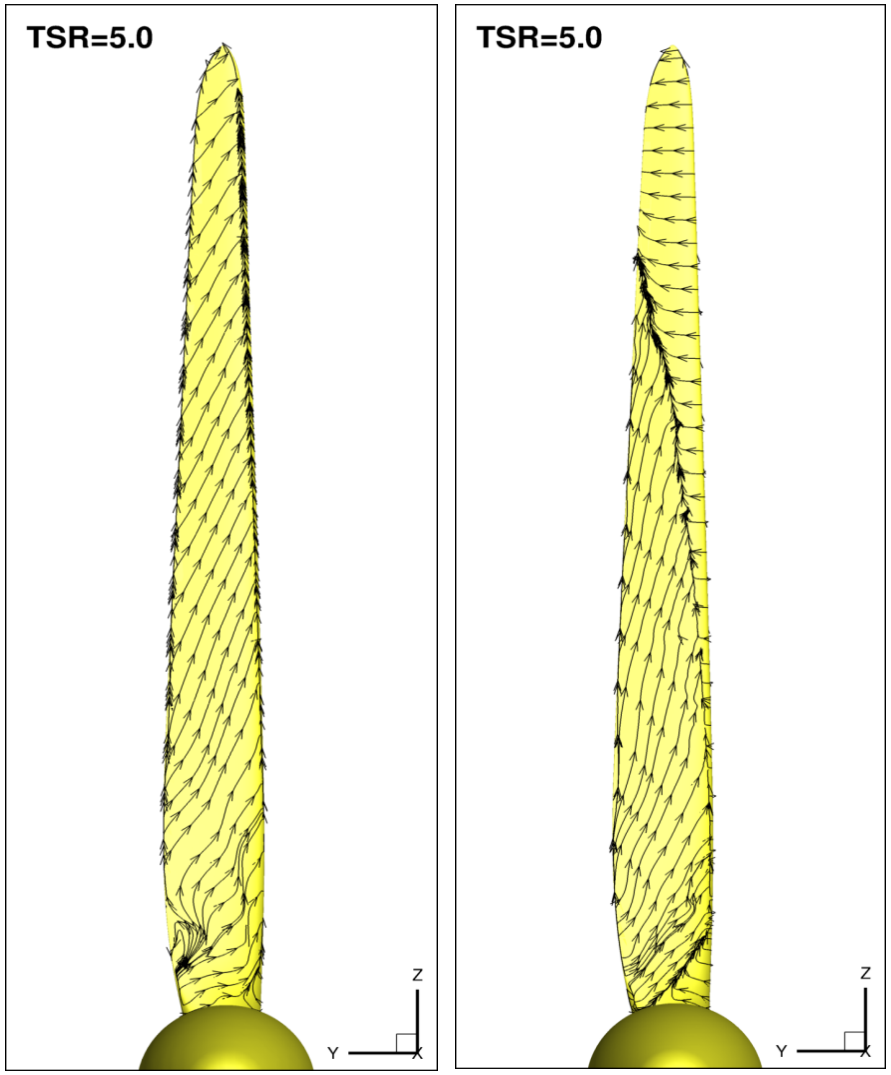


MSWT model-scale



CFD Recipe - **Analysis**

- MSWT, TSR=5



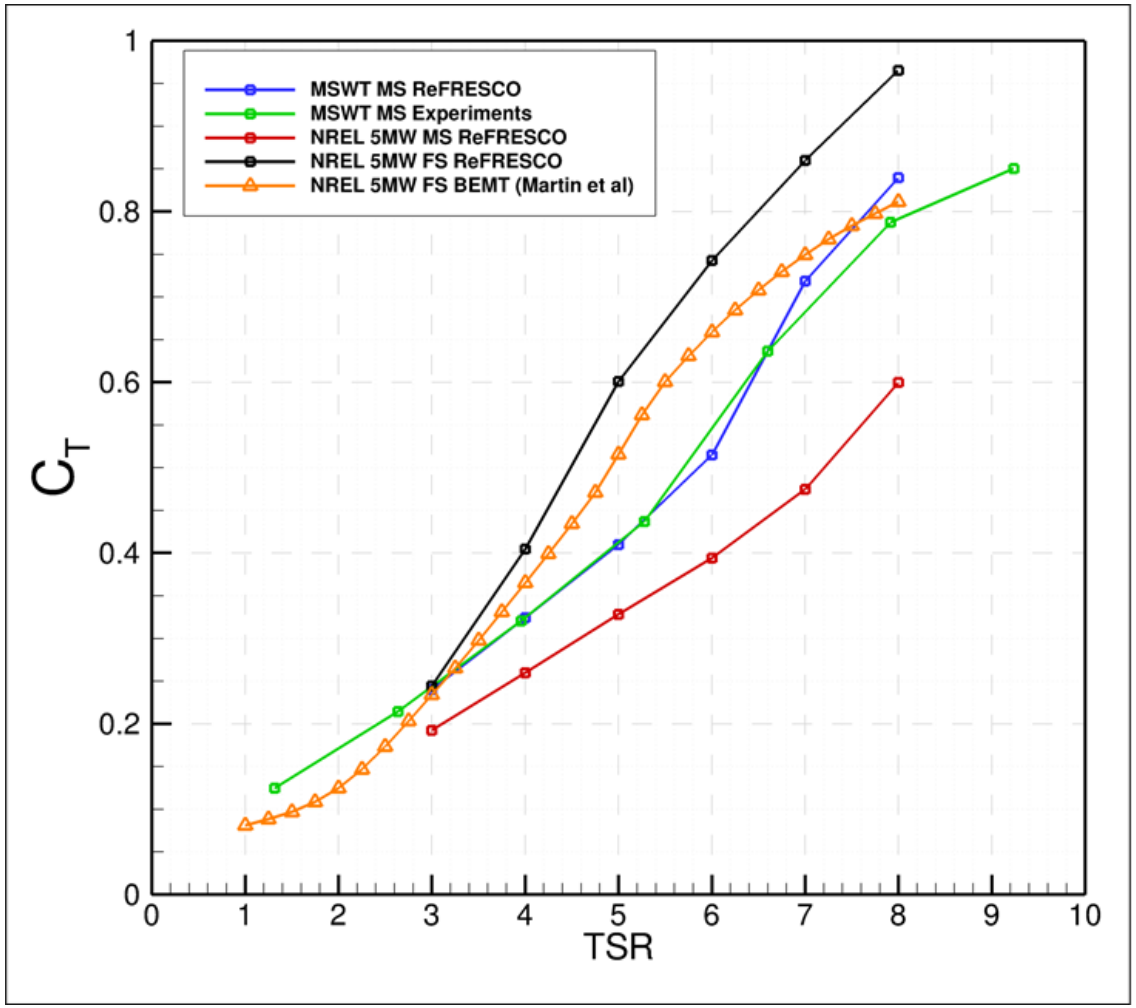
Model-Scale:

