Validation of a Floating Actuator Line Method

Dylan Green, Dr Markella Zormpa,
Prof Christopher Vogel

Floating Offshore Wind Energy

UK

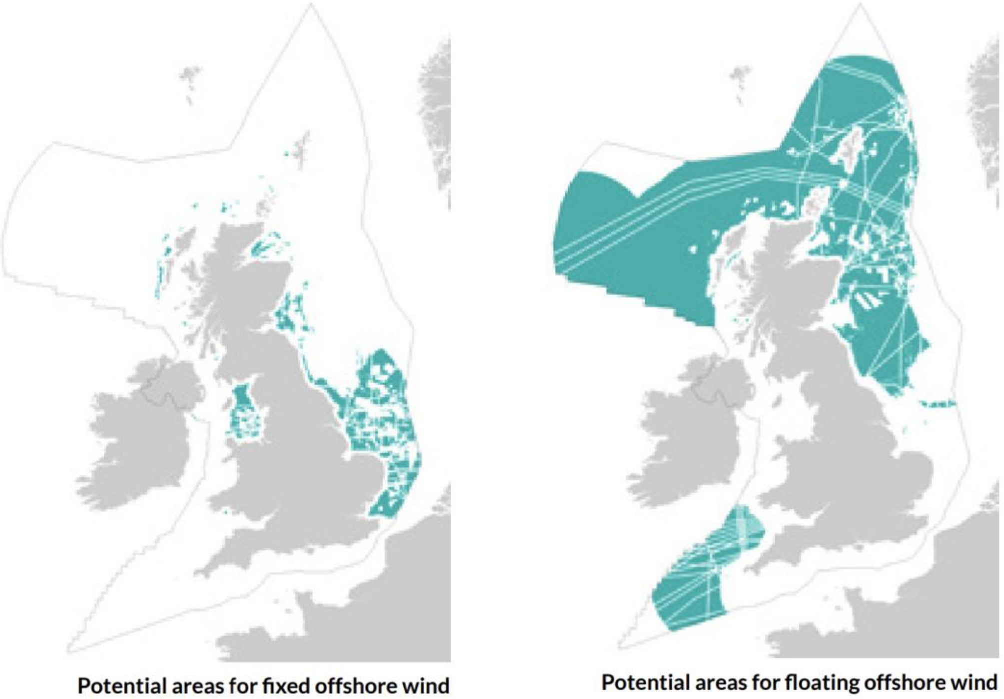
- 171 GW potential capacity in UK waters[1]

Global

- Deeper (60m+) waters hold 80% of all practical wind resource[2]

- Enough to produce 11× the current global energy demand[3]

2024 UK Offshore Wind Energy Installed: 14.7 GW



Floating Wind: Anchoring the next generation offshore – RenewableUk.com

[1] O'Callaghan et al. 2023 Could Britain's energy demand be met entirely by wind and solar?
[2] Gwec|global offshore wind report 2022
[3] Offshore Wind Outlook 2019 International Energy Agency

News in Floating Offshore Wind Energy

19/06/2025:

2024 UK Offshore Wind Energy Installed: 14.7 GW

- Leasing round 5 awards 2x1.5 GW sites in Celtic Sea
- Awarded to Equinor, EDF-ESB
- A further 1.5 GW site held in reserve (details expected in sept 2025)

Equinor, EDF-ESB Joint Venture Secure 1.5 GW Sites in UK Floating Wind Leasing Round

PLANNING & PERMITTING

June 19, 2025, by Adrijana Buljan

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The Crown Estate has selected Equinor and Gwynt Glas, a joint venture between EDF Renewables UK and ESB, as preferred bidders in the seabed leasing round for floating wind projects in the Celtic Sea.

Selected on 12 June, each of the two developers was awarded 1.5 GW of capacity in their respective project development area (PDA) for an annual option fee of GBP 350/MW (approximately EUR 410/MW).

Offshorewind.biz

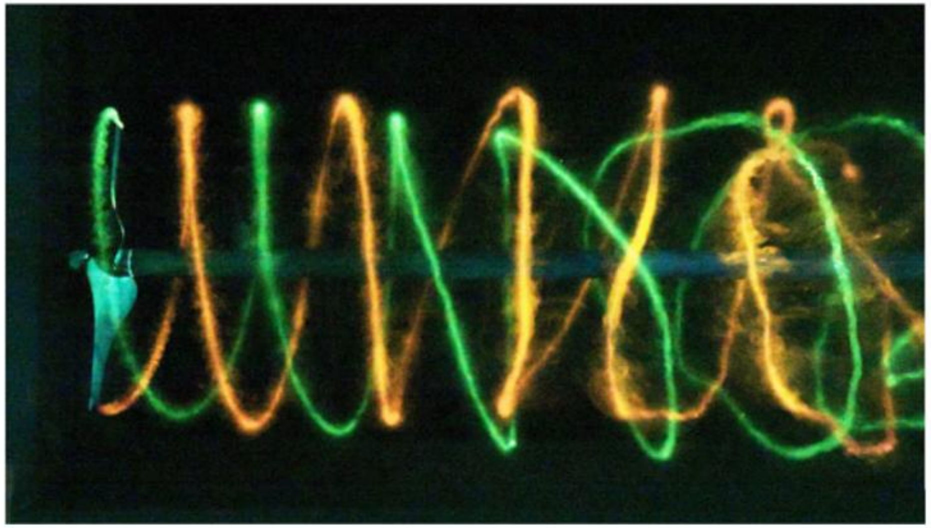
The Problem with Floating Wind

- Platform motions introduce unsteadiness into the wake

The Problem with Floating Wind

- Platform motions introduce unsteadiness into the wake

- Perturb the tip vortex structure
- Excite vortex instabilities[1-3]
- Suppress momentum shielding effect[4]
- Accelerate wake breakdown



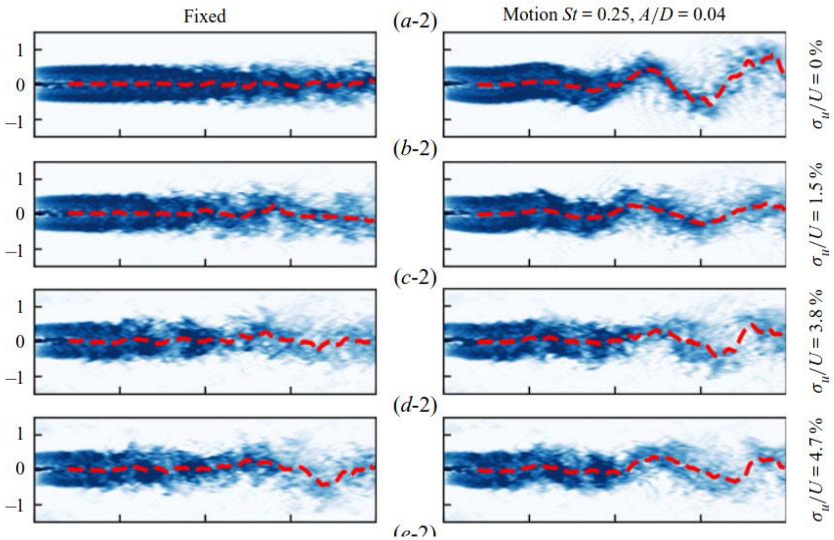
H. U. Quaranta et al. “Local and global pairing instabilities of two interlaced helical vortices”. Journal of Fluid Mechanics. 2019

[1] V. G. Kleine et al. “The stability of wakes of floating wind turbines”. Physics of Fluids. 2022
[2] H. U. Quaranta et al. “Local and global pairing instabilities of two interlaced helical vortices”. Journal of Fluid Mechanics. 2019
[3] S. Ivanell et al. “Stability analysis of the tip vortices of a wind turbine”. Wind Energy. 2010
[4] L. E. M. Lignarolo et al. “Tip-vortex instability and turbulent mixing in wind-turbine wakes”. Journal of Fluid Mechanics. 2015

The Problem with Floating Wind

Platform motions introduce **unsteadiness into the wake**

- Perturb the wake shear layer
- Excite meandering and pulsating modes[5,6]
- Accelerating wake recovery
- Increasing unsteady loads on downstream rotors.



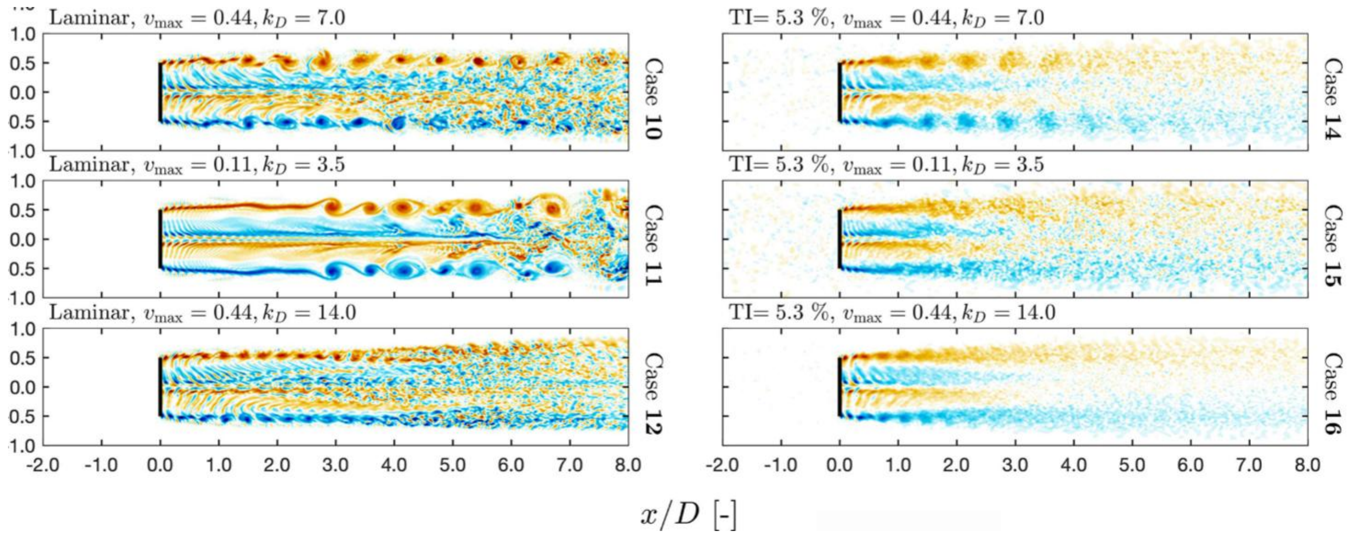
Z. Li et al. "Onset of wake meandering for a floating offshore wind turbine under side-to-side motion". Journal of Fluid Mechanics. 2022

[5] Z. Li et al. "Onset of wake meandering for a floating offshore wind turbine under side-to-side motion". Journal of Fluid Mechanics. 2022
[6] T. Messmer et al. "Enhanced recovery caused by nonlinear dynamics in the wake of a floating offshore wind turbine". Journal of Fluid Mechanics. 2024

The Problem with Floating Wind

- Platform motions introduce **unsteadiness into the wake**

- Produce coherent structures
- Enhance advection of kinetic energy into the wake[7]



Y. Li et al. "Wake Structures and Performance of Wind Turbine Rotor With Harmonic Surging Motions Under Laminar and Turbulent Inflows". Wind Energy. 2025

[7] Y. Li et al. "Wake Structures and Performance of Wind Turbine Rotor With Harmonic Surging Motions Under Laminar and Turbulent Inflows". Wind Energy. 2025

The Model

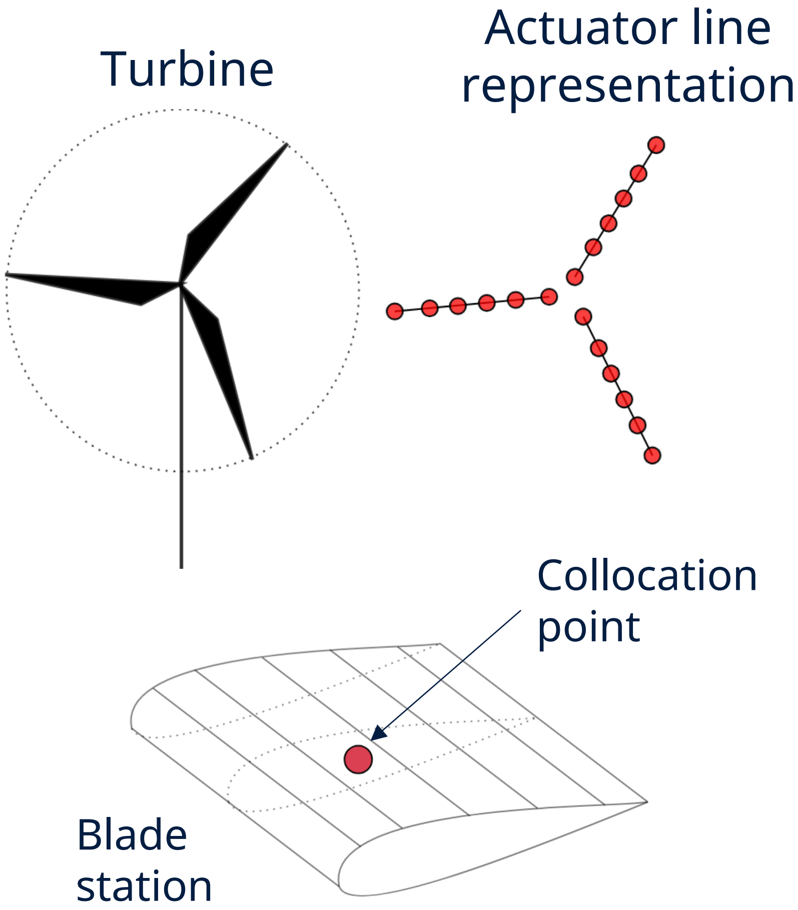
MARINE 2025 | Department of Engineering Science | University of Oxford

🌬 Requirements:

- 🌬 High Fidelity - resolved shear layers
- 🌬 3D Flow field – accurate vortical structure
- 🌬 Efficient – cheaper than blade resolved simulations

