Wind Farm Detached-Eddy Simulations Using an Immersed Boundary Method-Actuator Surface Model Solver

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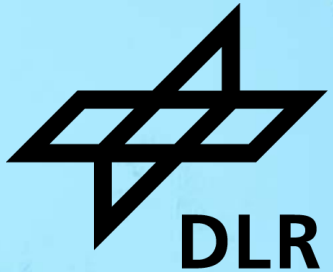
THE UNIVERSITY OF SYDNEY



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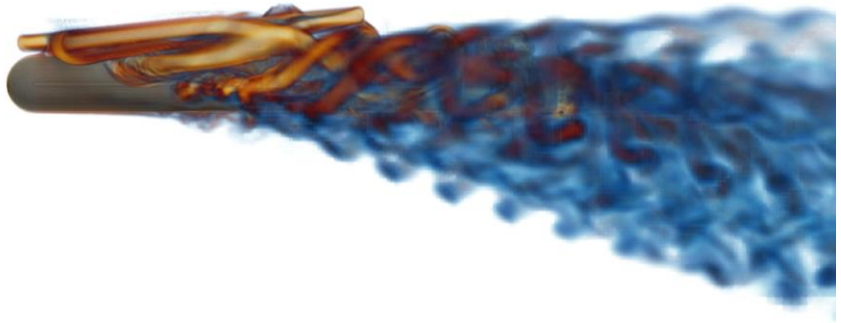
Introduction: Objective

- IBM-ASM solver that is capable of
  i. Large-scale parallel computations
  ii. Accurate predictions of aerodynamic properties and flow characteristics at significantly reduced setup and computational cost
  iii. Moving body simulations where multiple objects are in relative motion
  iv. Adaptive mesh refinement with dynamic load balancing

Source: Heli Service International GmbH

Introduction: Progress

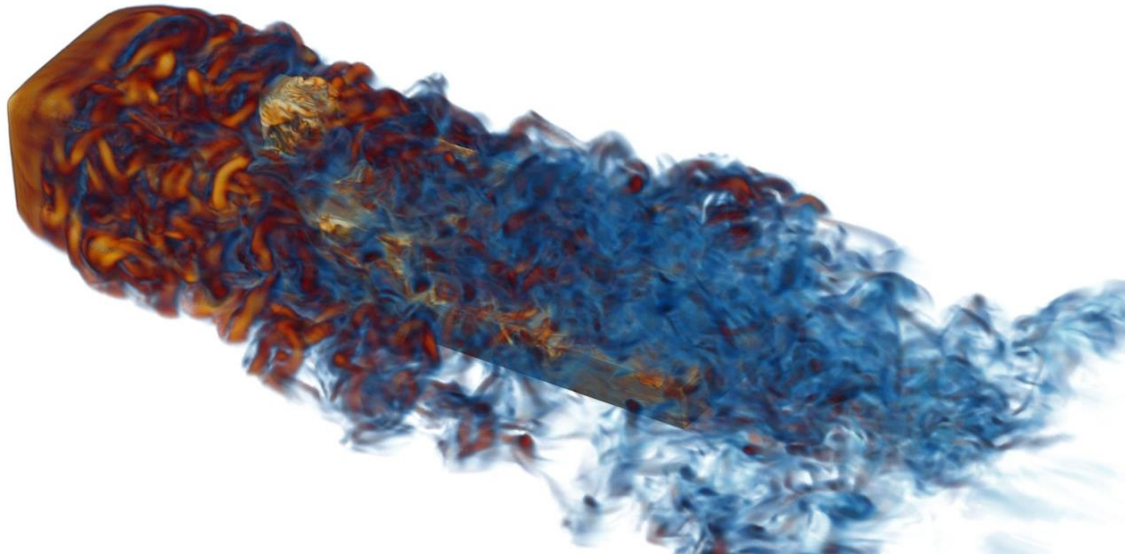


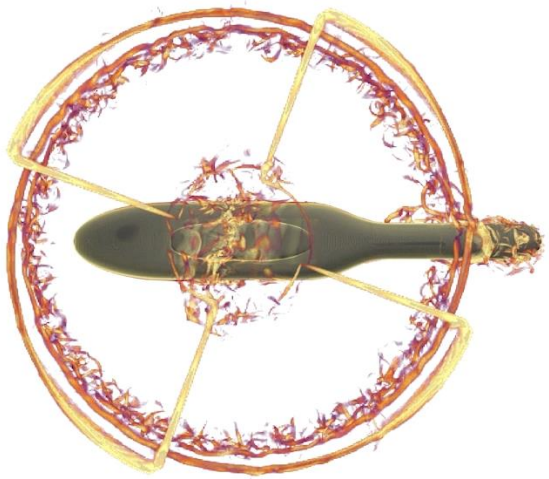
GIT rotor-airframe

Park et al. (2020), AIAA J.

Simple Frigate Shape 1

Park et al. (2022), Int. J. Heat. Fluid Flow





ROBIN-mod7/PSP rotor

Park et al. (2023), J. Am. Helicopter Soc.

IBM-ASM Solver

Immersed boundary method

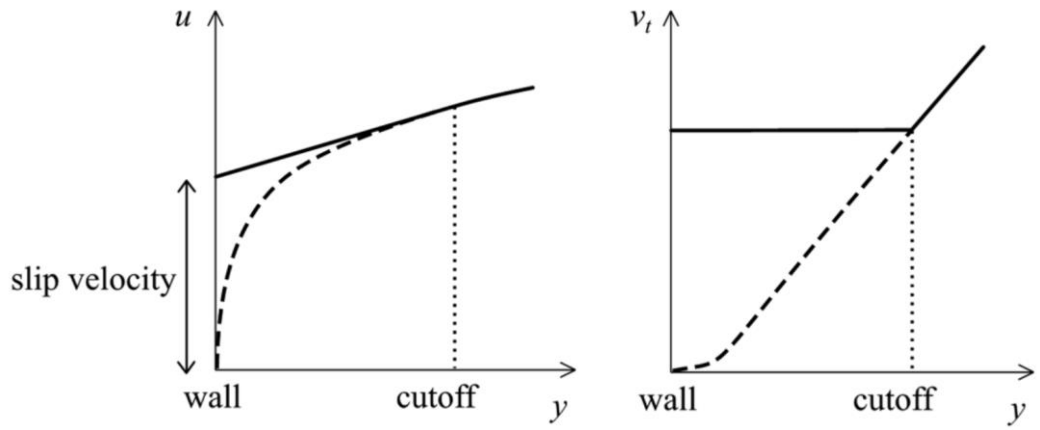
- Governing equations: incompressible RANS equations

$$\frac{\partial \langle \boldsymbol{U} \rangle}{\partial t} + (\langle \boldsymbol{U} \rangle \cdot \nabla)\langle \boldsymbol{U} \rangle = -\nabla \langle p \rangle + \nabla \cdot (\nu \nabla \langle \boldsymbol{U} \rangle + \boldsymbol{R}) + \boldsymbol{S}$$

$$\nabla \cdot \langle \boldsymbol{U} \rangle = 0$$

- Assumptions for the wall modelling
  - Boussinesq approximation.
  - Zero pressure gradient.
  - Tangential component of $\langle \boldsymbol{U} \rangle$ is a function of y only.
  - Vertical component of $\langle \boldsymbol{U} \rangle$ is very small.
  - $\partial/\partial x \ll \partial/\partial y$

$$\longrightarrow \boxed{(\nu + \nu_t)\left(\frac{du}{dy}\right) = \text{const.} = u_\tau^2}$$



Source: Tamaki et al. (2017)

- Wall function adopted from Tamaki et al. (2017)

1. Identify sample point at normal distance $y_{\mathrm{sp}} = 3\Delta x$ (2-D) or $2\Delta x$ (3-D)
2. Compute friction velocity u_τ by Newton-Raphson iterative method using S-A analytical wall formula (Allmaras et al., 2012):