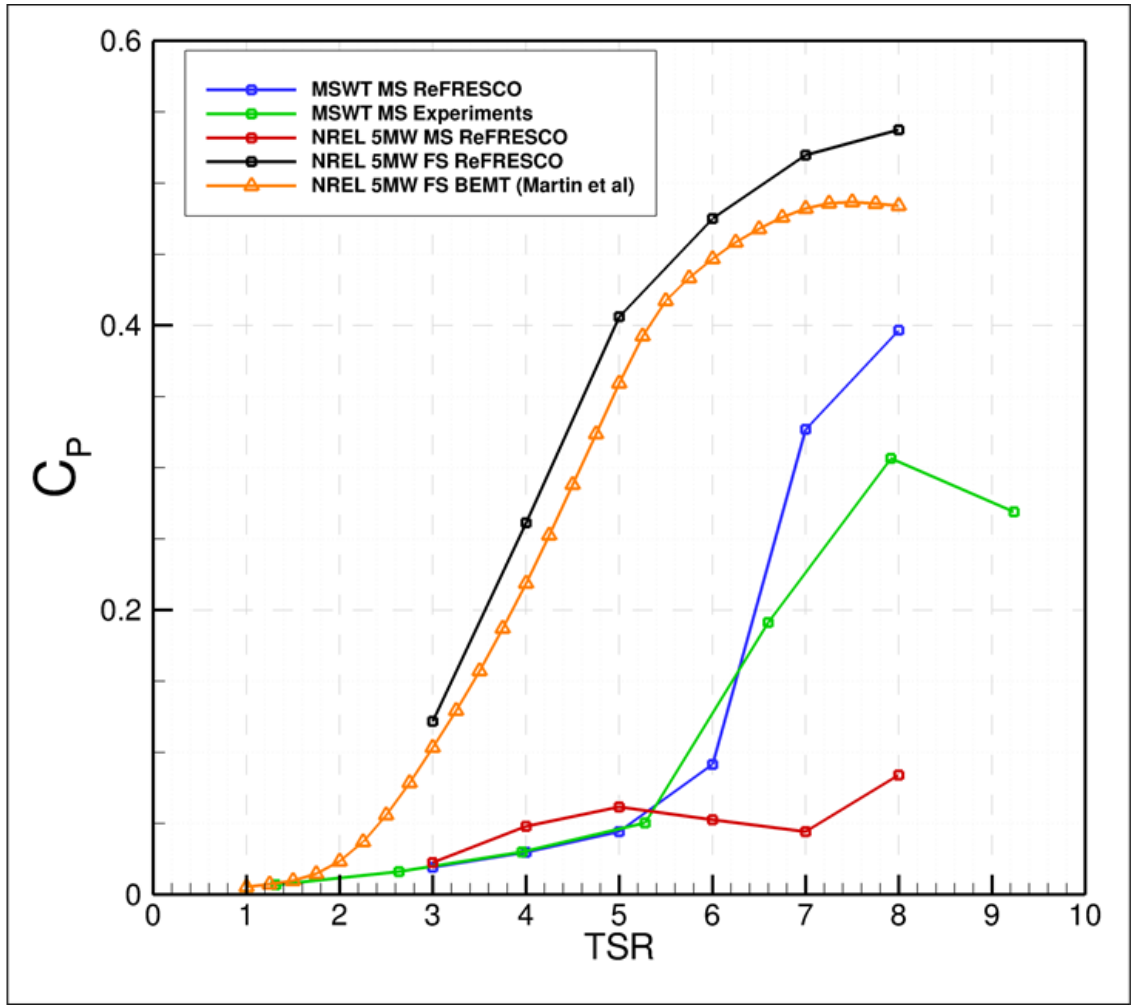
- Re =3.6e4
- Laminar
- Fully separated
- C_T = 0.409
- C_p =0.044

Full-Scale:

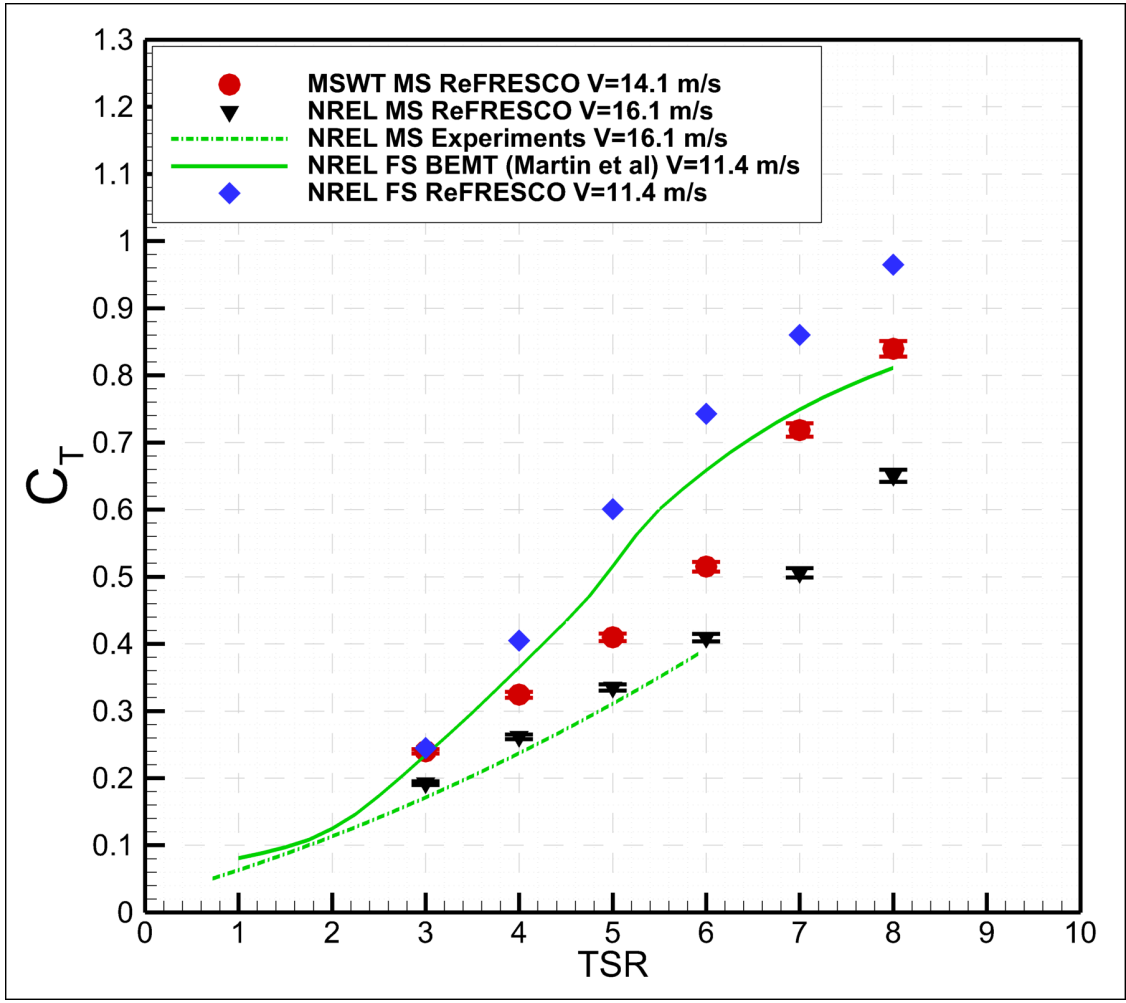
- Re =8.1e6
- Turbulent
- Partially separated
- C_T = 0.574
- C_p =0.354