Floating Actuator Line Method (FALM)

The Floating Actuator line Method



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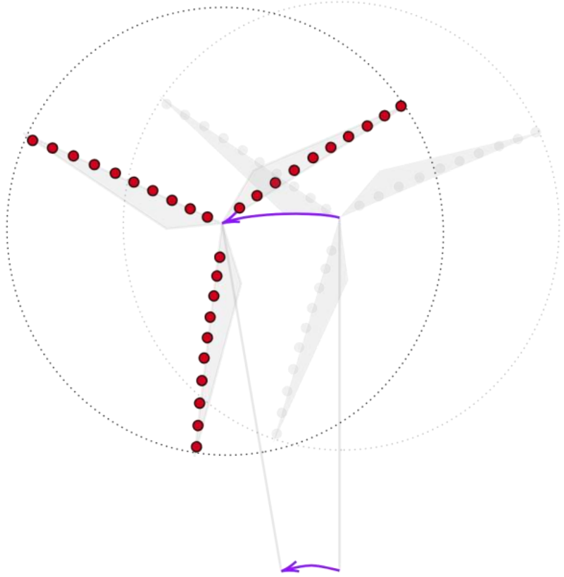
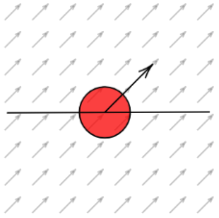
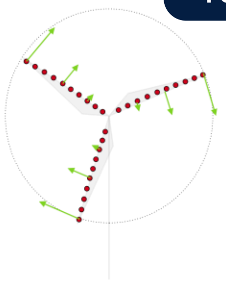


The Floating Actuator Line Method

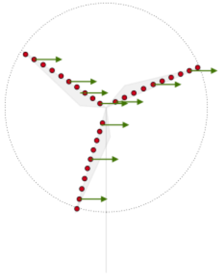
Sample Flow Field

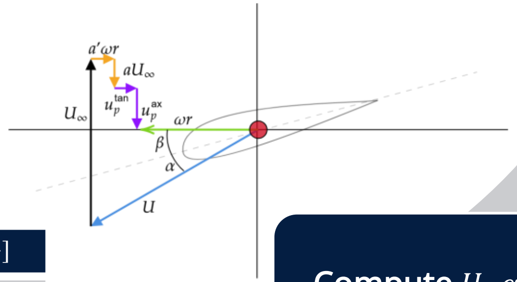


Compute blade rotational velocity



Compute platform motion induced velocity





Compute U, α

Lookup C_l, C_d

α [°]	C_l [−]	C_d [−]
-144	0.9133	0.4350
…	…	…

Compute Body Force

$$\boldsymbol{f} = \frac{1}{2}\rho U^2 (C_l \hat{\boldsymbol{e}}_l + C_d \hat{\boldsymbol{e}}_d)$$

Map Body Force

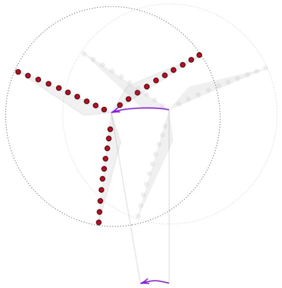
$$\boldsymbol{f}^* = \boldsymbol{f} \otimes \boldsymbol{g}(\varepsilon)$$

Solve Governing Equations

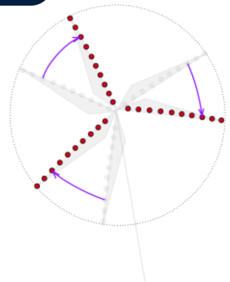
$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \boldsymbol{u} + \rho \boldsymbol{f}^*$$

$$\boldsymbol{\nabla} \cdot \boldsymbol{u} = 0$$

Move platform



Rotate Blades



The Floating Actuator Line Method

- Previously used for wind energy applications[7-12]

- **Aims:**
  - **Extend In-House[13,14] OpenFOAM-based ALM to account for platform motions**
  - **Validate against latest experimental data sets**
  - **Validate integrated forces + wake dynamics**

[7] Y. Li et al. "Wake Structures and Performance of Wind Turbine Rotor With Harmonic Surging Motions Under Laminar and Turbulent Inflows". Wind Energy. 2025
[8] Arabgolarcheh, Alireza, Sahar Jannesarahmadi, and Ernesto Benini. "Modeling of near wake characteristics in floating offshore wind turbines using an actuator line method." Renewable Energy, 2022.
[9] Li, Chengyi, et al. "Effects of surge and roll motion on a floating tidal turbine using the actuator-line method." Physics of Fluids", 2023
[10] Arabgolarcheh, Alireza, Ernesto Benini, and Morteza Anbarsooz. "Development of an actuator line model for simulation of floating offshore wind turbines." ASME Power Conference, 2021.
[11] Arabgolarcheh, Alireza, et al. "Modelling of two tandem floating offshore wind turbines using an actuator line model." Renewable Energy, 2023.
[12] Sanvito, Andrea G., et al. "A novel vortex-based velocity sampling method for the actuator-line modeling of floating offshore wind turbines in windmill state." Renewable Energy, 2024.
[13] Wimshurst, Aidan, and Richard HJ Willden. "Extracting lift and drag polars from blade-resolved computational fluid dynamics for use in actuator line modelling of horizontal axis turbines." Wind Energy, 2017.
[14] R. Willden et al. Tidal turbine benchmarking project : Stage I - steady flow blind predictions. In Proceedings of 15th European Wave and Tidal Energy Conference, 2023.

The Validation Case

UNAFLOW[13] & Nettuno[14]:

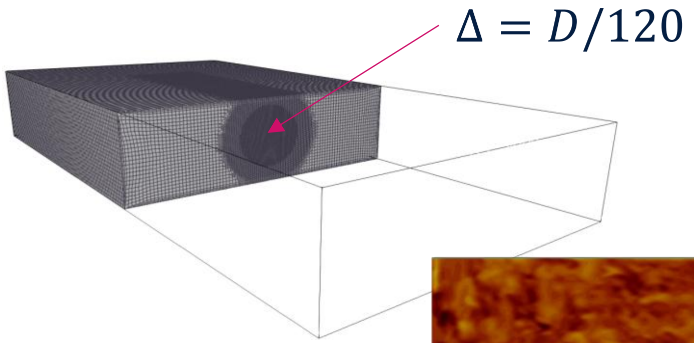
- Politecnico di Milano Wind Tunnel
- 1:75 Scale DTU 10MW
- Simplified sinusoidal motions
- Low turbulence ($I \sim 2\%$)

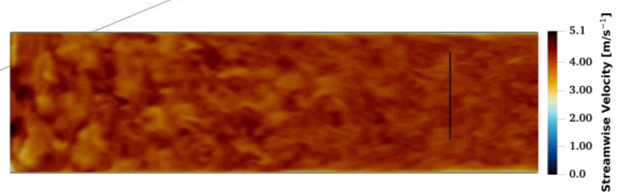
The Nettuno Project - LinkedIn

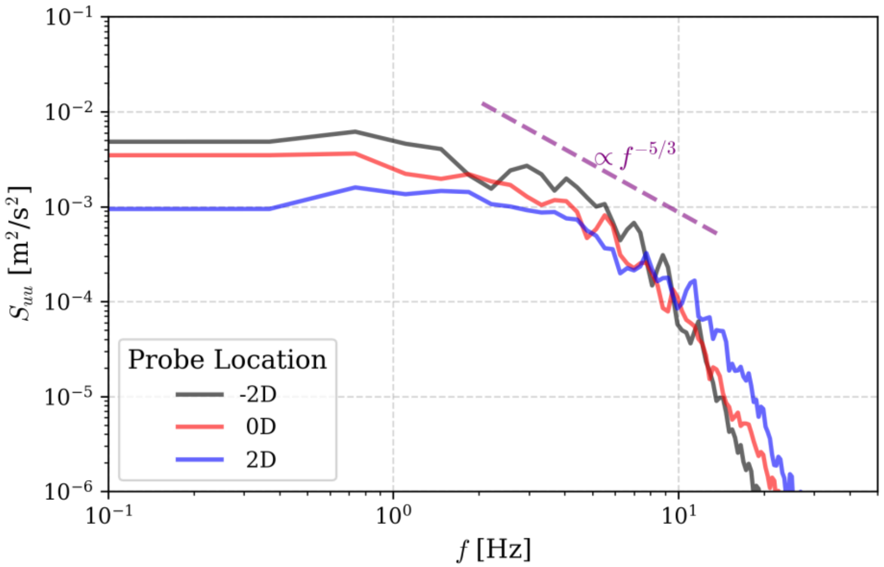
[13] Fontanella, A., et al. (2021). UNAFLOW: UNsteady Aerodynamics of FLOating Wind turbines [Data set].
[14] Fontanella, A., et al. (2024). NETTUNO Experiment 1 – Wake Development in Floating Wind Turbines [Data set].

The Numerical Setup

- Turbulence - LES + Smagorinsky turbulence closure
- Inlet – divergence free synthetic eddy method[15]
- Wind tunnel blockage – wall modelled boundary layers





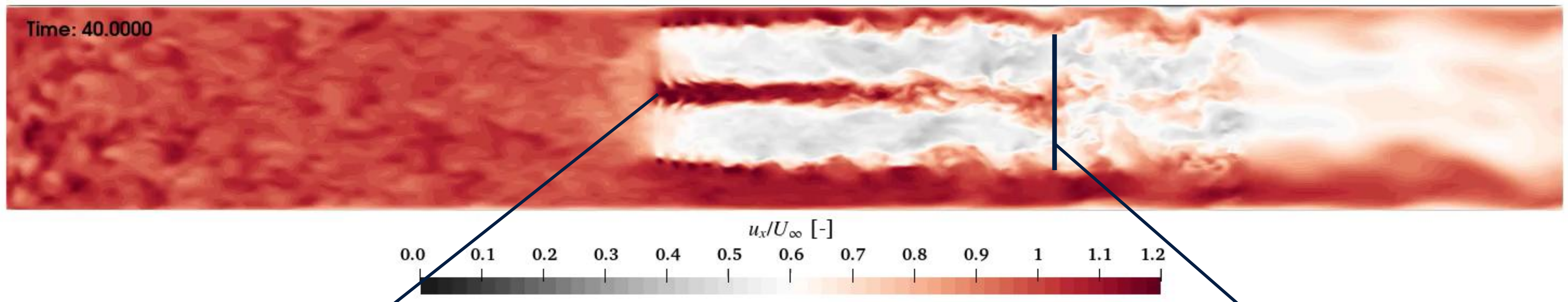


[15] R. Poletto et al. "A New Divergence Free Synthetic Eddy Method for the Reproduction of Inlet Flow Conditions for LES". Flow, Turbulence and Combustion 91.3 (2013), pp. 519–539. issn: 1573-1987.

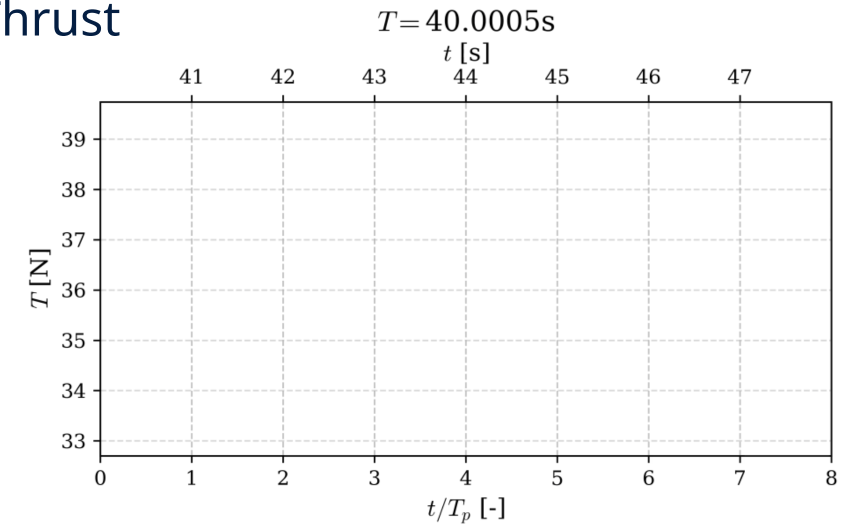
Model Output

Pitching turbine ($A_p = 1.9°,\ St = f_p D/U_\infty = 0.595$)