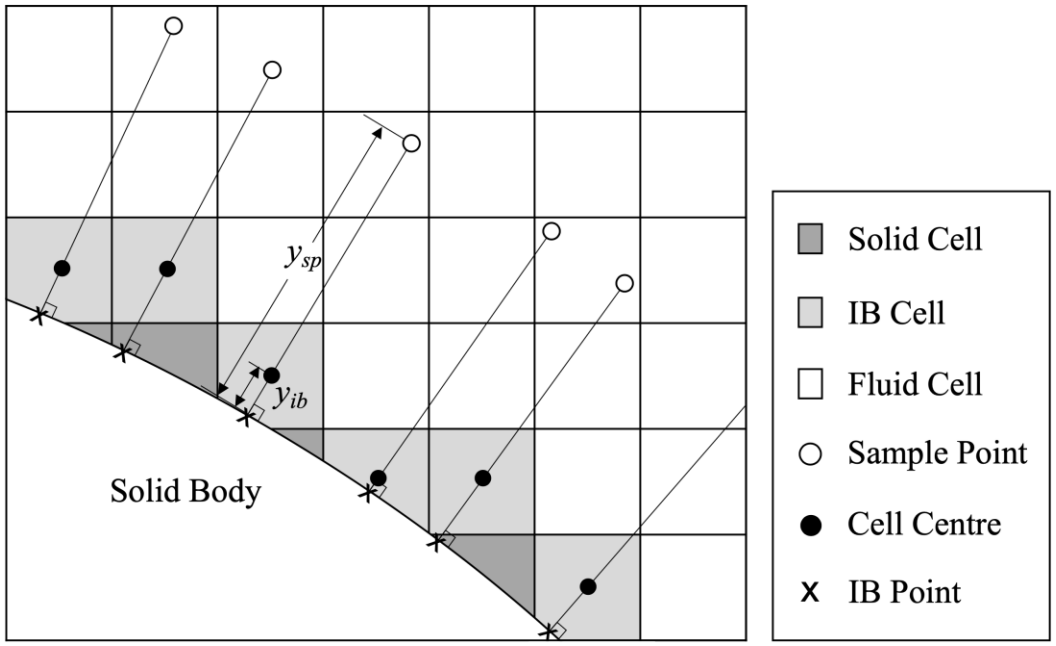
$$u^+(y^+) = \bar{B} + c_1 \log\left[(y^+ + a_1)^2 + b_1^2\right] - c_2 \log\left[(y^+ + a_2)^2 + b_2^2\right] - c_3 \tan^{-1}\left(\frac{b_1}{y^+ + a_1}\right) - c_4 \tan^{-1}\left(\frac{b_2}{y^+ + a_2}\right)$$

3. Obtain tangential velocity at IB cells by:

$$u_{\mathrm{ib},t} = u_{\mathrm{sp},t} - \left\{\frac{\partial u^+}{\partial y^+}\left(y^+_{\mathrm{sp}}\right)\right\}\left(y^+_{\mathrm{sp}} - y^+_{\mathrm{ib}}\right) u_\tau$$

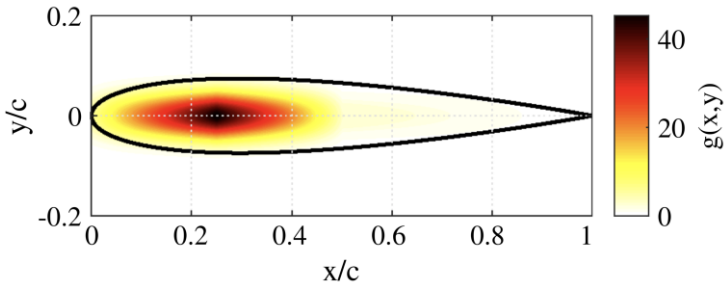
4. Obtain normal velocity by: $u_{\mathrm{ib},n} = u_{\mathrm{sp},n}\dfrac{y_{\mathrm{ib}}}{y_{\mathrm{sp}}}$

5. Obtain pseudo eddy viscosity by: $\tilde{\nu}_{\mathrm{ib}} = \kappa u_\tau y_{\mathrm{ib}}$

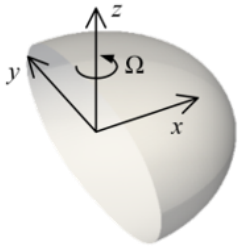


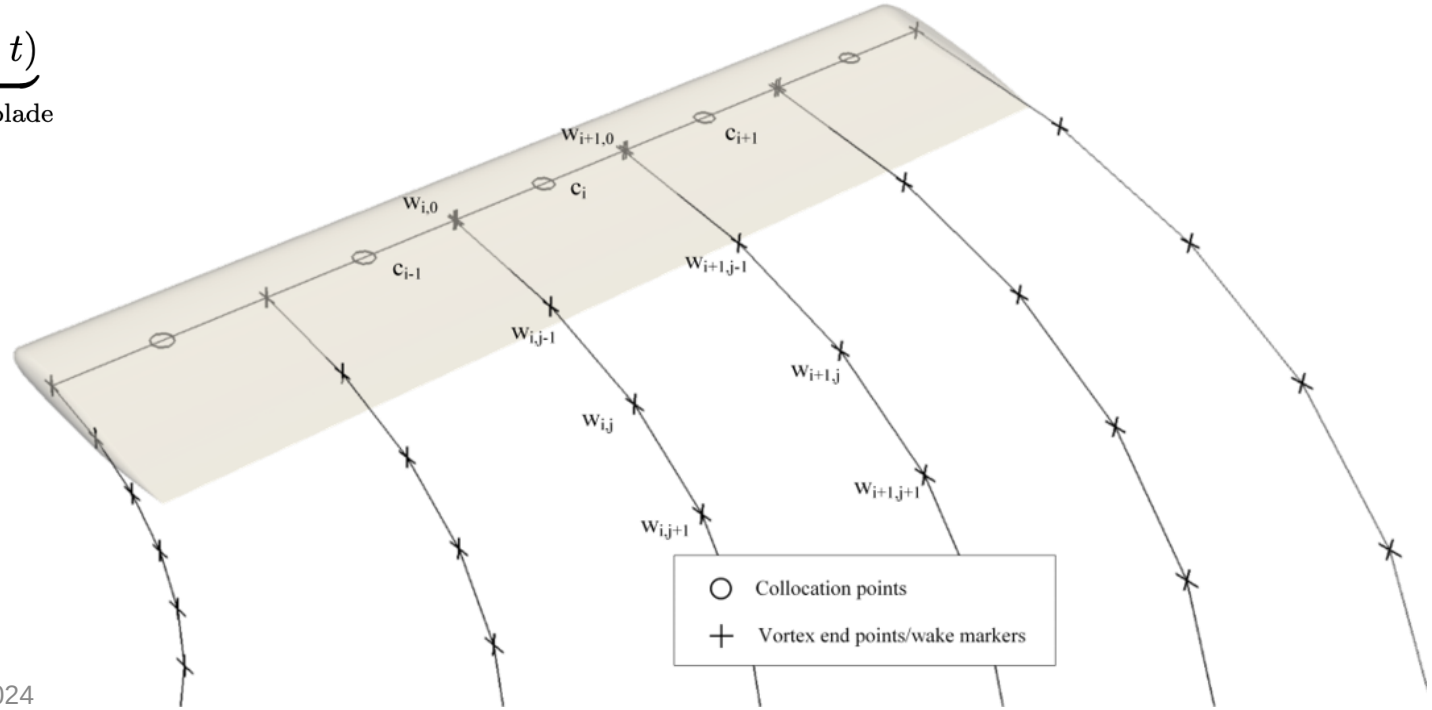
Actuator surface model from Linton et al. (2021)