CFD Recipe - **Analysis**



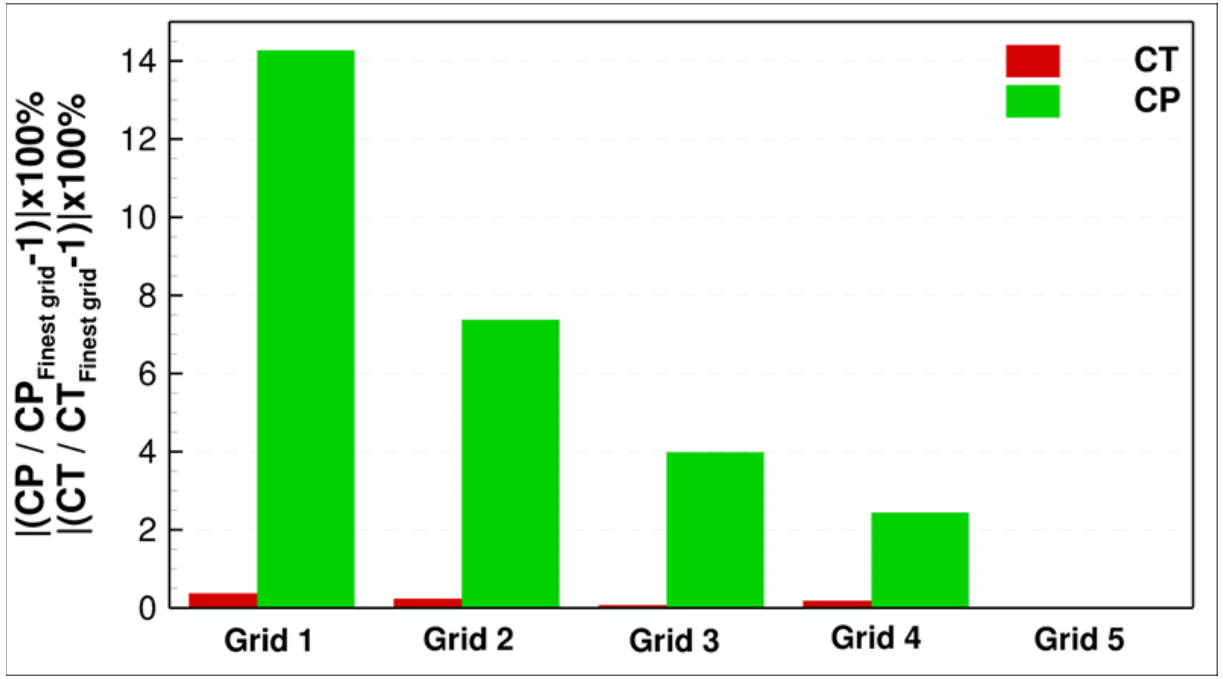


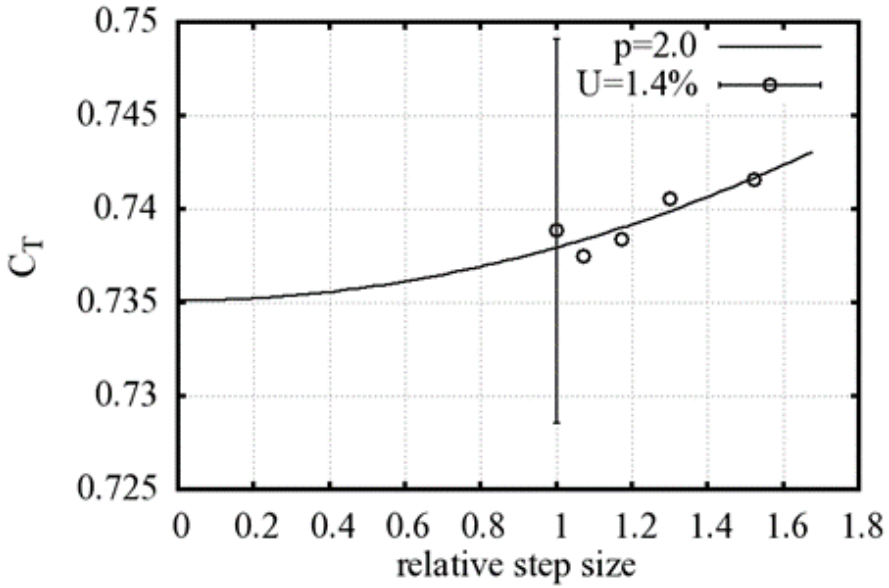
CFD Recipe - **Analysis**

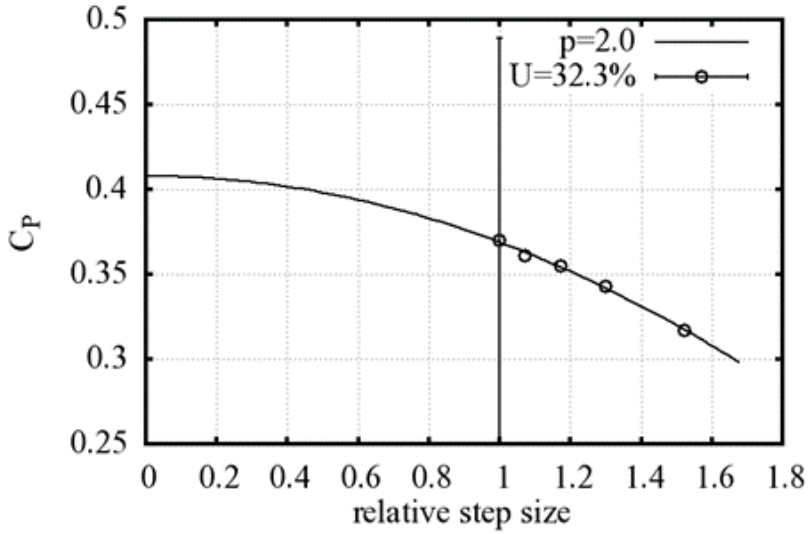


CFD Recipe – **V&V**

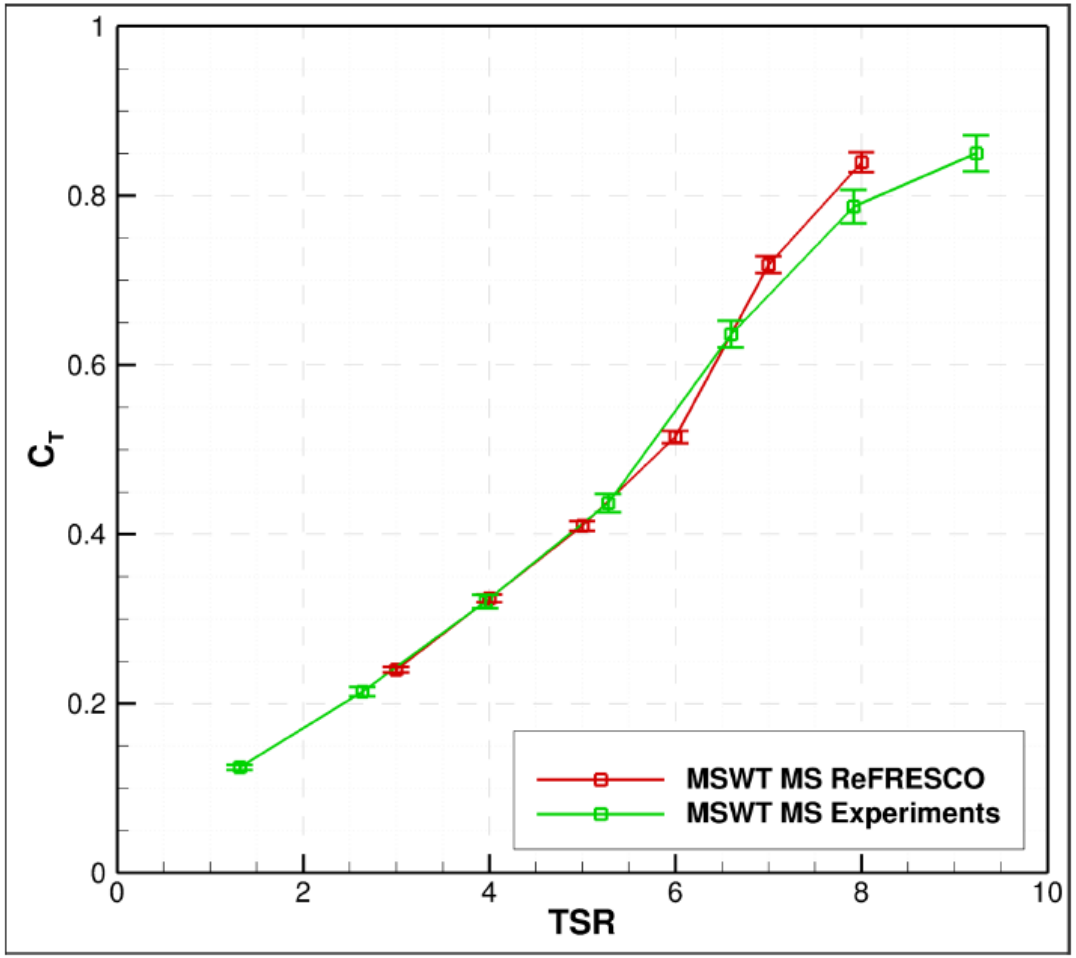
Grid refinement	1	2	3	4	5
Total no. Cells	8371928	13406225	18559122	23907087	29558234
Minimum Orthogonality	10.34	13.74	15.406	12.541	11.726
Average Orthogonality	77.871	78.197	78.420	78.157	77.966
Maximum Skewness	0.903	0.877	0.874	0.864	0.879
Grid ref. ratio	1.52	1.30	1.17	1.07	1.00