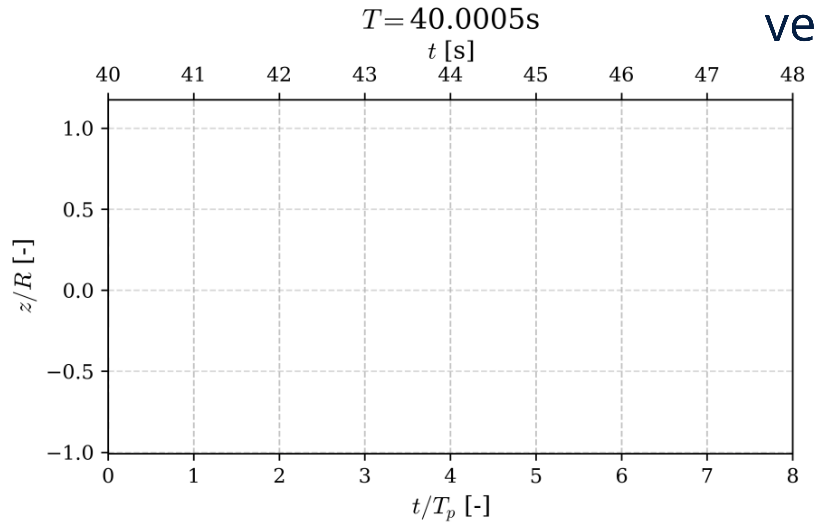
$3D$



Thrust

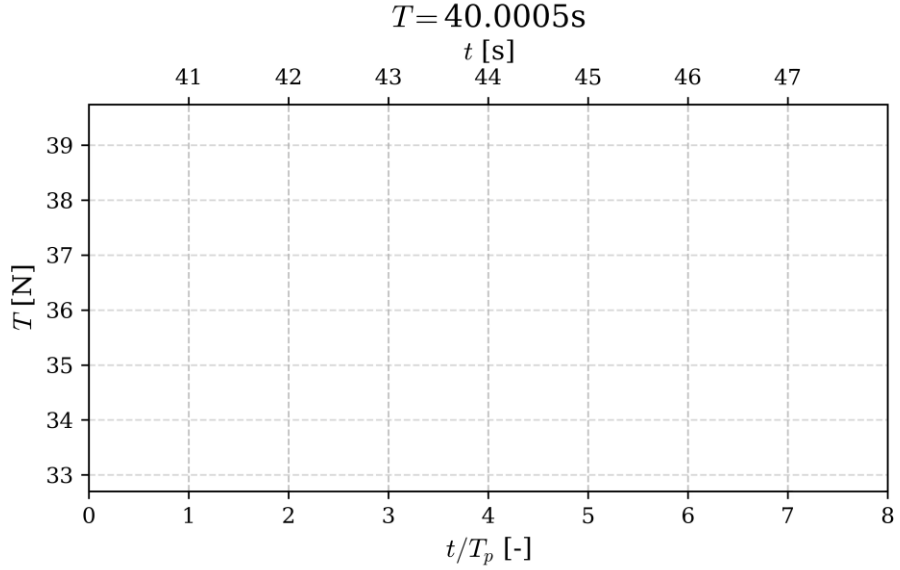


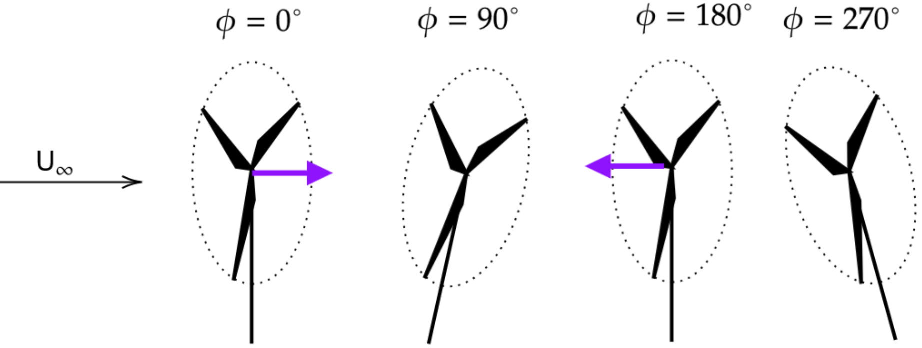
Streamwise velocity



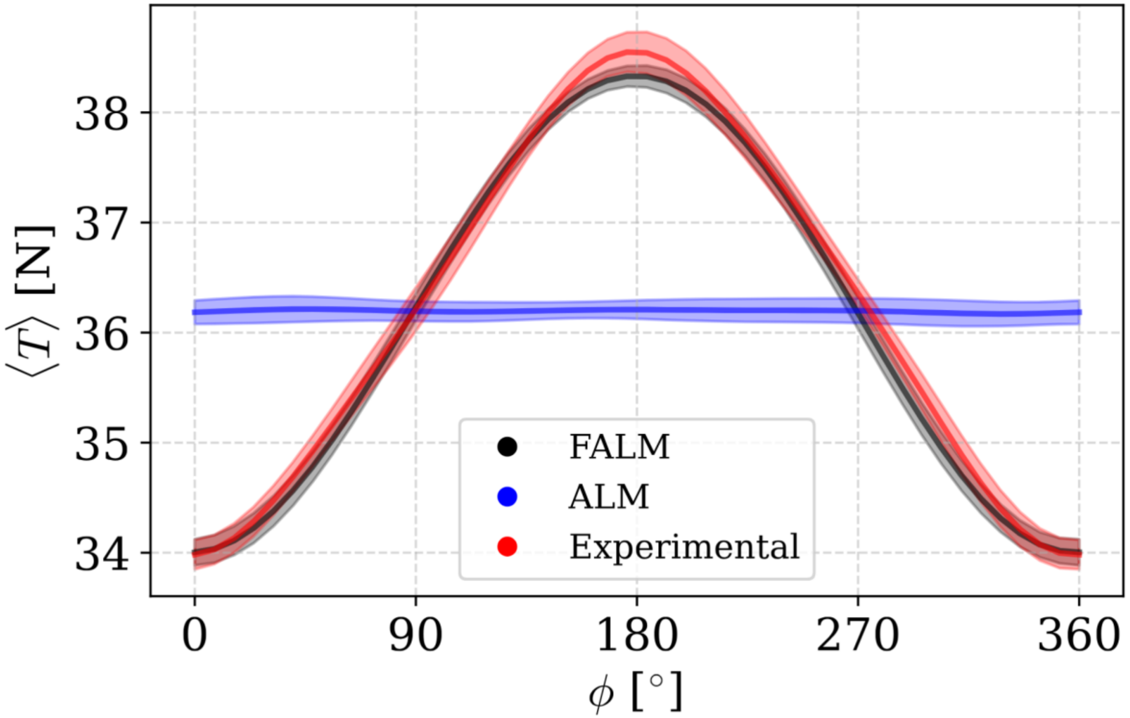
Rotor Loads

Thrust Time Series





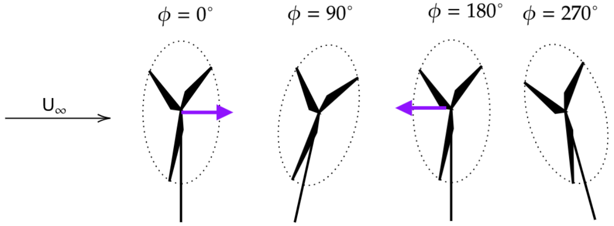
Phase Averaged Thrust



Surging turbine, $A_p = 0.0147D$, $St = 0.595$

ALM = fixed-bottom simulation
FALM = floating simulation
Experimental = floating experimental

Rotor Loads



Time Averaged Thrust

	$\overline{T}$ [N]	ΔT [N]
ALM	36.20	0.035
FALM	36.15	4.36
Experiment	36.20	4.33

Remarks:

Time averaged thrust is approx. unchanged.

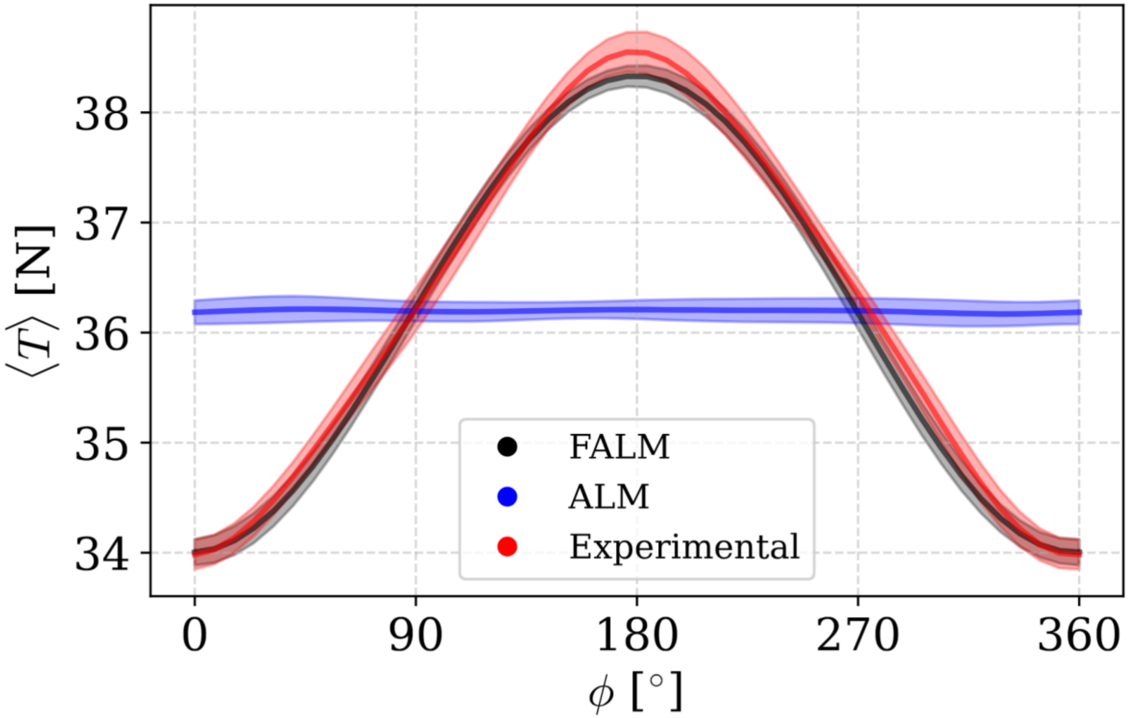
Time averaged values agree***

Phase averaged thrust approx. varies linearly with platform induced velocity.

ΔT is in agreement with experimental results.

$\varepsilon_{\Delta T} = 0.69\%$

Phase Averaged Thrust



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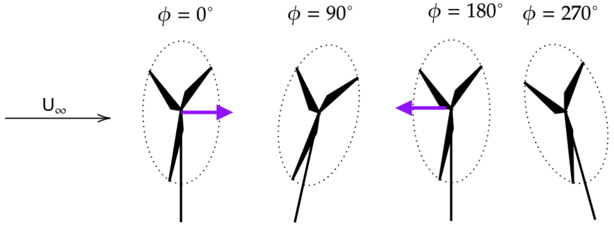

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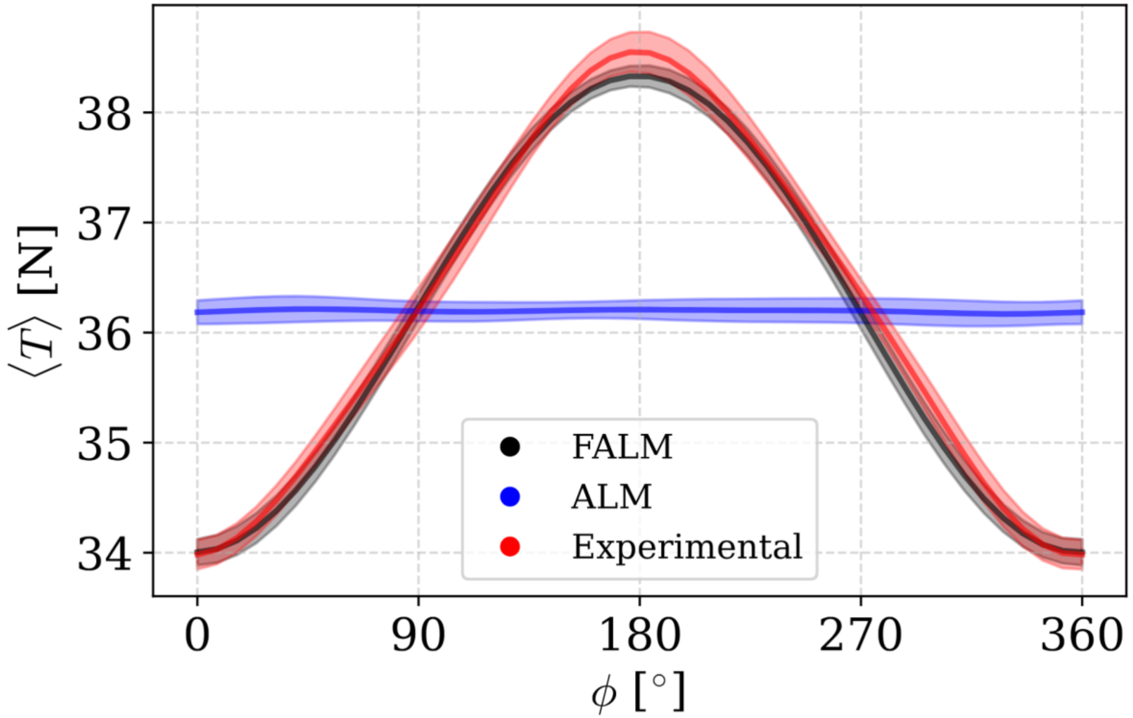