1. 2-D airfoil aerodynamics coefficient tables used.
2. Loading distribution projected onto CFD solution as momentum source.
3. Induced velocity calculated using CFD solution and passed to rotor model.
4. Velocity from CFD solver is used to convect the vortex elements.



$$\boldsymbol{U}_{\text{in}} = \underbrace{\boldsymbol{U}_g(\boldsymbol{p}_c,\, t)}_{\text{geometric velocity}} + \underbrace{\boldsymbol{U}_{\text{CFD}}(\boldsymbol{p}_s,\, t_s)}_{\text{sampled velocity}} + \underbrace{\boldsymbol{U}_{\text{in},w}(\boldsymbol{p}_c,\, t)}_{\text{downwash at blade}} - \underbrace{\boldsymbol{U}_{\text{in},w}(\boldsymbol{p}_s,\, t_s)}_{\text{wake correction}} - \underbrace{\boldsymbol{U}_{\text{in},b}(\boldsymbol{p}_s,\, t_s)}_{\text{bound vorticity correction}}$$



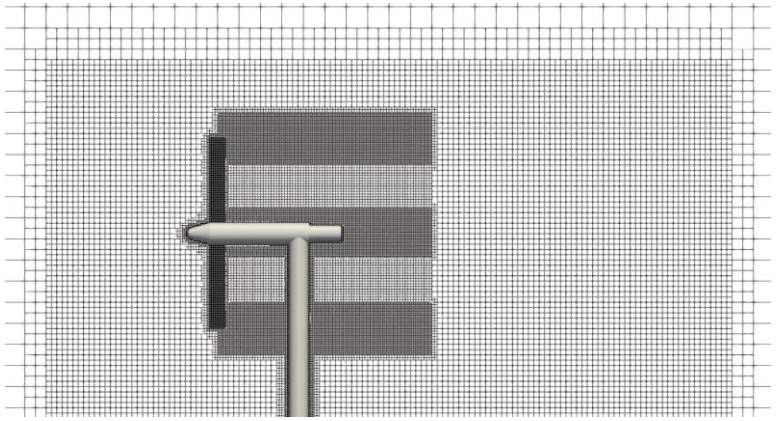


Single Turbine Validation: Uniform Inflow

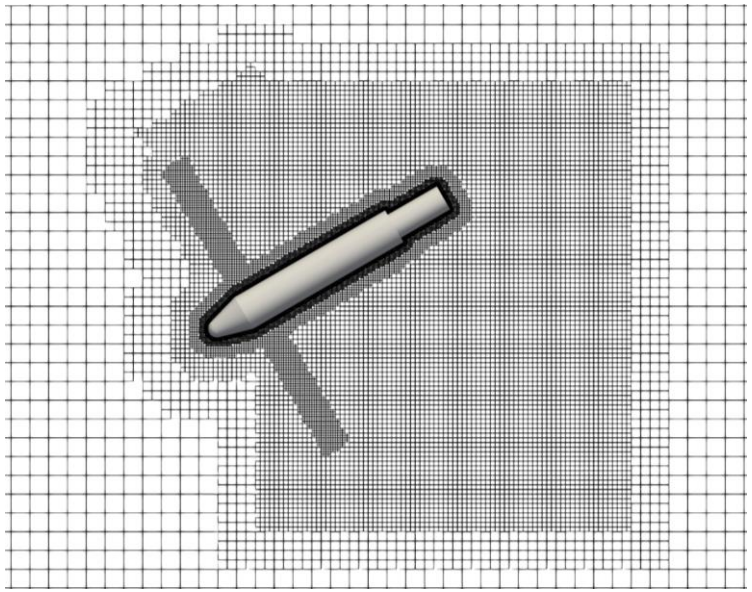
MEXICO wind turbine

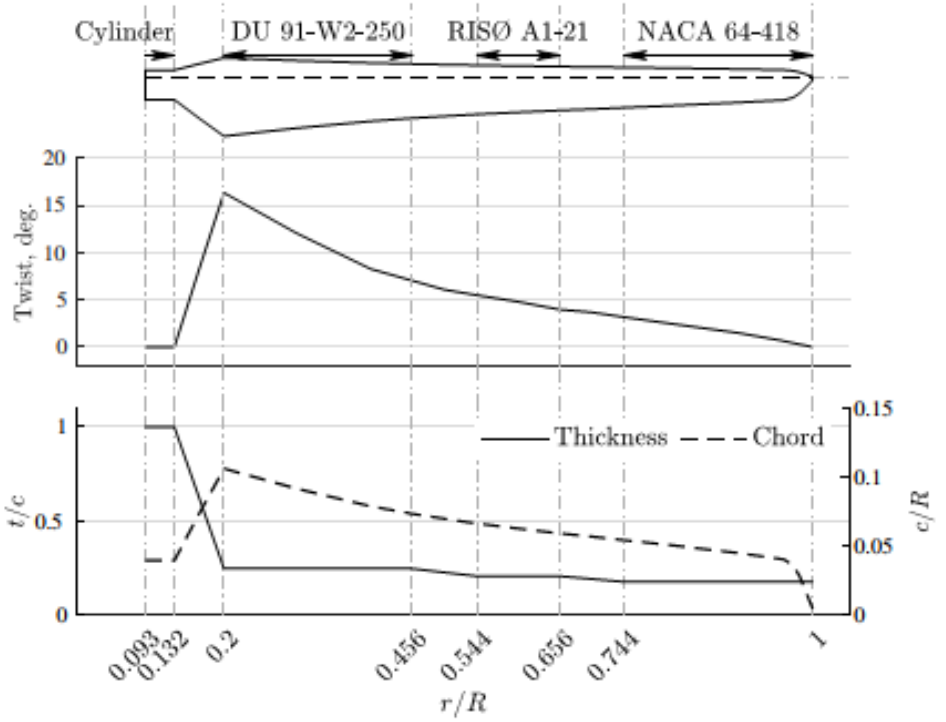
- 425.1 rpm, 3 tip speed ratios, 0° and 30° yaw

Axial flow



Yawed flow (30°)

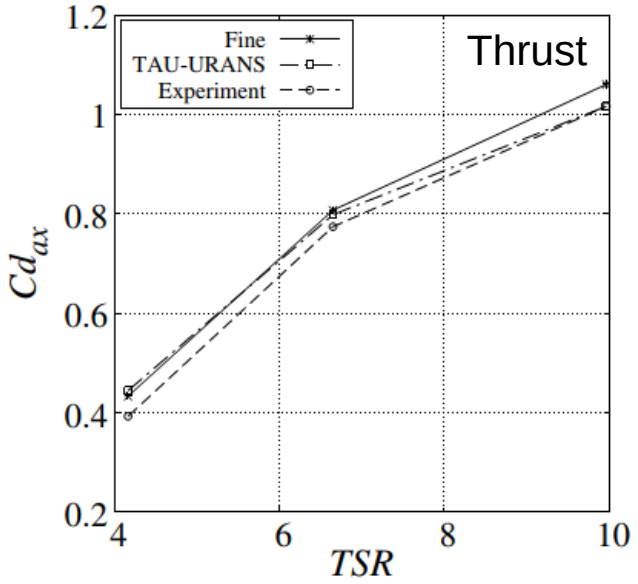


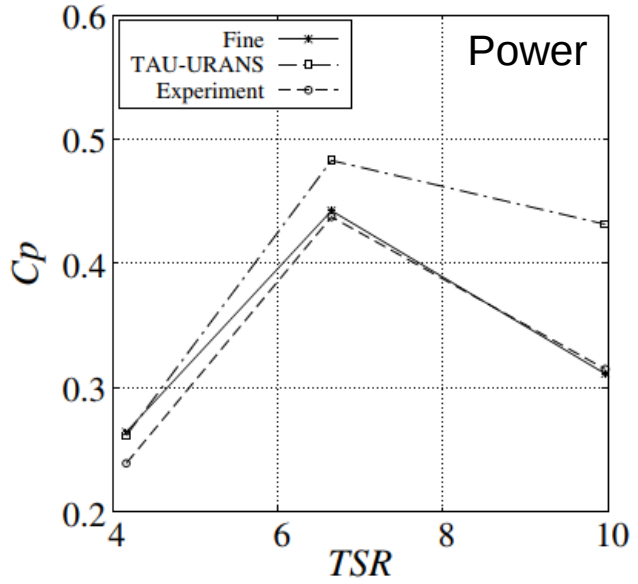


Grid	Near-wall region Δ	$y^+_{sp,max}$	Cell count ($\times 10^6$ cells)
Axial flow			
Coarse	4.4×10^{-3} m	840	8.2×10^6
Medium	2.9×10^{-3} m	600	18.9×10^6
Fine	2.0×10^{-3} m	435	42.3×10^6
Yawed flow			
Coarse	4.4×10^{-3} m	945	8.5×10^6
Medium	2.9×10^{-3} m	740	19.9×10^6
Fine	2.0×10^{-3} m	520	46.0×10^6