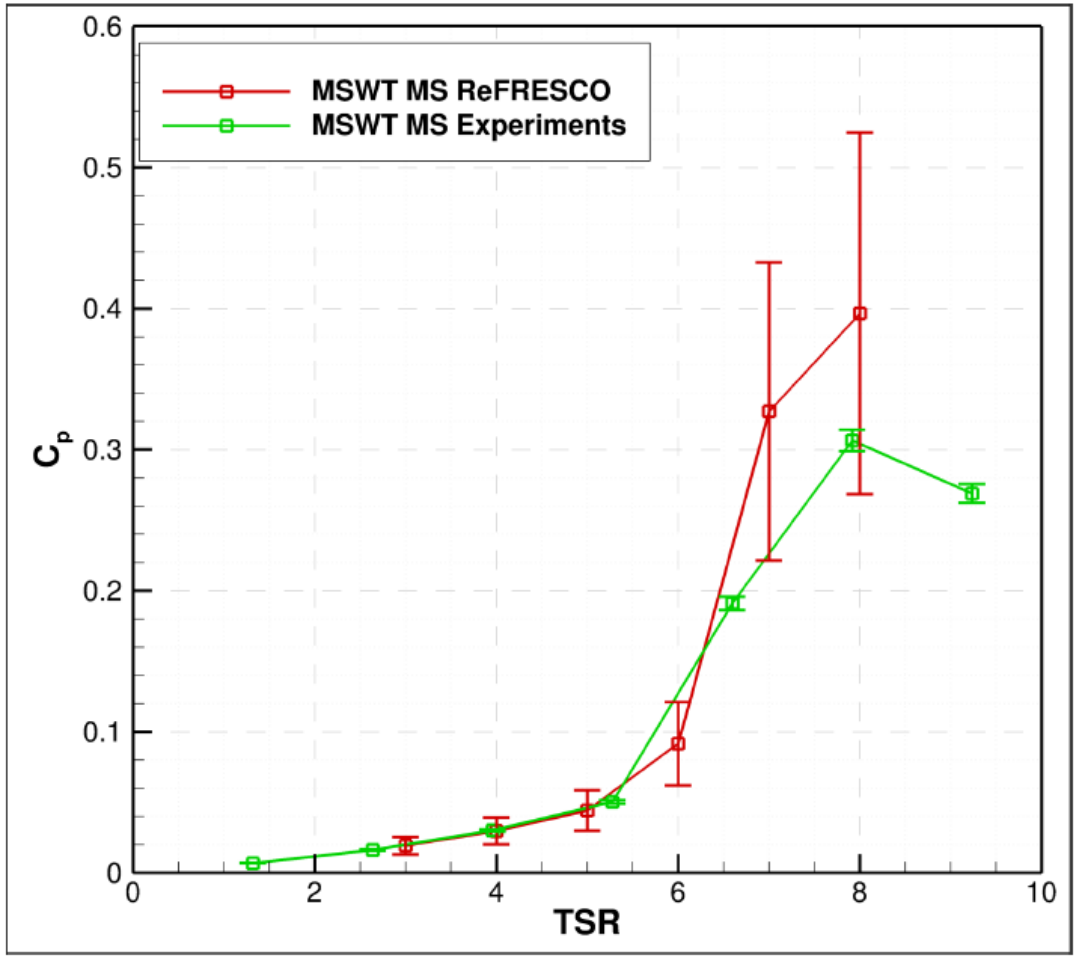




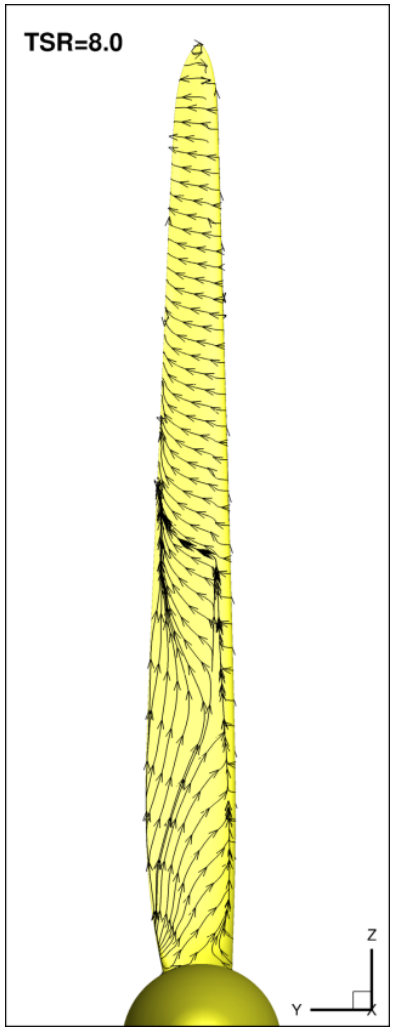


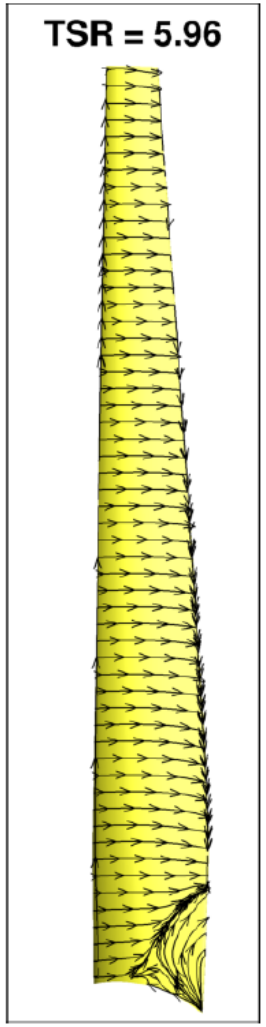
CFD Recipe – **V&V**

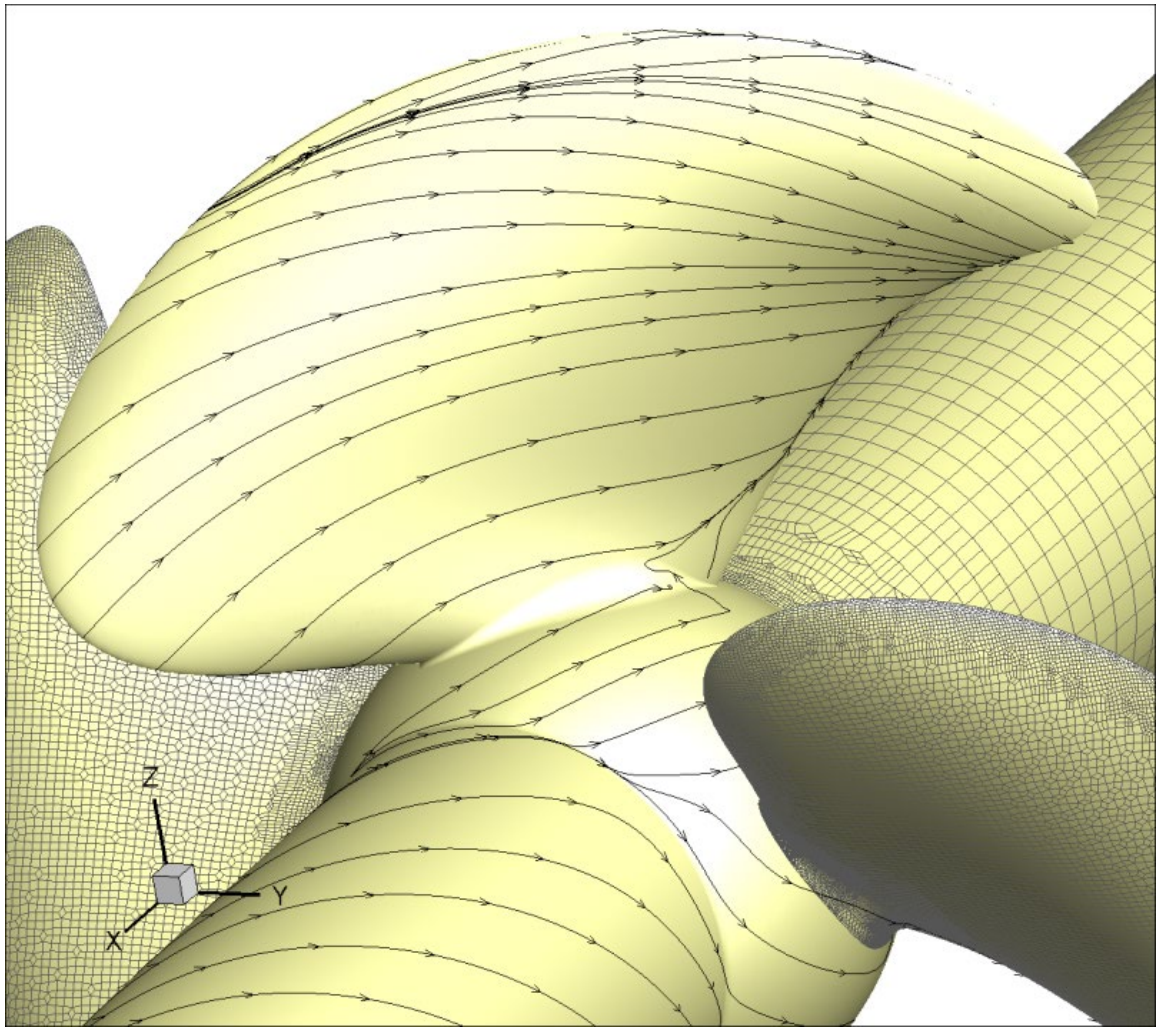




Wind Turbine, Current Turbine, Propeller