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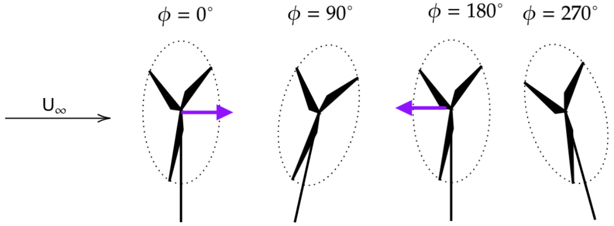
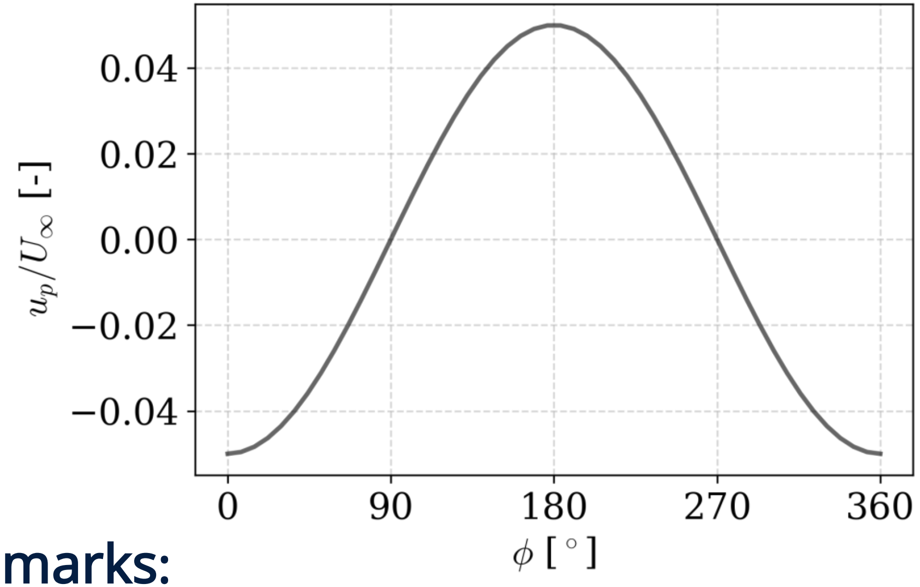
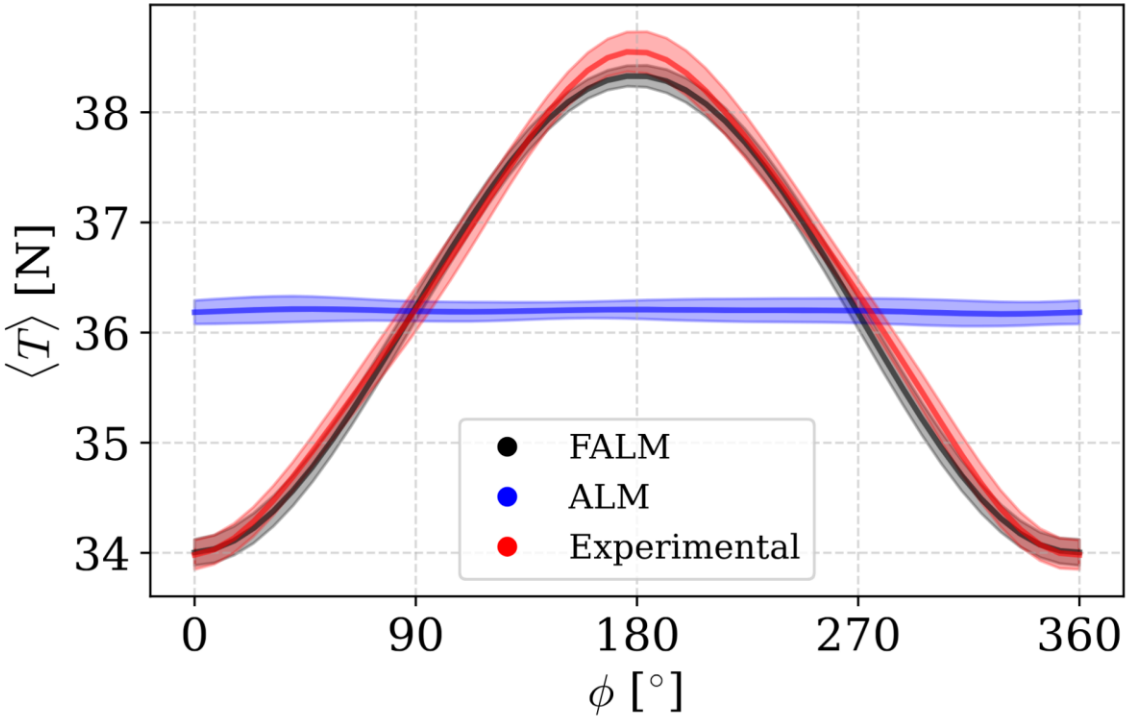


Platform Induced Velocity



$\propto$

Phase Averaged Thrust



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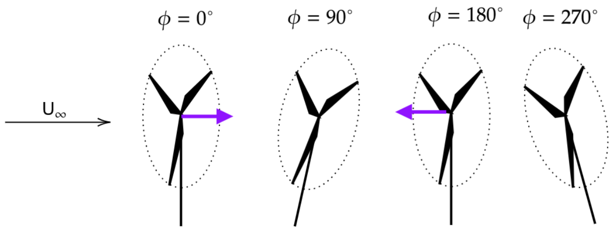

$$\Delta T = 2\left|\int T(t)e^{i2\pi f_p t}\,\mathrm{d}t\right|$$

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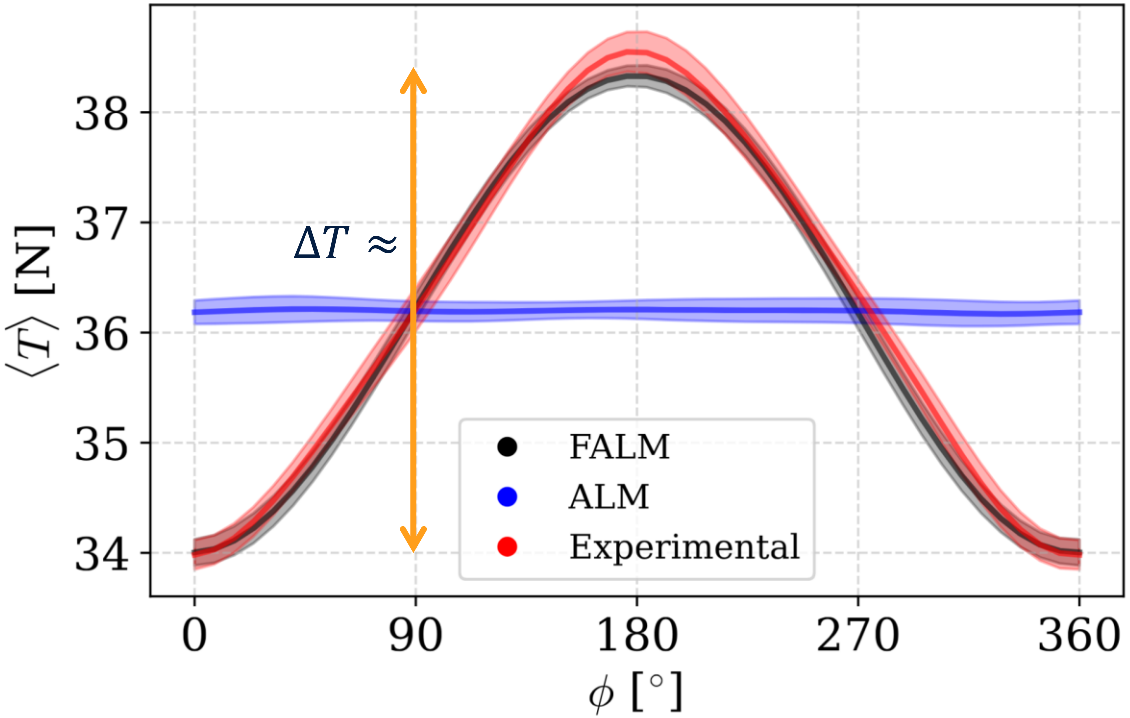

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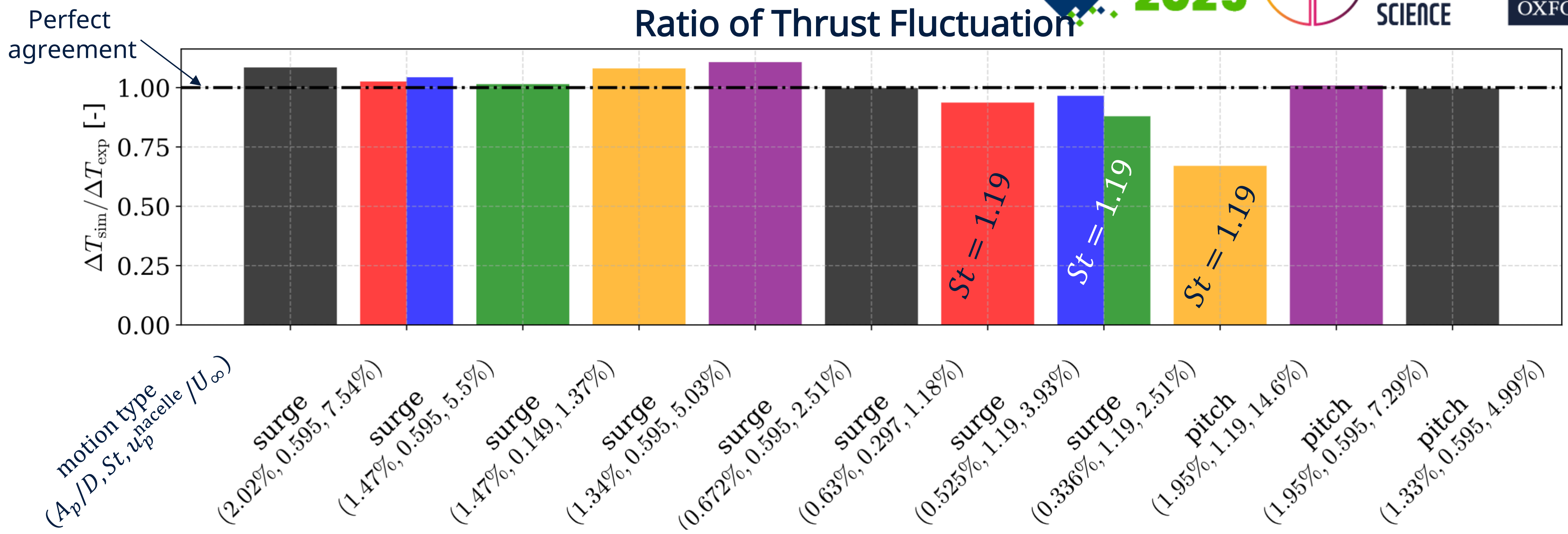
The Rotor Loads



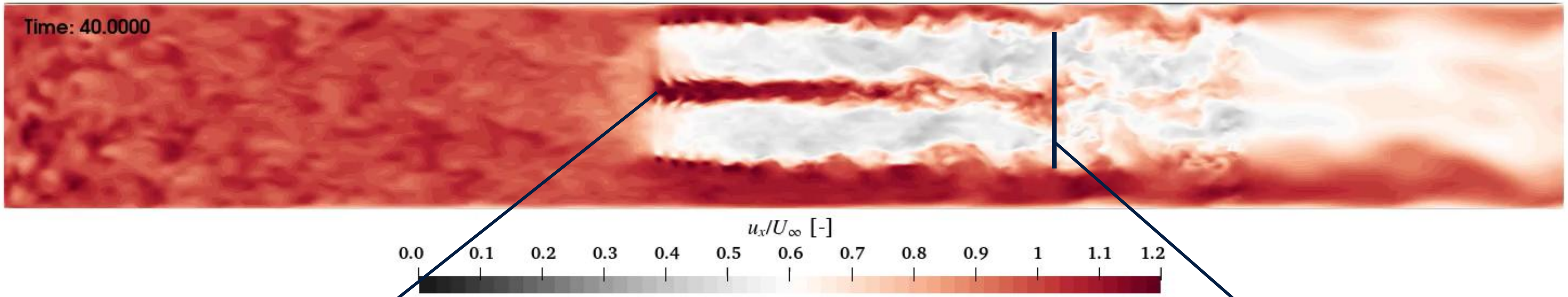
Remarks:

- **Good general agreement.**
- Cases with $St = 1.19$ deviate suggesting **unrealised unsteady aerodynamics**.
- However, $St = 1.19$ is considered **an extreme case**.

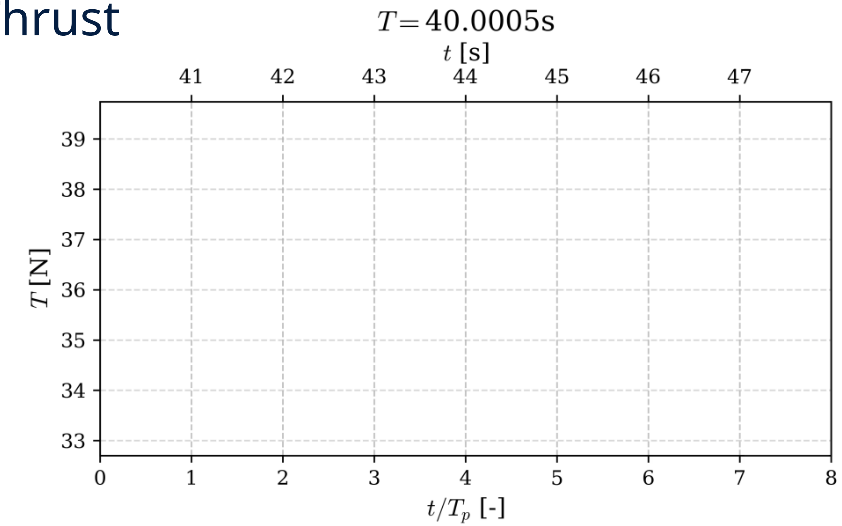
Model Output

Pitching turbine ($A_p = 1.9°,\ St = f_p D/U_\infty = 0.595$)