Single Turbine Validation: Uniform Inflow

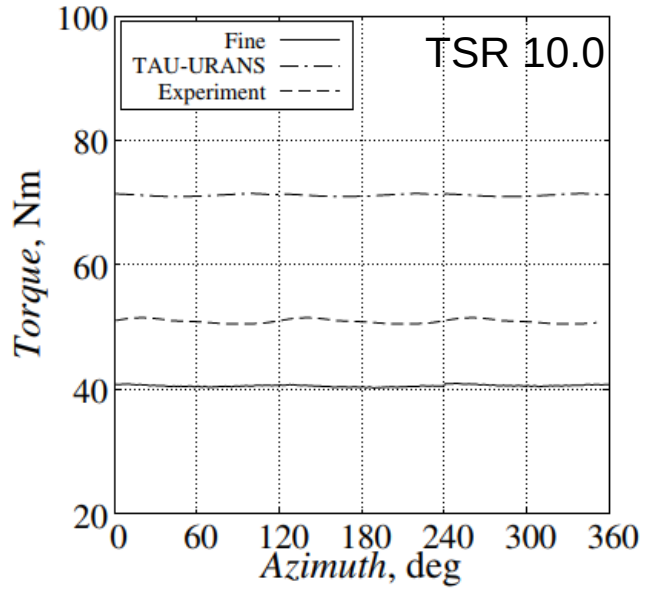
Axial flow

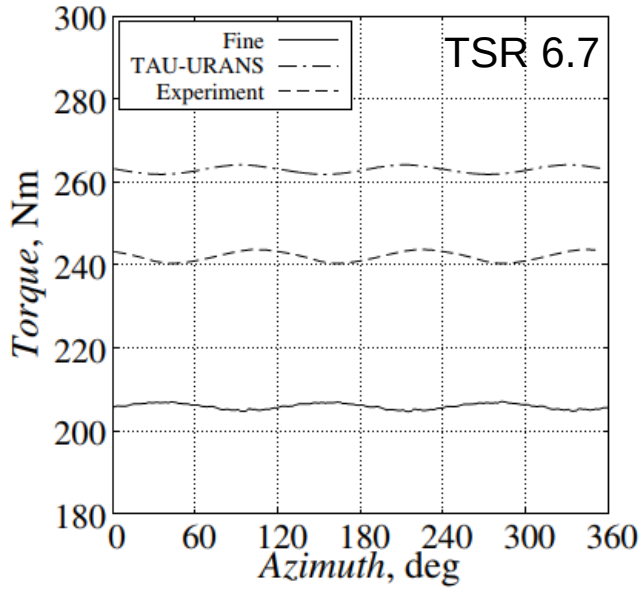


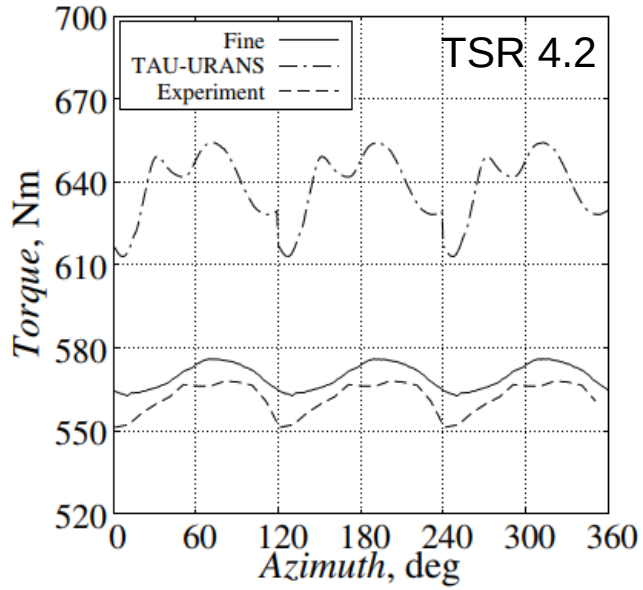


- Fine → Fine grid (IBM-ASM)
- TAU-URANS→ Reference
- Experiment → Reference

Yawed flow (30º)