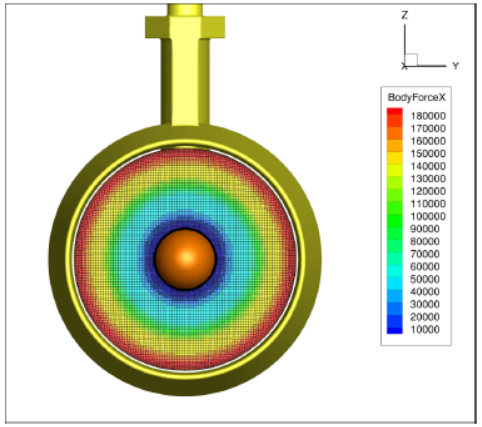




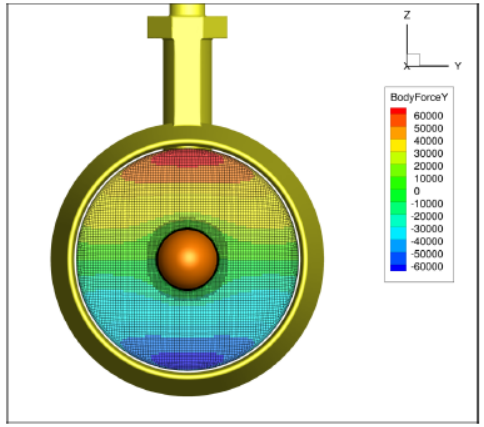


Turbine Modelling vs Simulation

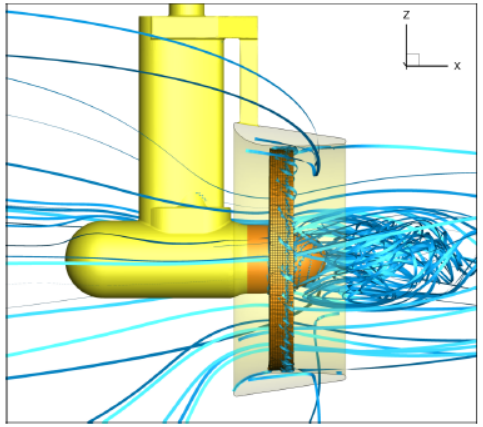
- When and Why?
  - More than 1, 2. Parks! Still too expensive
- RANS-ActuatorDisk
- RANS-Steady, RANS-FR, RANS-SI