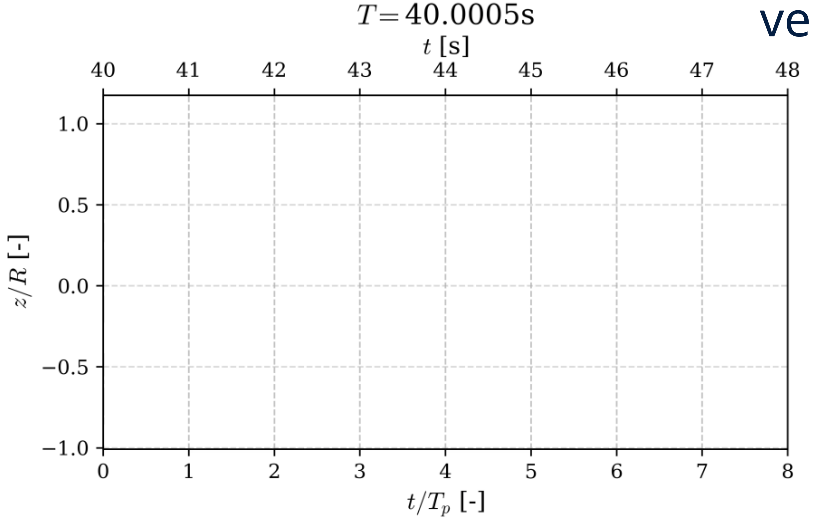
$3D$



Thrust



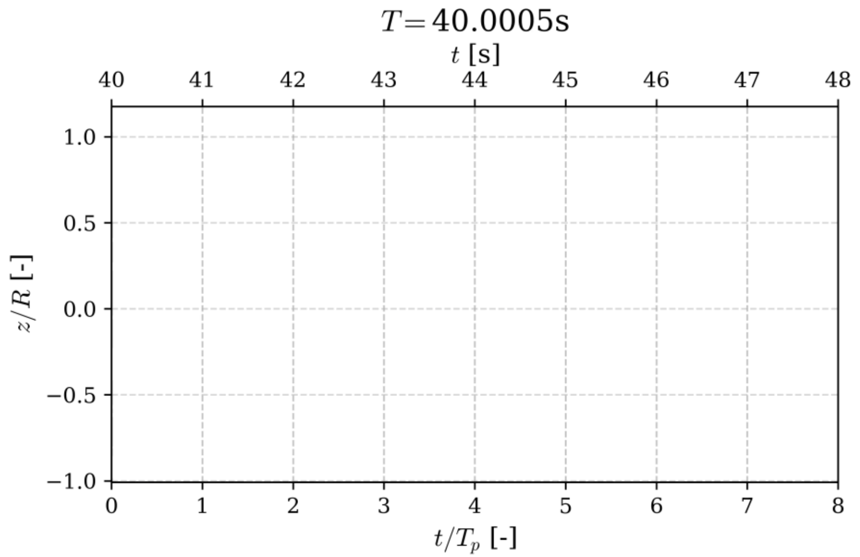
Streamwise velocity



$x = 3D$

The Rotor Wake

Streamwise Velocity Time Series



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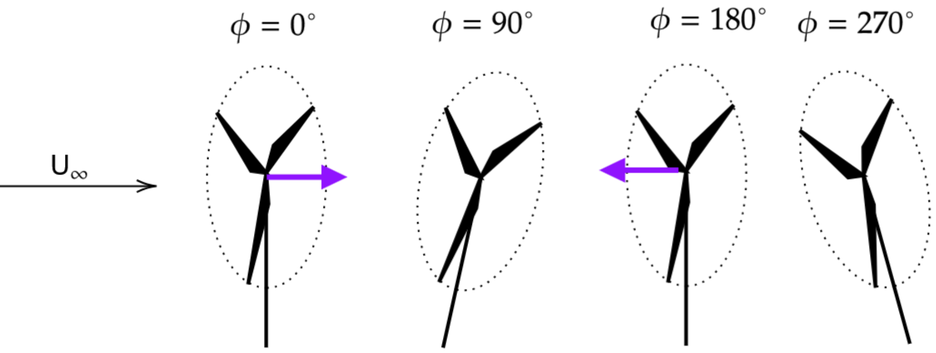
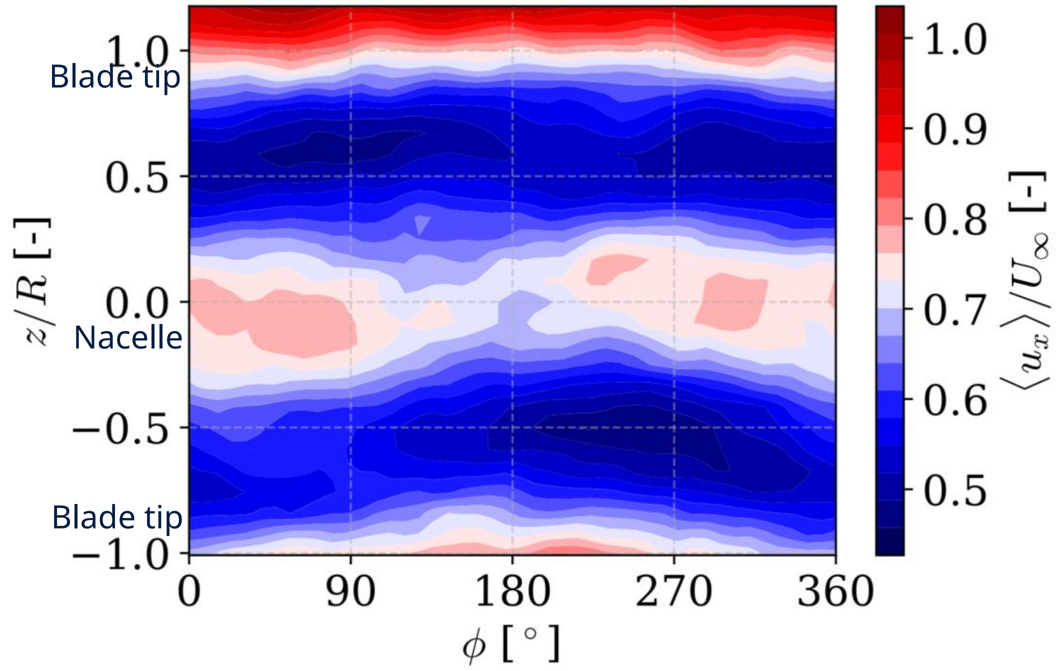
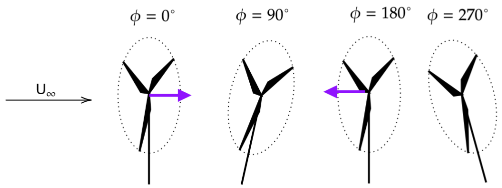


Phase Averaged Streamwise Velocity



The Rotor Wake

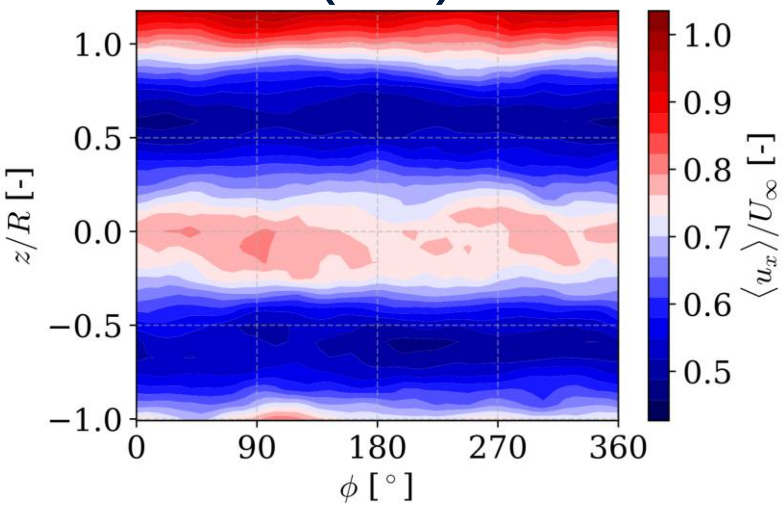


DEPARTMENT OF ENGINEERING SCIENCE

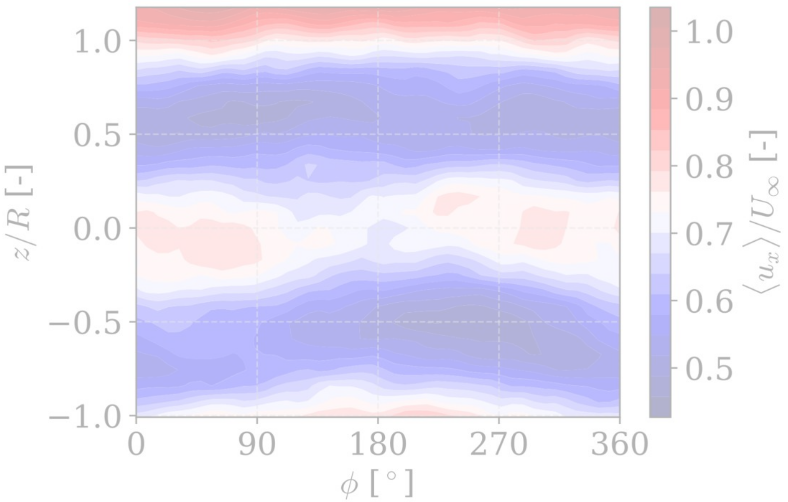
UNIVERSITY OF OXFORD

MARINE 2025

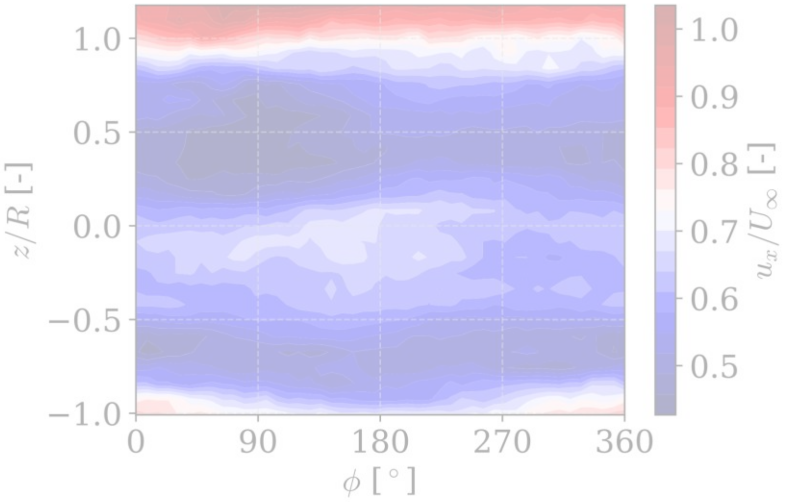
Fixed-Bottom Simulation (ALM)



Floating Simulation (FALM)



Floating Experiment

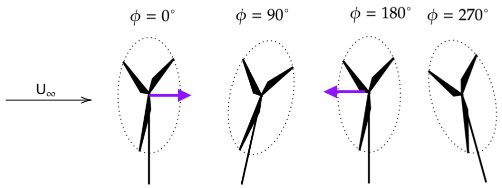


Remarks:

1. ALM is approx. invariant w.r.t ϕ.
2. ALM and FALM contain a spurious nacelle jet.
3. FALM reproduces the platform motion-induced lower wake bending.
4. The bypass flow constrains the upper wake bending.
5. Velocity deficit is upper wake velocity deficit is underpredicted by the FALM.
6. The spurious nacelle jet reenergises the platform motion-induced

Fixed-bottom simulation cost:
Time Averaged: 9,000 CPU Hours
Phase Averaged: 18,000 CPU Hours

The Rotor Wake



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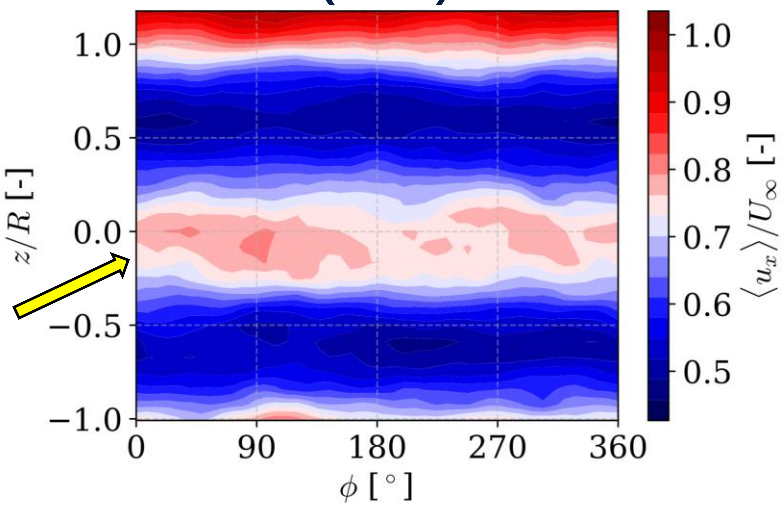

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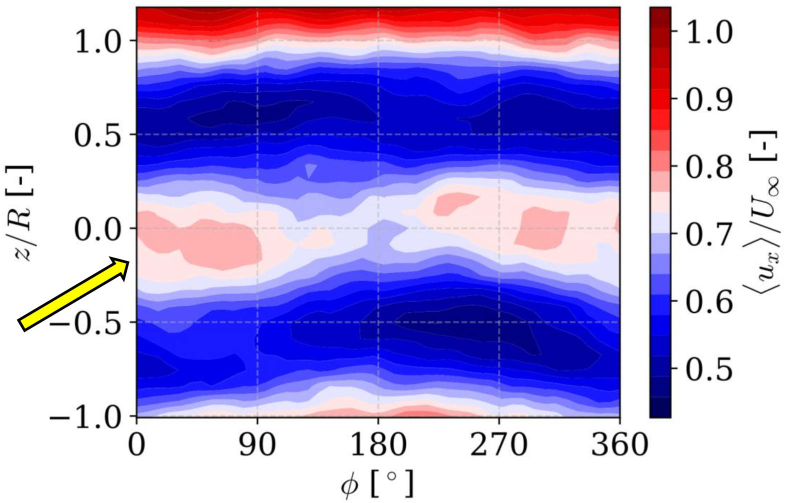

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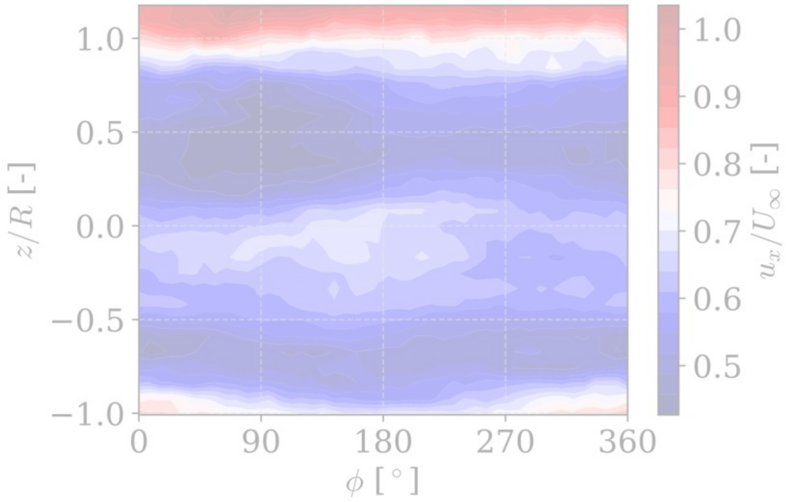