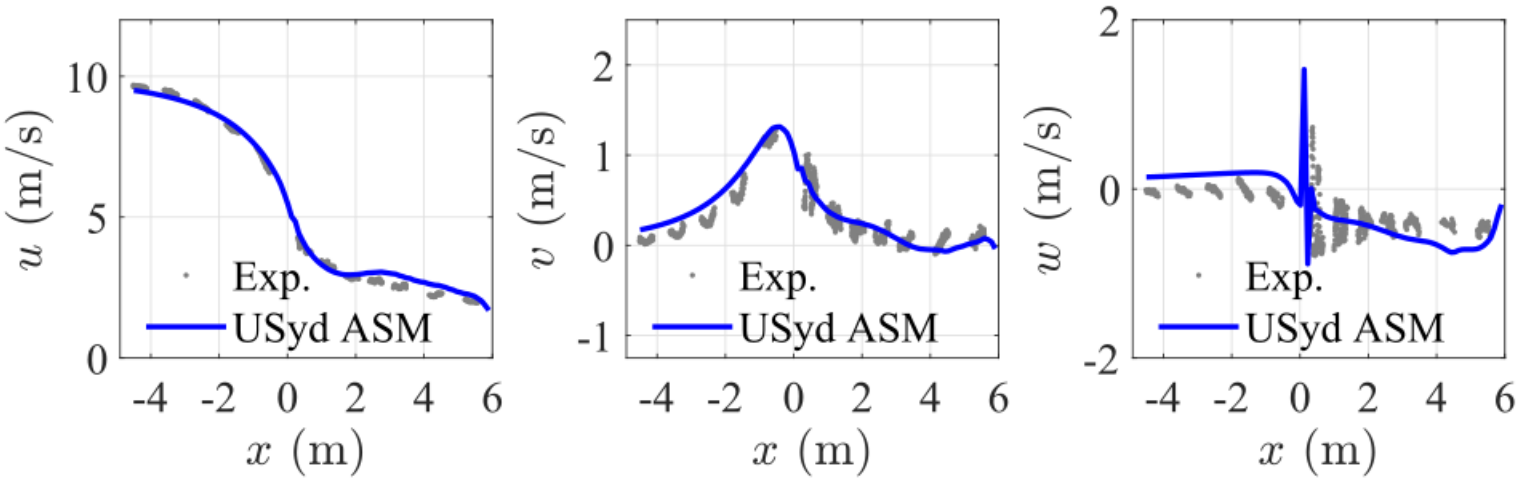


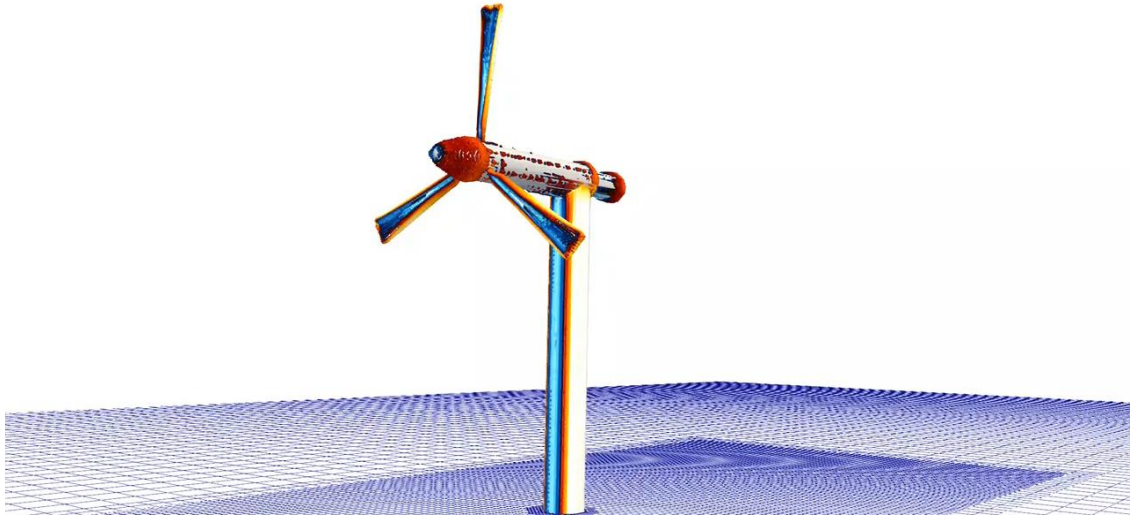


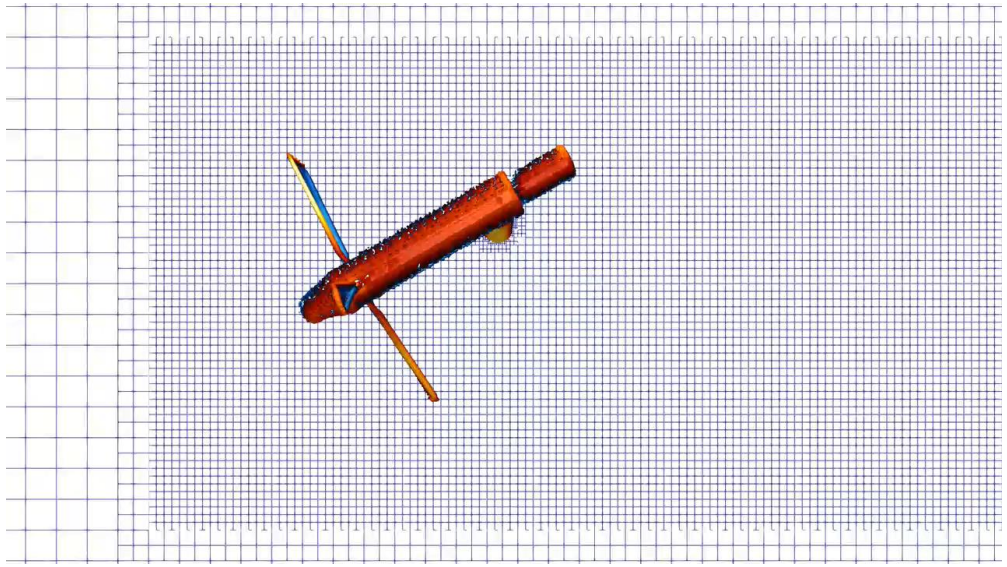


Single Turbine Validation: Uniform Inflow

Axial Traverse – Axial Flow – TSR 4.2

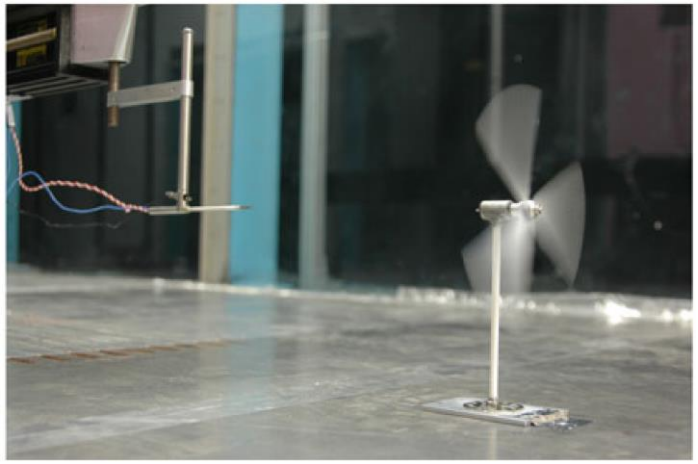


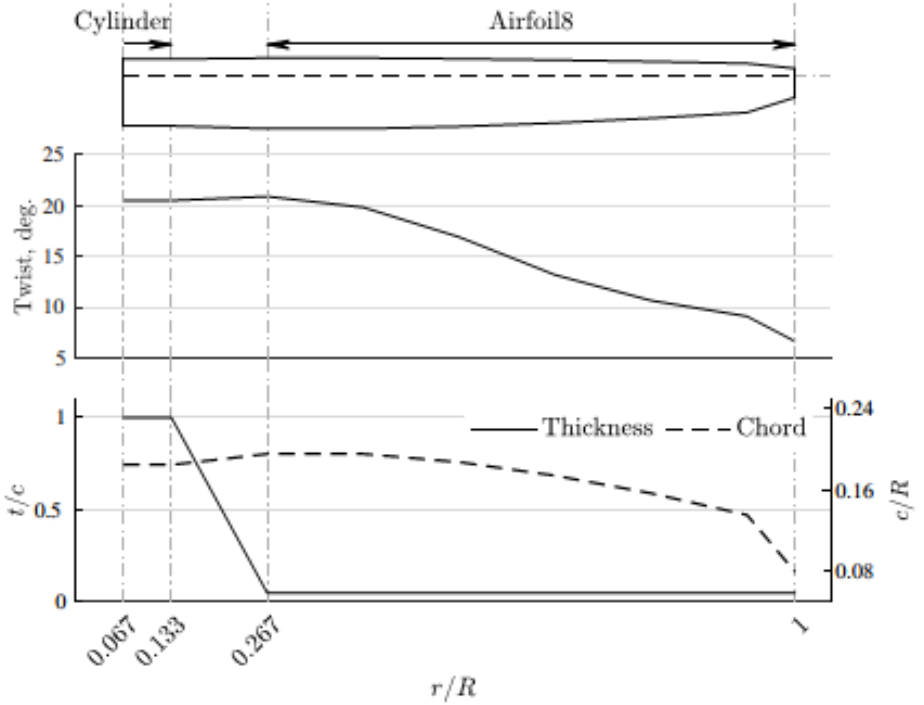




Single Turbine Validation: Neutral ABL Inflow

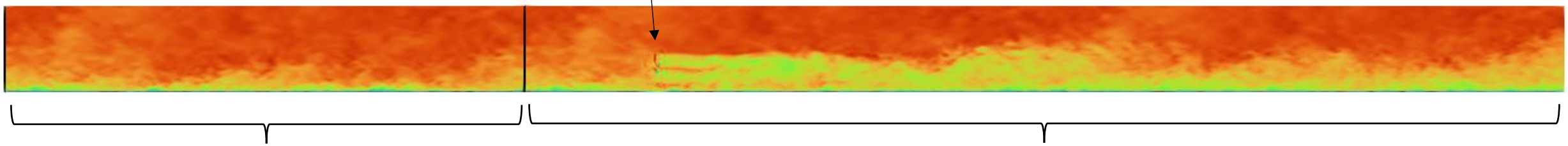
- Model wind turbine: Neutral ABL inflow, 1120rpm