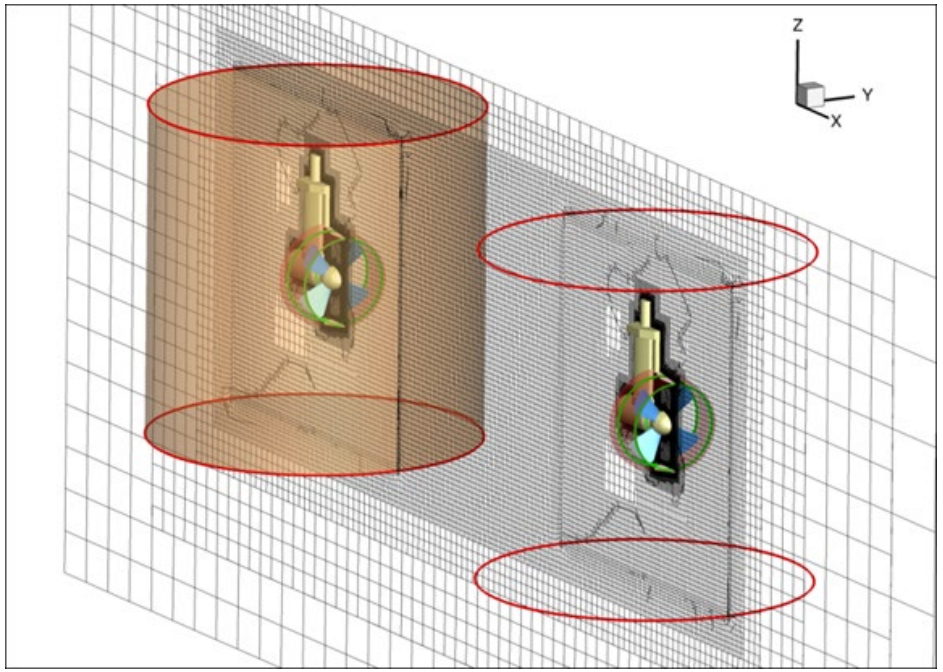
(a) Grid cells body-force axial component with identifiable gap between propeller and nozzle



(b) Grid cells body-force tangential component (y contribution).



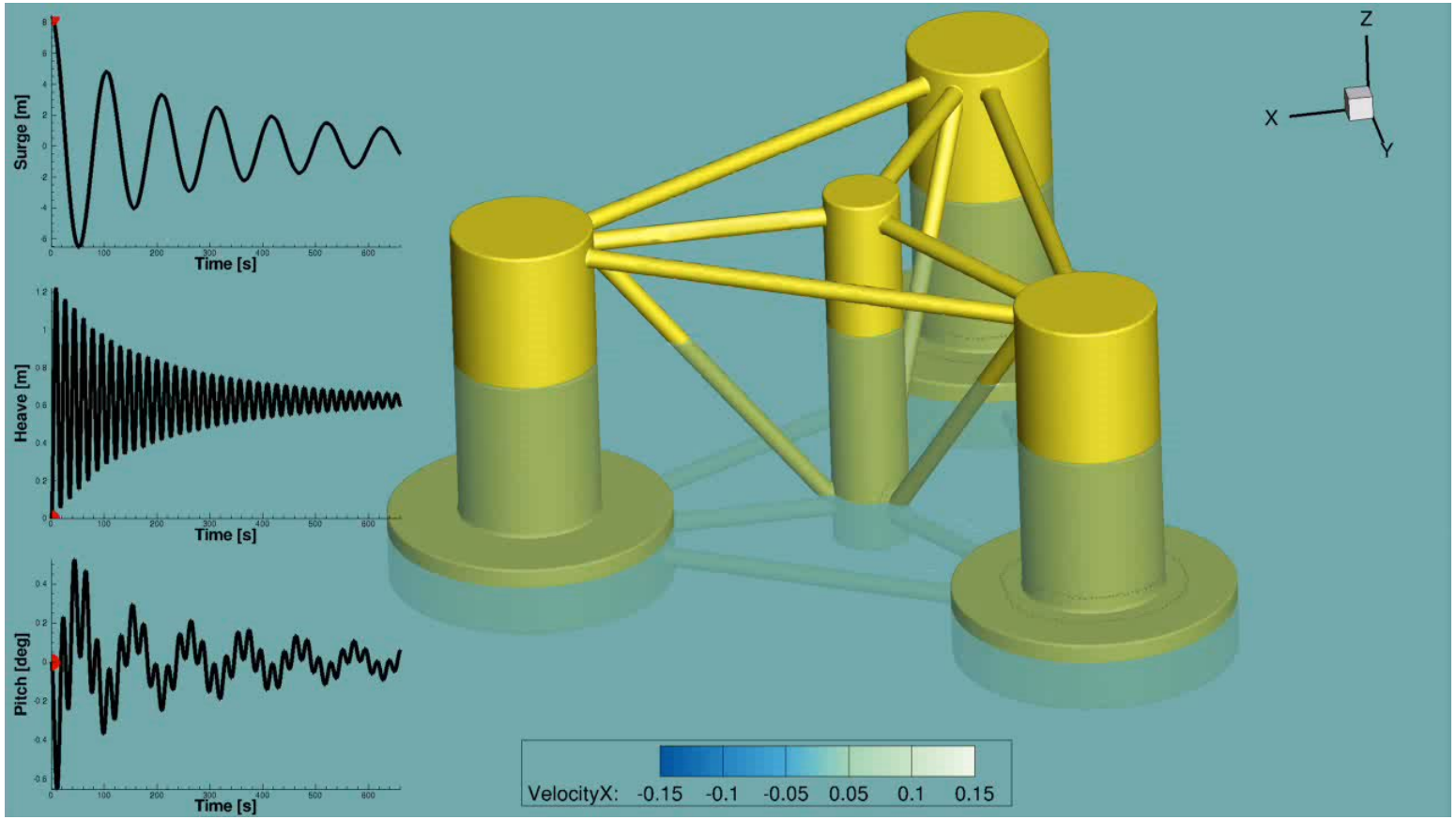
(c) Flow streamlines indicating a wide capturing of upstream flow, with recirculation zone at the rotating hub tip.