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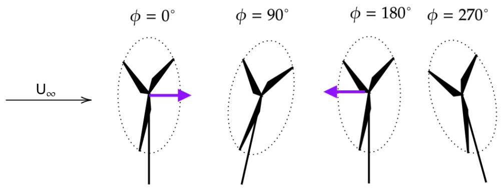
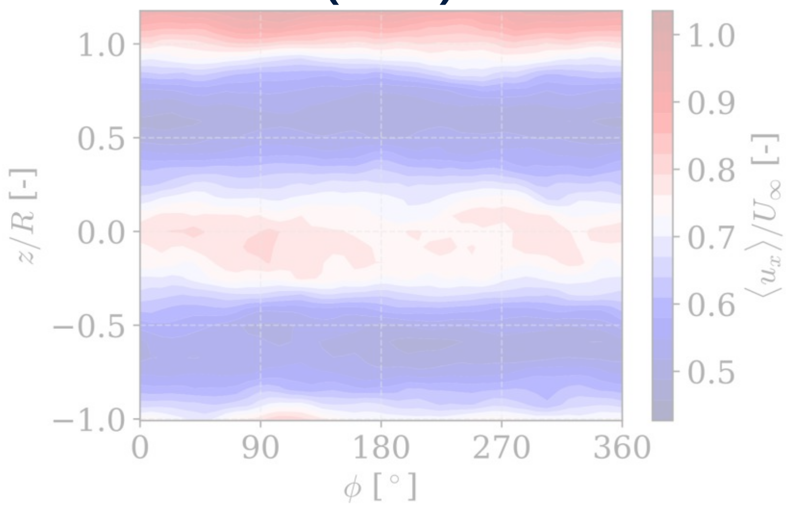
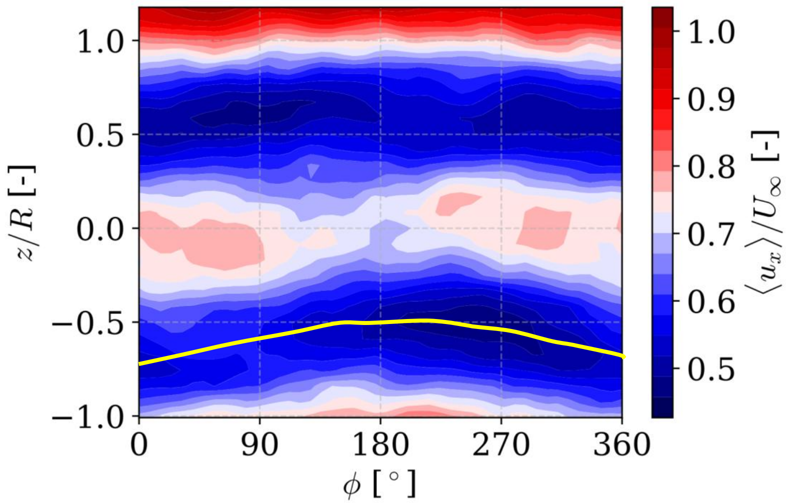
The Rotor Wake



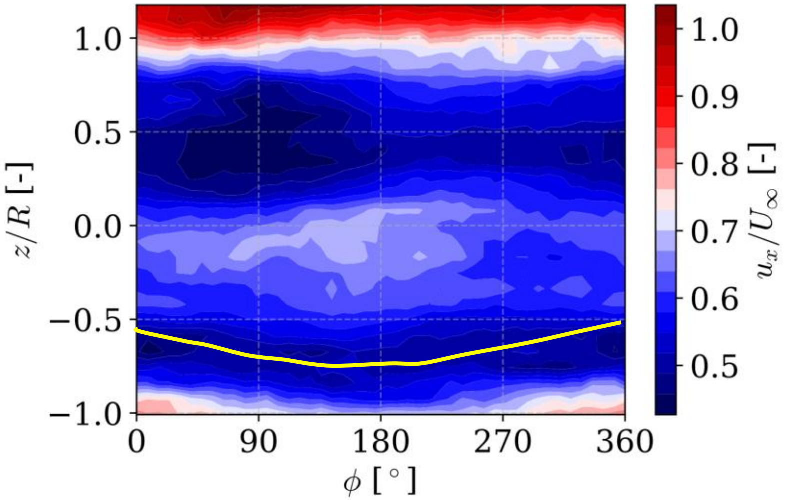
Fixed-Bottom Simulation (ALM)



Floating Simulation (FALM)



Floating Experiment



Remarks:

1. ALM is approx. invariant w.r.t ϕ.
2. ALM and FALM contain a spurious nacelle jet.
3. **FALM reproduces the platform motion-induced lower wake bending.**
4. The bypass flow constrains the upper wake bending.
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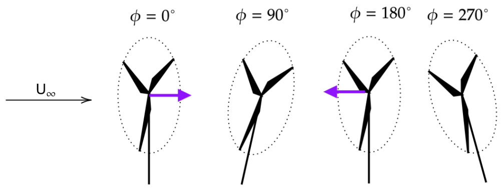

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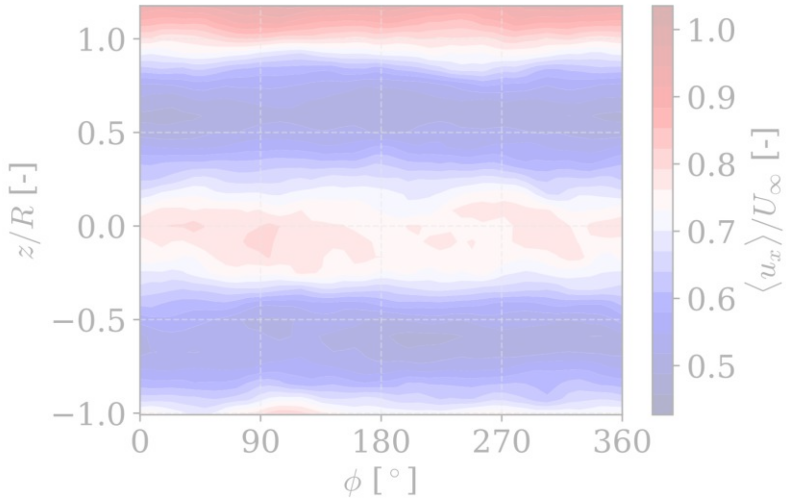

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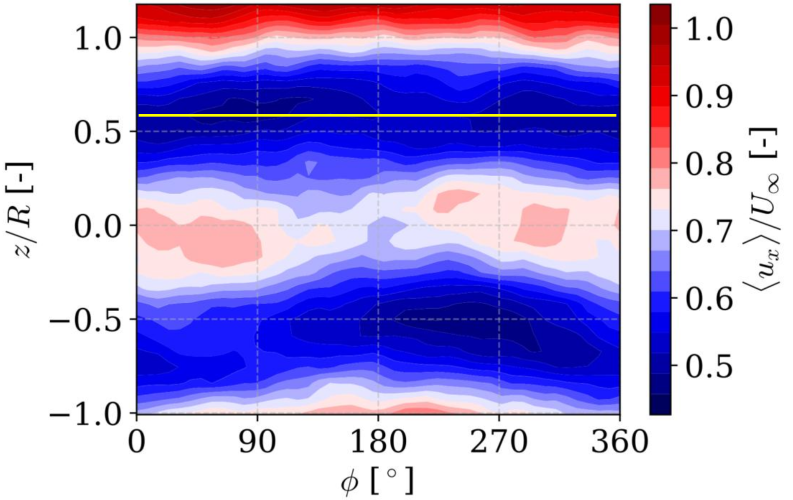

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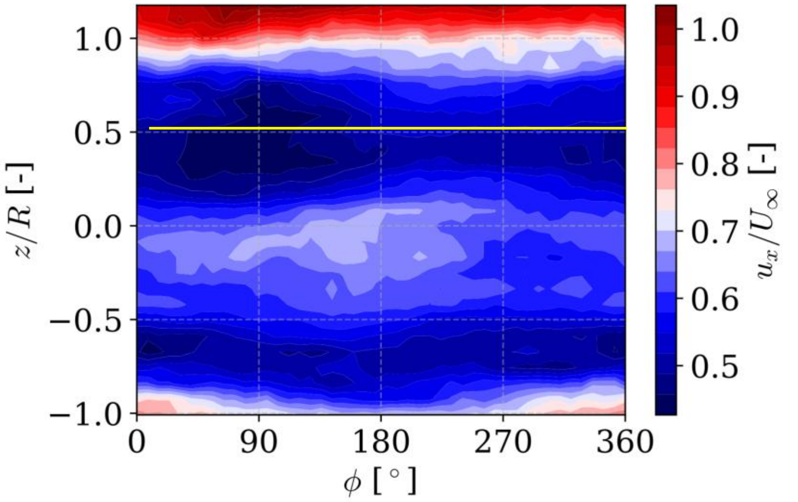

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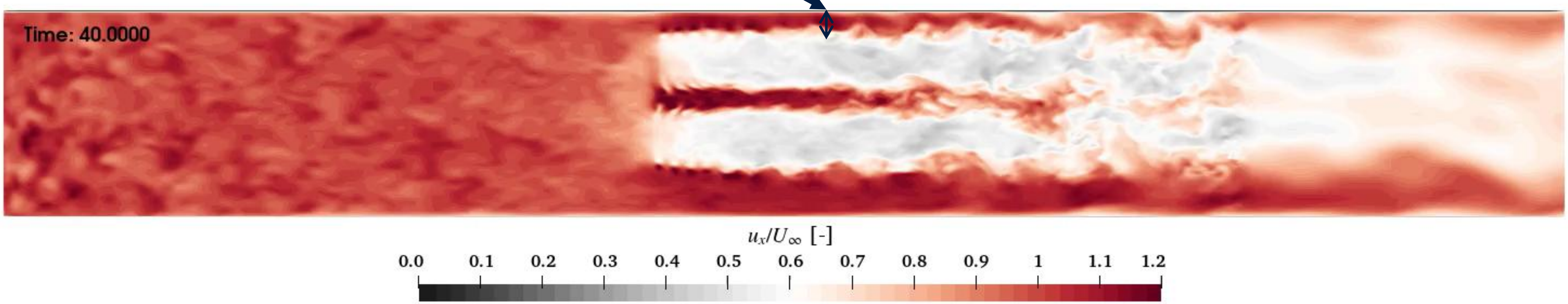
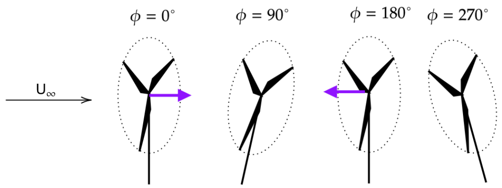
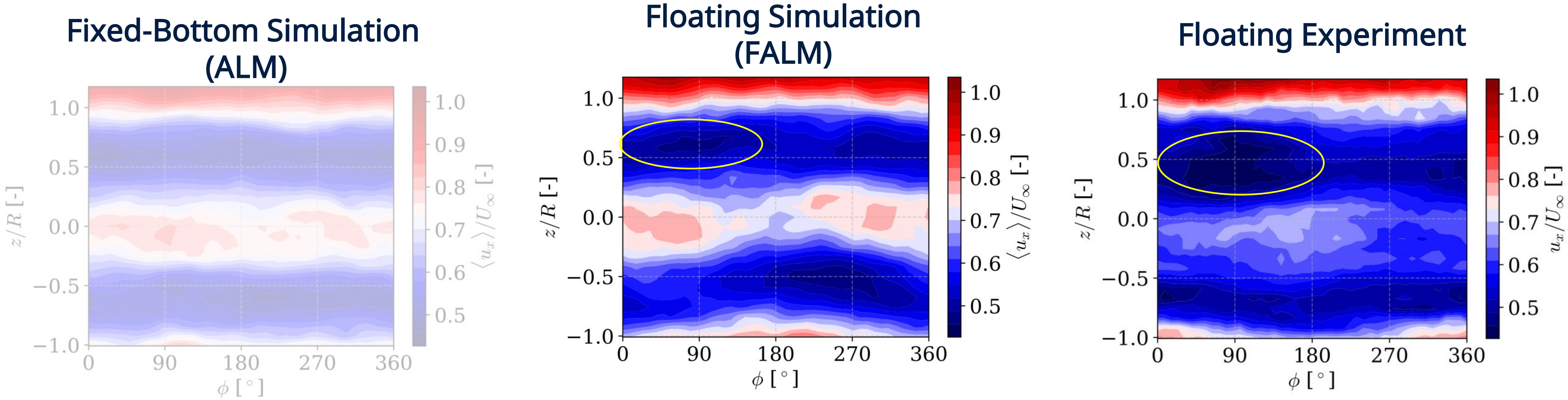
Model Output

Proximity to wind tunnel ceiling forms a stabilising bypass flow



The Rotor Wake





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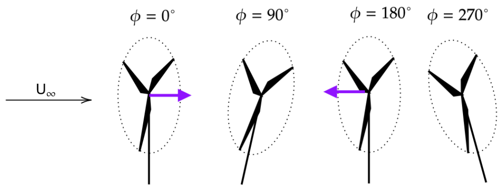