Recycled inflow/outflow

Turbine



Source: DLR

Precursor domain: 18D

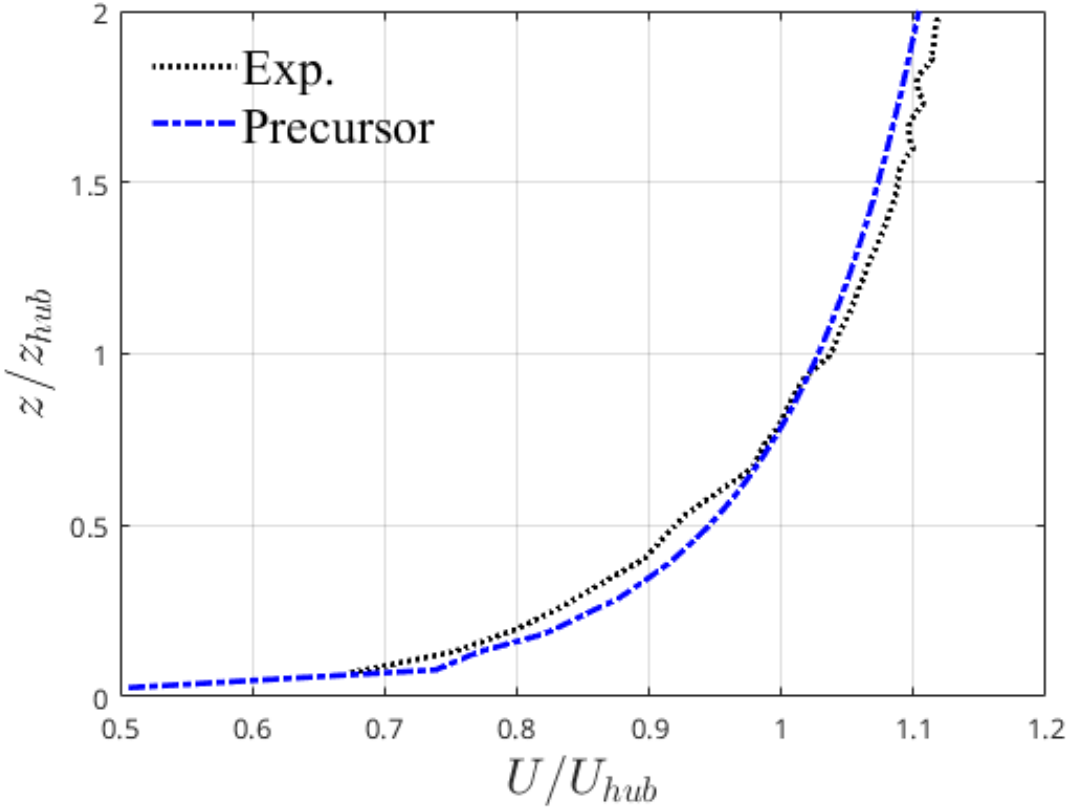
Main domain: 36D

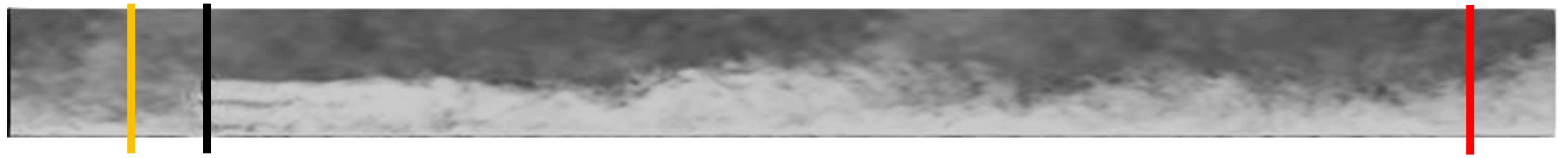
Single Turbine Validation: Neutral ABL Inflow

- Flow in precursor domain driven by uniform momentum source term
- Precursor and main domain initialised with 50 main domain flow throughs
- Mean computed from 100 flow throughs

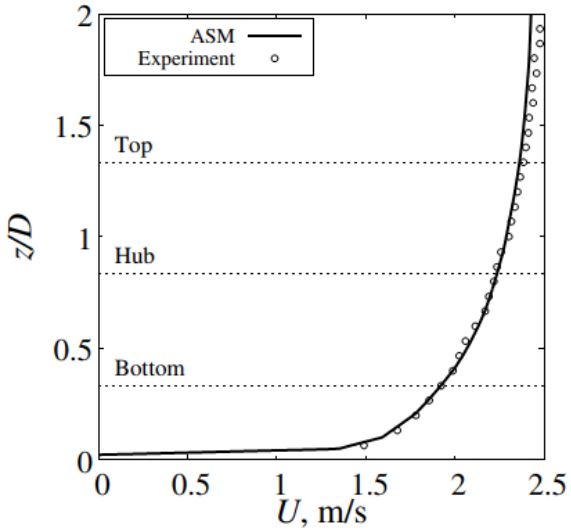
  → Approximately 3600 revolutions in total