Offshore Wind

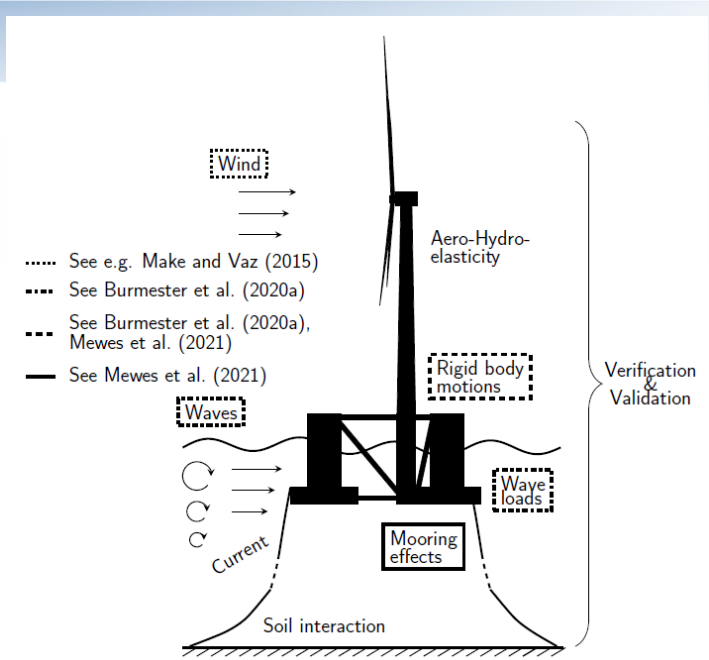
- Fixed Turbines
  - Current, waves loads
  - Tower and blades FSI.
  - Soil interaction.

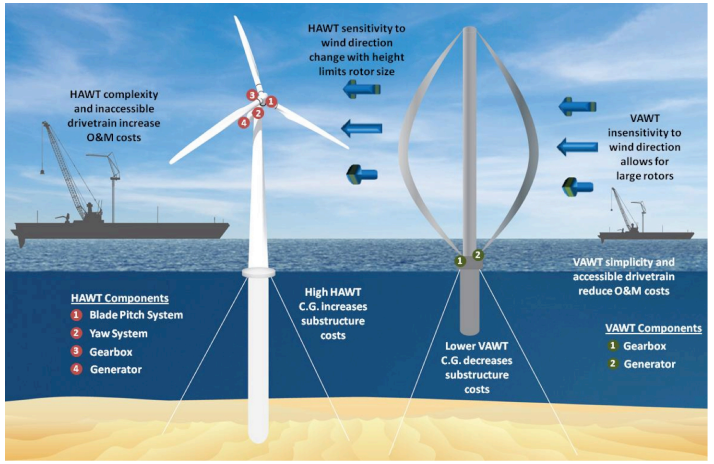
- Floating Turbines
  - Current, waves loads.
  - Platform loads and motion.
  - Coupling of hydrodynamic-aerodynamics
  - Tower and blades FSI.
  - Moorings.

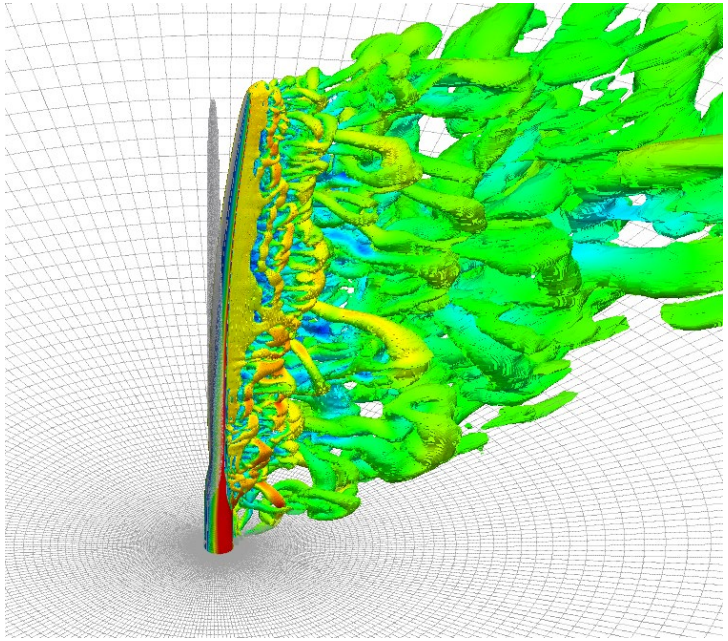


Current Research

- Aero+Platform Imposed Motion
- Aero+Hydrodynamic
- SRS and Turbine Wake
- Aero-elasticity FSI
- Parks
- VAWT
- Control@CFD
- Holistic Analysis







WavEC

Offshore Renewables

Making the World Green and the Oceans Blue…

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