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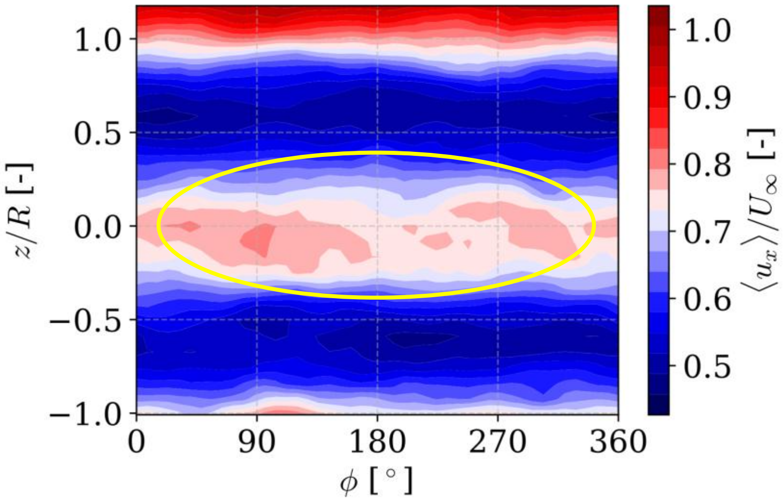
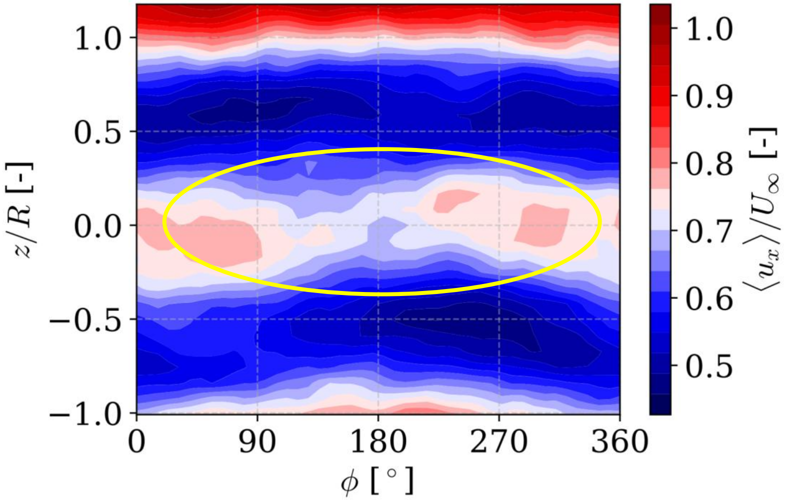
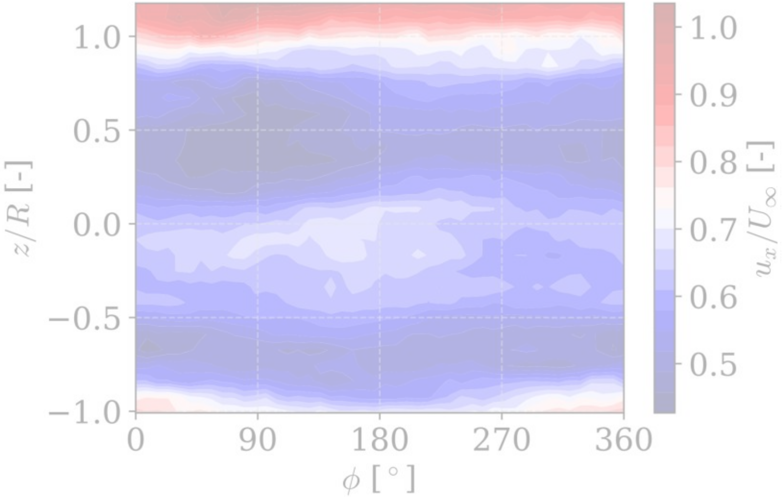


Floating Simulation (FALM)



Floating Experiment



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Conclusions

- **Implemented** & **validated** a numerical method for simulating floating turbines

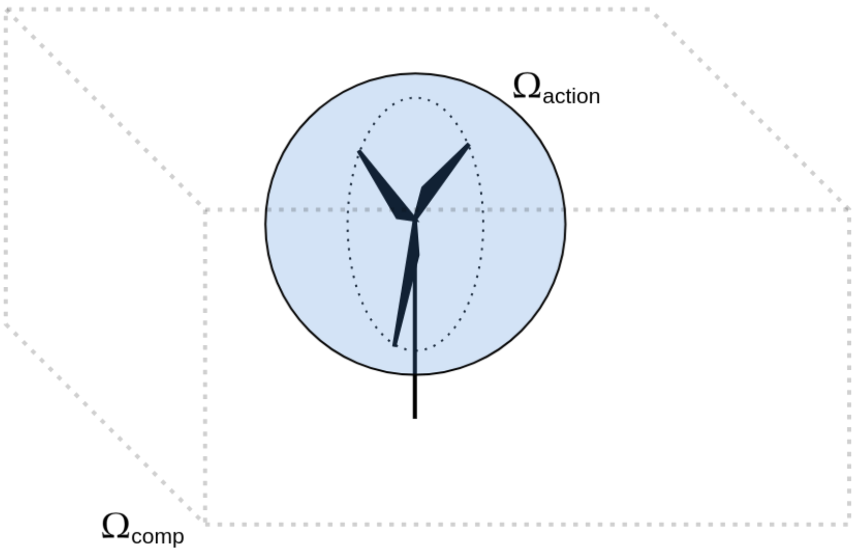
- The FALM:
  - Produces fluctuating rotor loads with excellent agreement in ΔT
  - Generates the dynamic features observed in the wake flow field
  - Requires a fraction of the cost of blade resolved simulations

→ suitable tool for future work

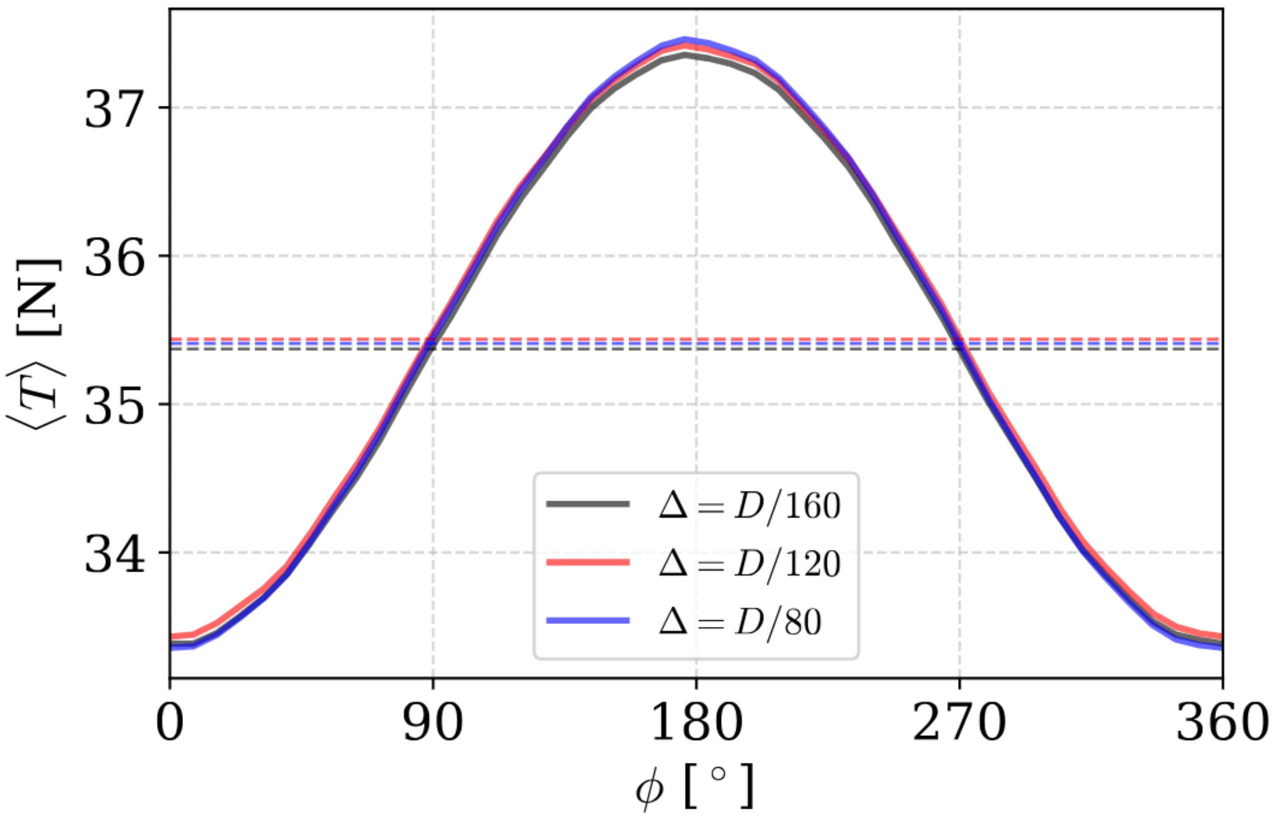
Methodology Subtleties

Is the FALM more expensive?

- ALM defines a sphere of actions – limits cell search requirements
- FALM requires increasing sphere radius
- **Conclusion: insignificant overhead – cost is dominated by flow sampling method**



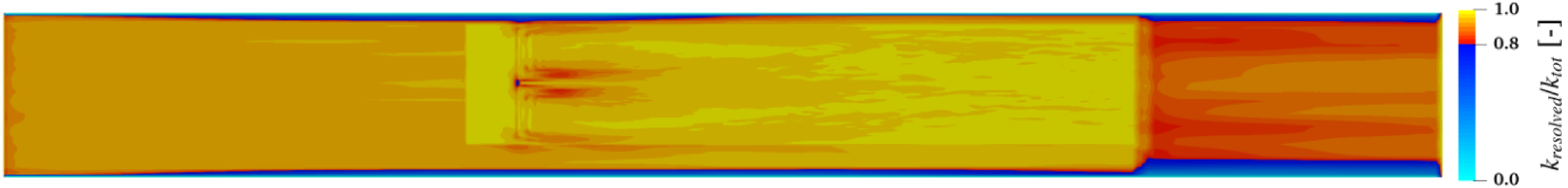
Convergence of Rotor Load Fluctuations



(a)

D/Δ [-]	80	120	160
$\overline{T}$ [N]	35.41	35.44	35.37
ΔT [N]	4.087	3.979	3.976
$\epsilon_{\Delta T}$ [-]	2.79%	0.75%	-

Resolved Turbulence



Wake Phase

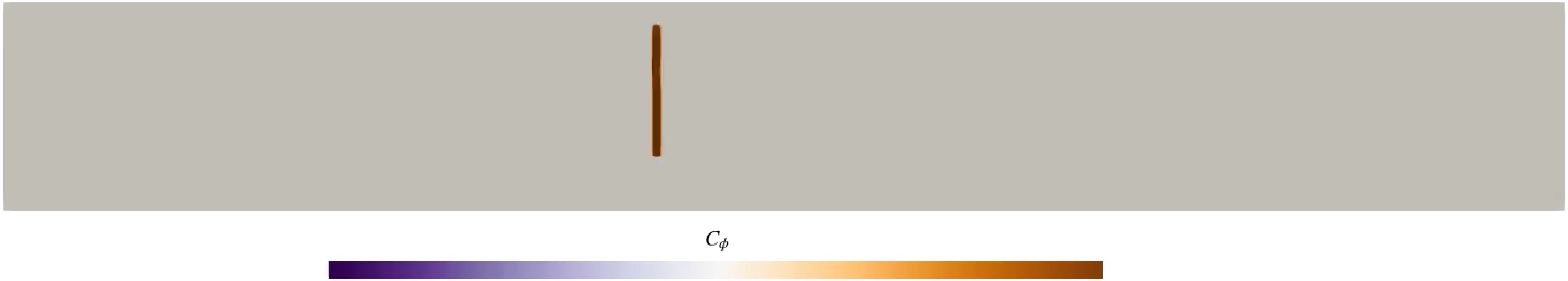
- The wake phase can be calculated in a Lagrangian sense like so

$$\Delta\phi(x,t) = 2\pi f \int_0^x \frac{1}{u(x',t(x'))}\,\mathrm{d}x',$$

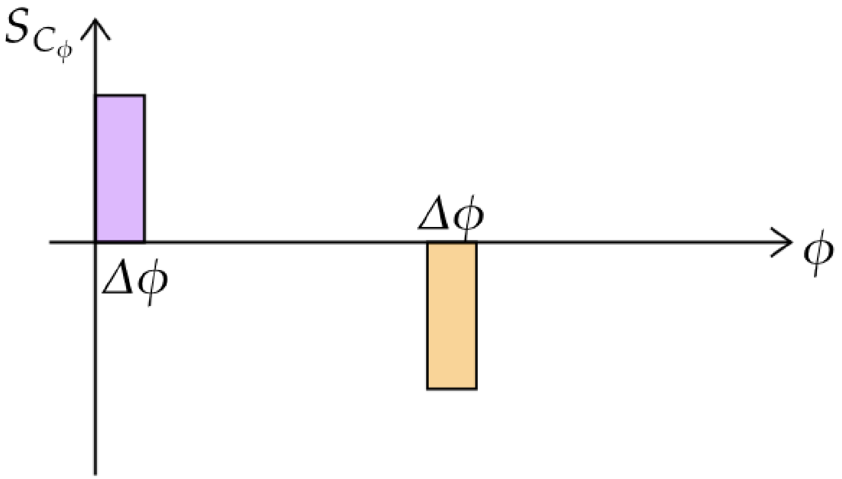
(neglecting non streamwise velocity).

- Therefore, computing wake phase requires complete flow field history.