Neutral ABL profile comparison

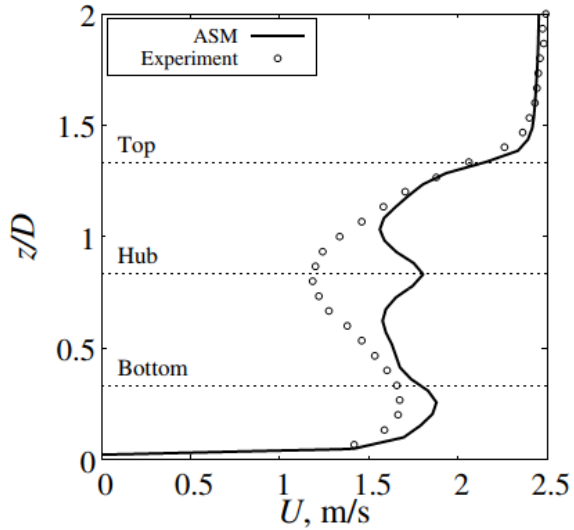




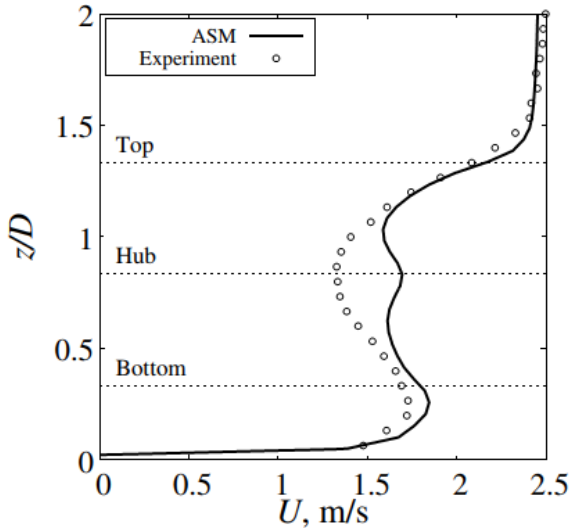
x/D = -1



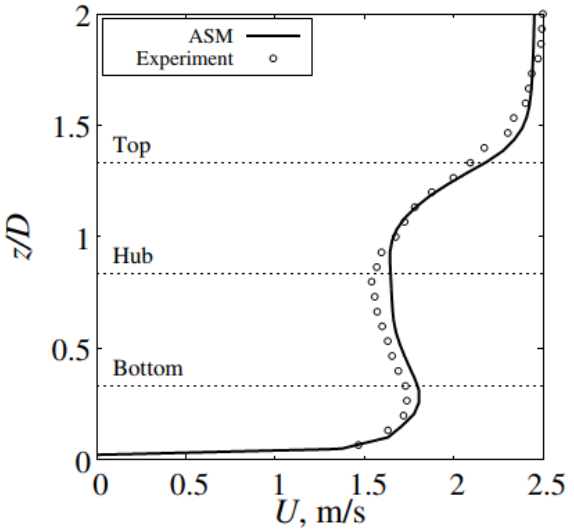
x/D = 2



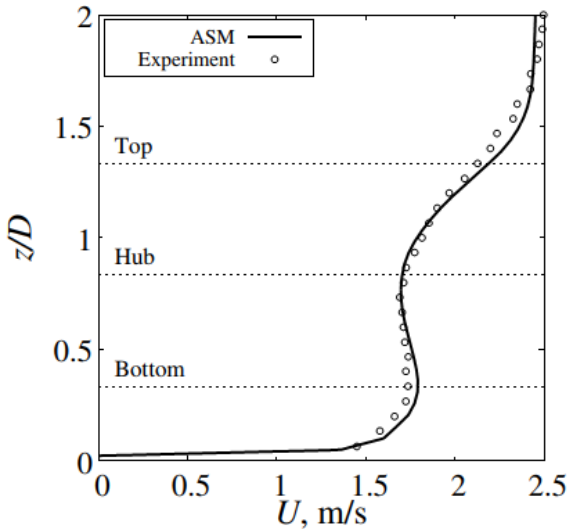
x/D = 3



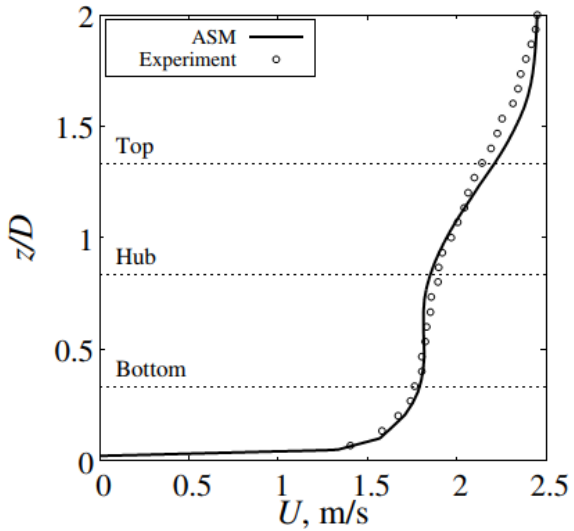
x/D = 5



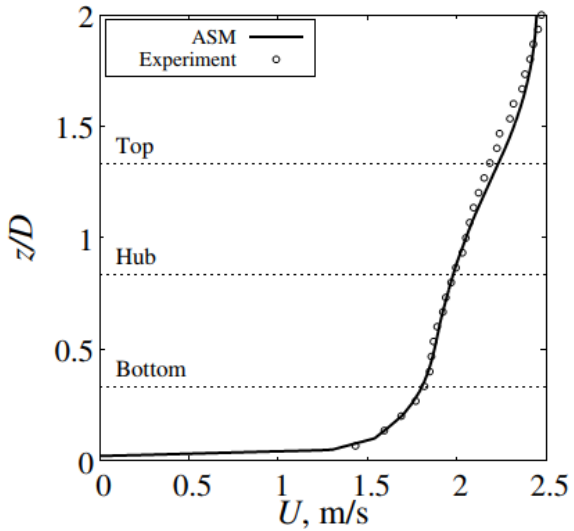
x/D = 7



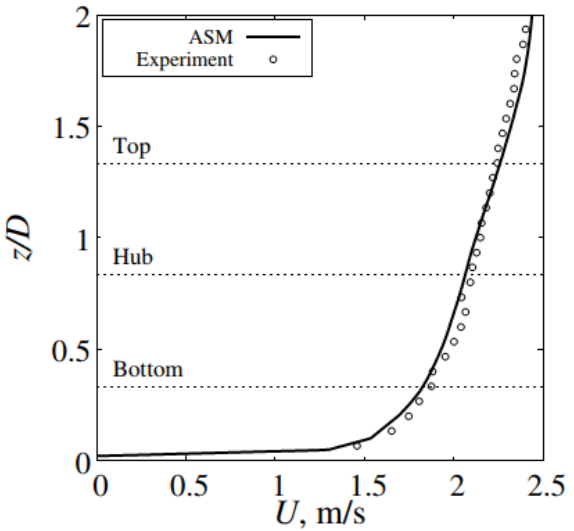
x/D = 10



x/D = 14

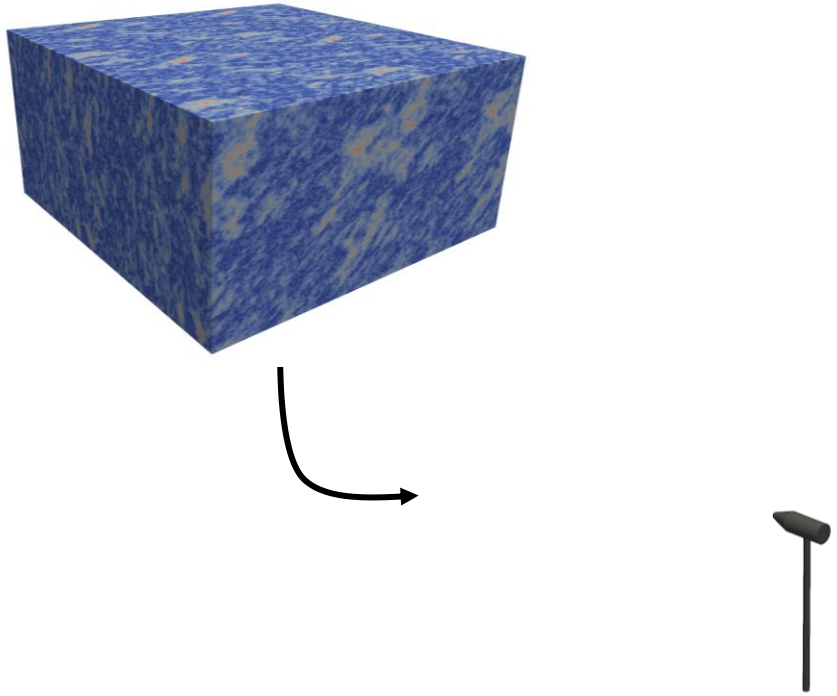


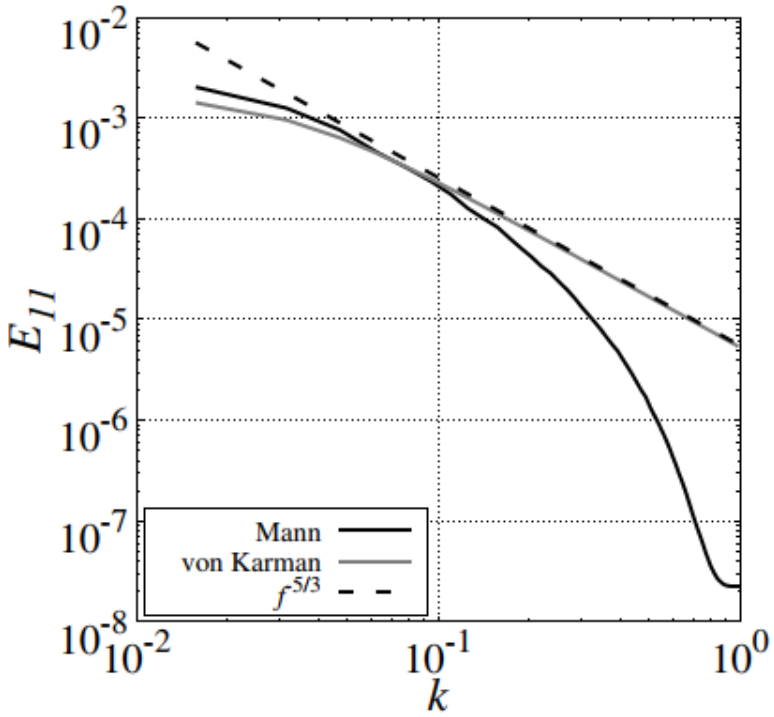
x/D = 20



Work in Progress: Synthetic Turbulence

- Atmospheric turbulence generator from Mann (1998)
  - Cost-efficient alternative to precursor approach for ABL inflow
  - Slice of turbulence box in streamwise direction is imposed on CFD domain as a source plane



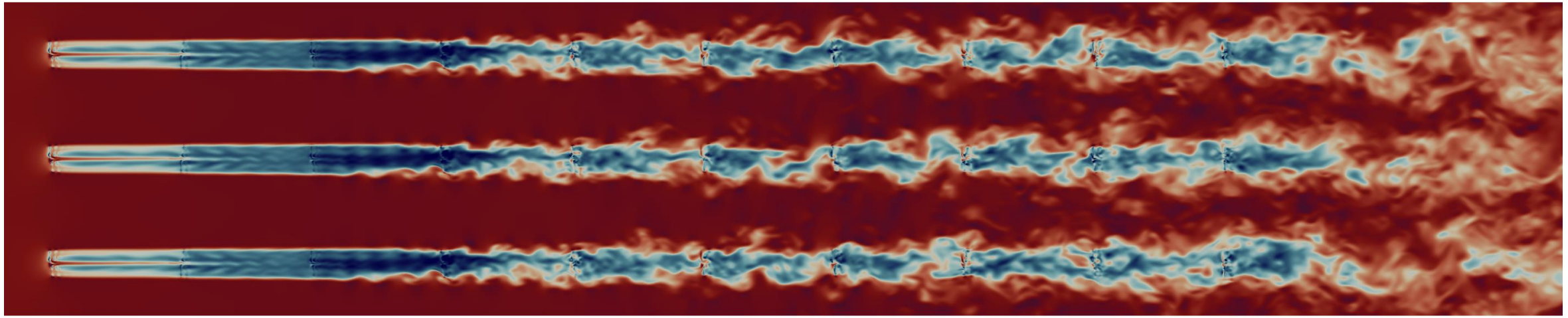


- Mann → Current simulation
- von Karman → Reference

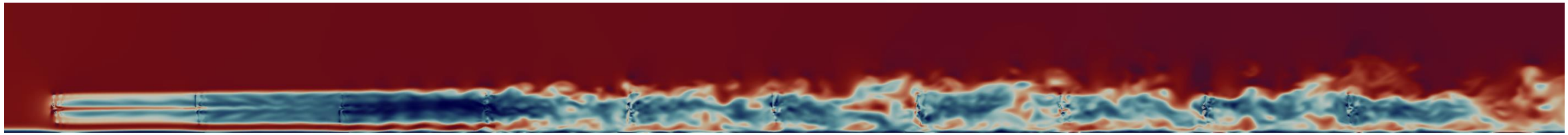
Full-Scale Wind Farm Simulations

- Aligned array wind farm
  - 30 model wind turbines

Top view

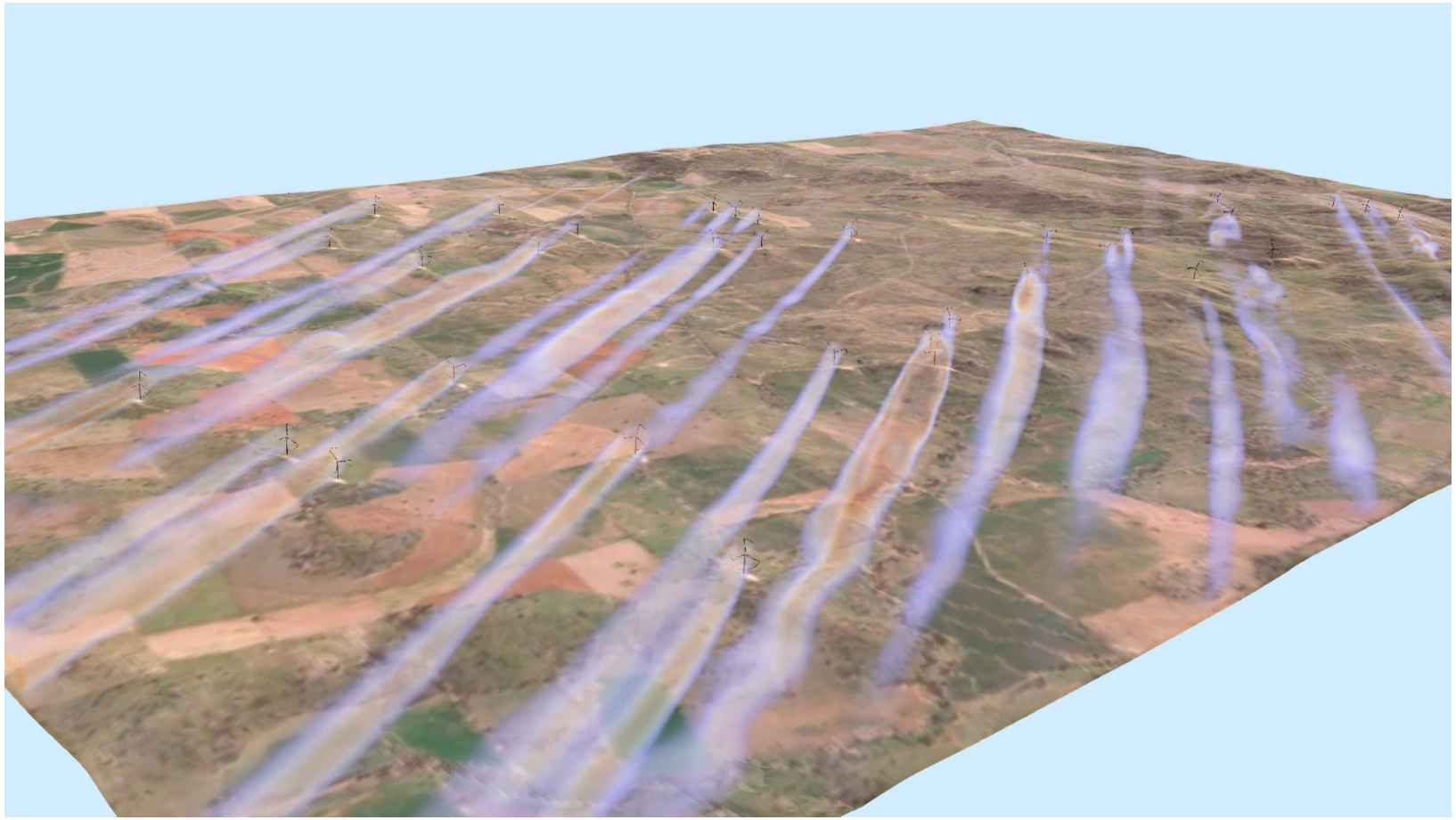


Side view (mid-plane)



Full-Scale Wind Farm Simulations

- Complex terrain wind farm in Australia
  - 33 wind turbines as isolated rotor by ASM, complex terrain by IBM (CAD model from land elevation data)



Summary

- IBM-ASM solver has been validated for single wind turbine cases:
  - MEXICO wind turbine in uniform inflow
  - Model wind turbine in neutral atmospheric boundary layer inflow
- Concurrent simulation approach for neutral ABL inflow has been performed, and its drawbacks pointed out:
  - Precursor domain required (more cell counts)
  - Large number of flow throughs required for flow initialisation (more computational time)
- Synthetic turbulence approach is discussed as an alternative to the concurrent simulation approach for more cost-efficient simulations with ABL inflow
- Full-scale wind farm simulations are demonstrated:
  - Aligned array of 30 model wind turbines
  - Complex terrain wind farm in Australia, comprised of 33 wind turbines
- Helicopter operations around a wind turbine will be simulated in future work

Thanks for listening!