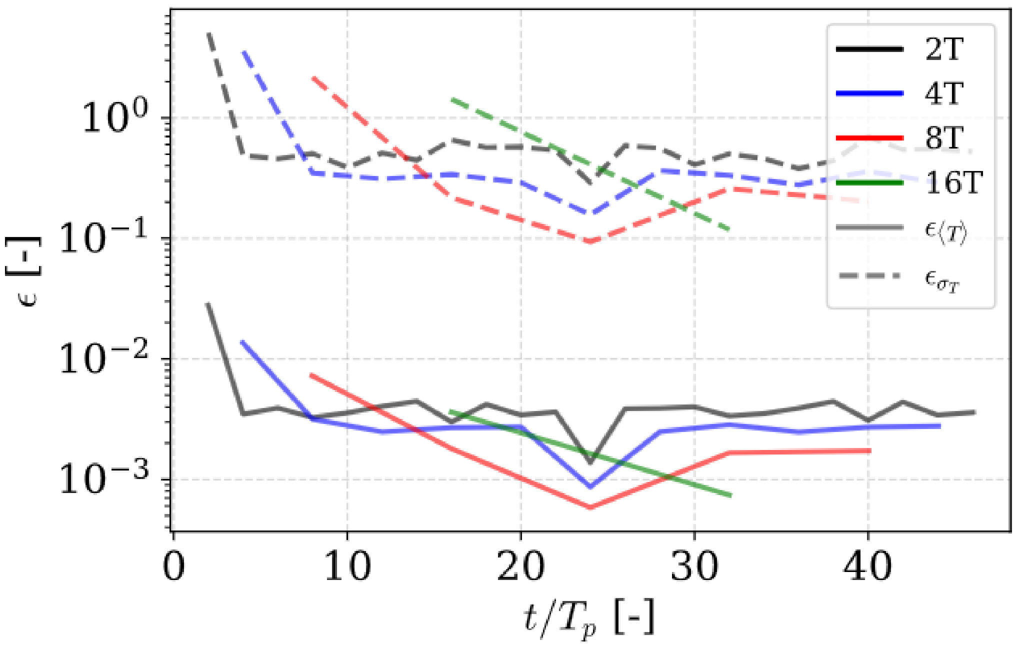
Scalar Phase Tracer

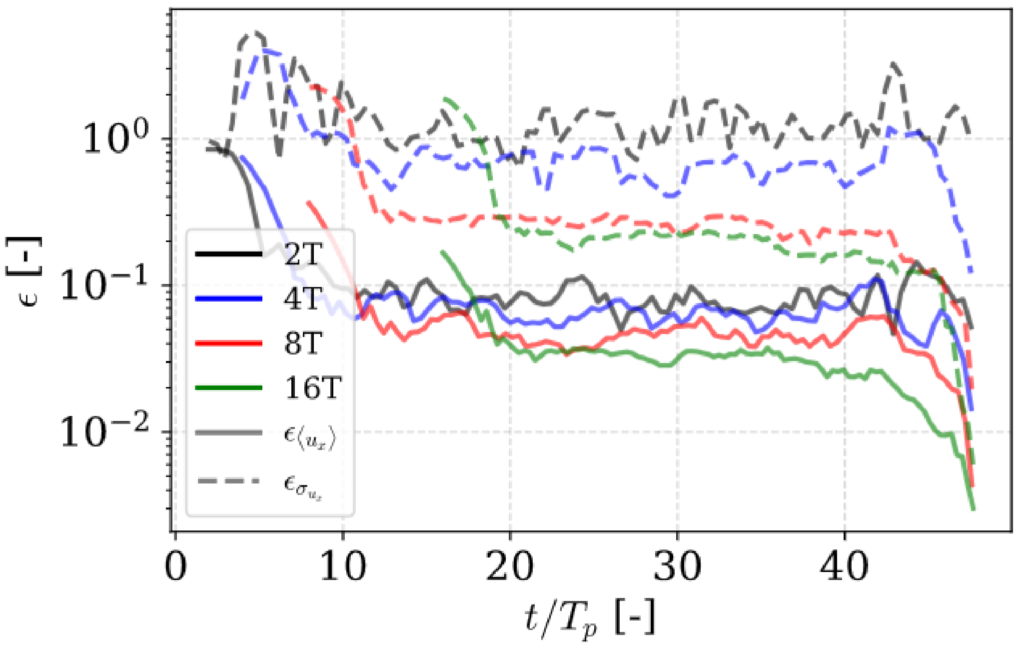


$$\frac{\partial C_\phi}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla})\mathrm{C}_\phi = \mathrm{S}_{\mathrm{C}_\phi}$$



Temporal Convergence

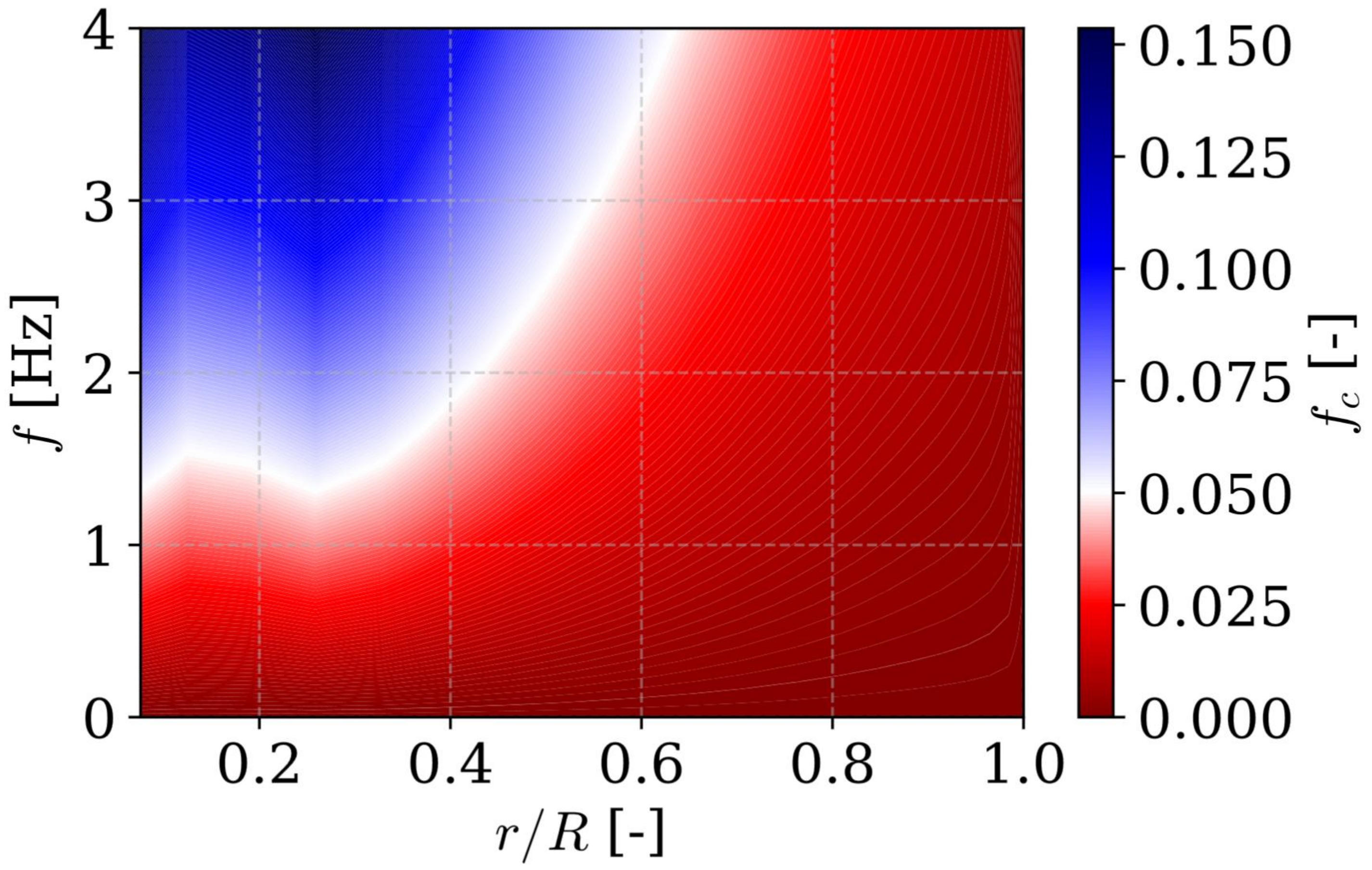




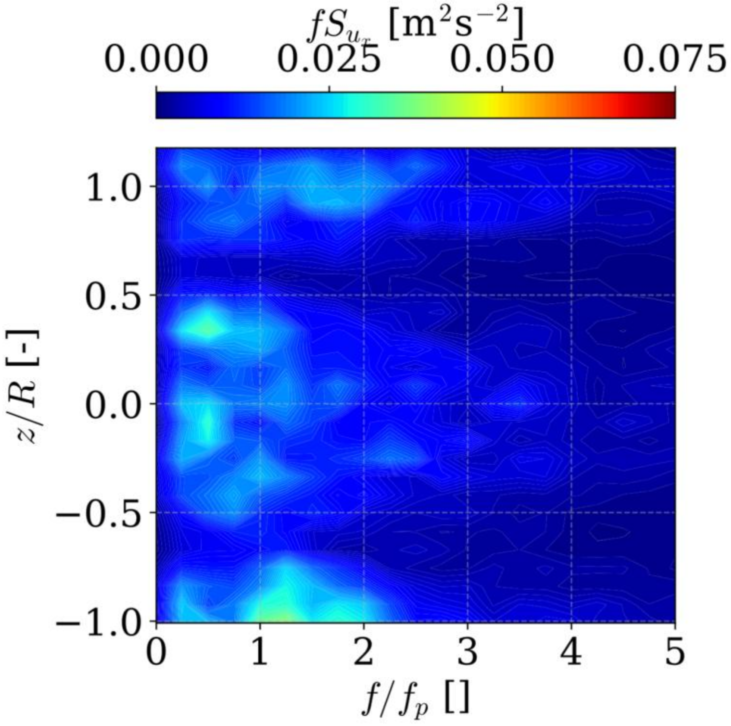
$$\epsilon_q(\tau) = \frac{1}{360}\int_0^{360} \left| \frac{q(\tau,\phi) - q(\tau_{\text{final}},\phi)}{q(\tau_{\text{final}},\phi)} \right| \, \mathrm{d}\phi.$$

Unsteady Aerodynamics

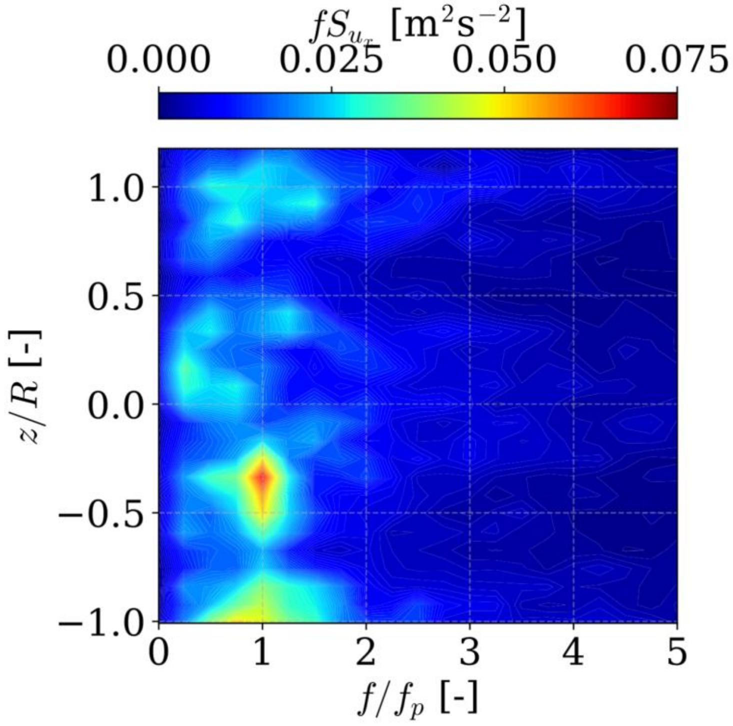
$$f_c = \frac{\pi f c}{U_\infty}$$



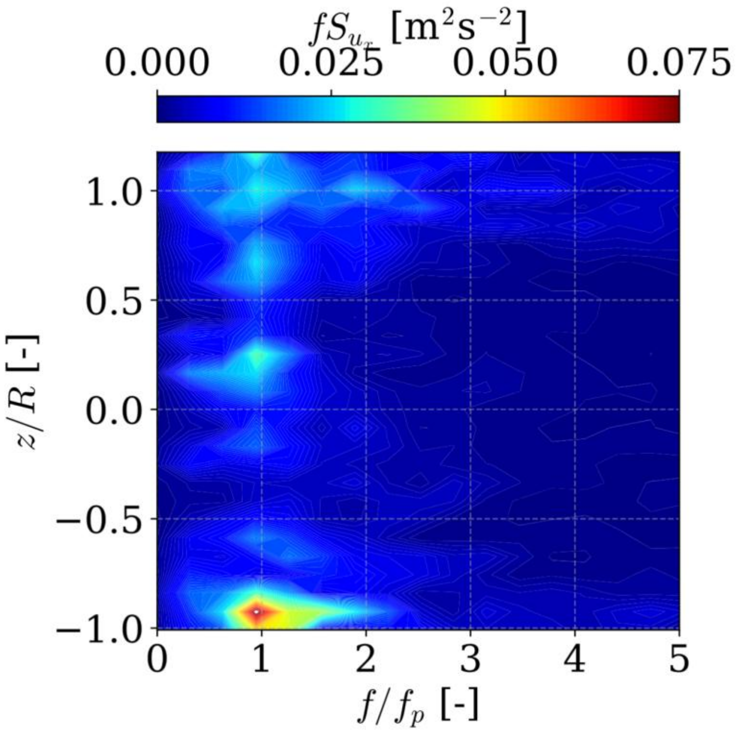
Wake Spectra



ALM (fixed-bottom)

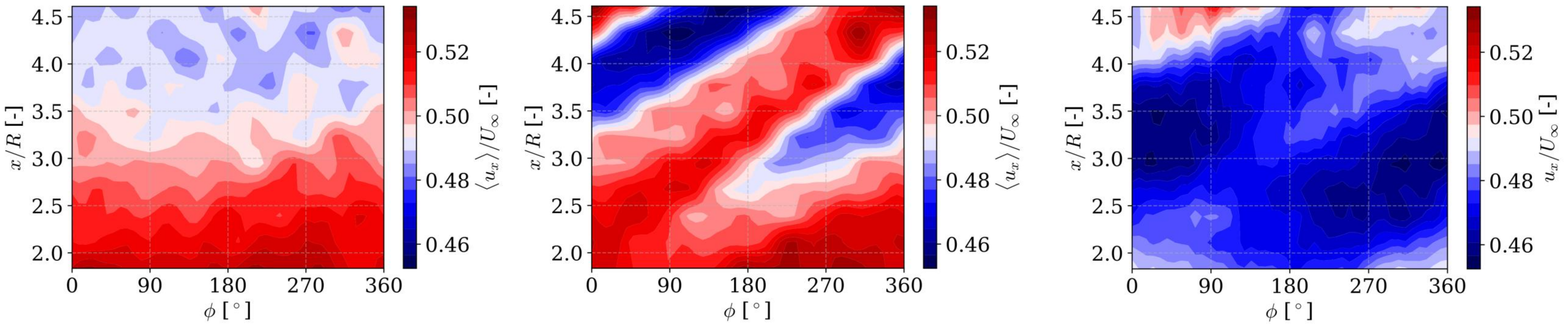


FALM (floating)

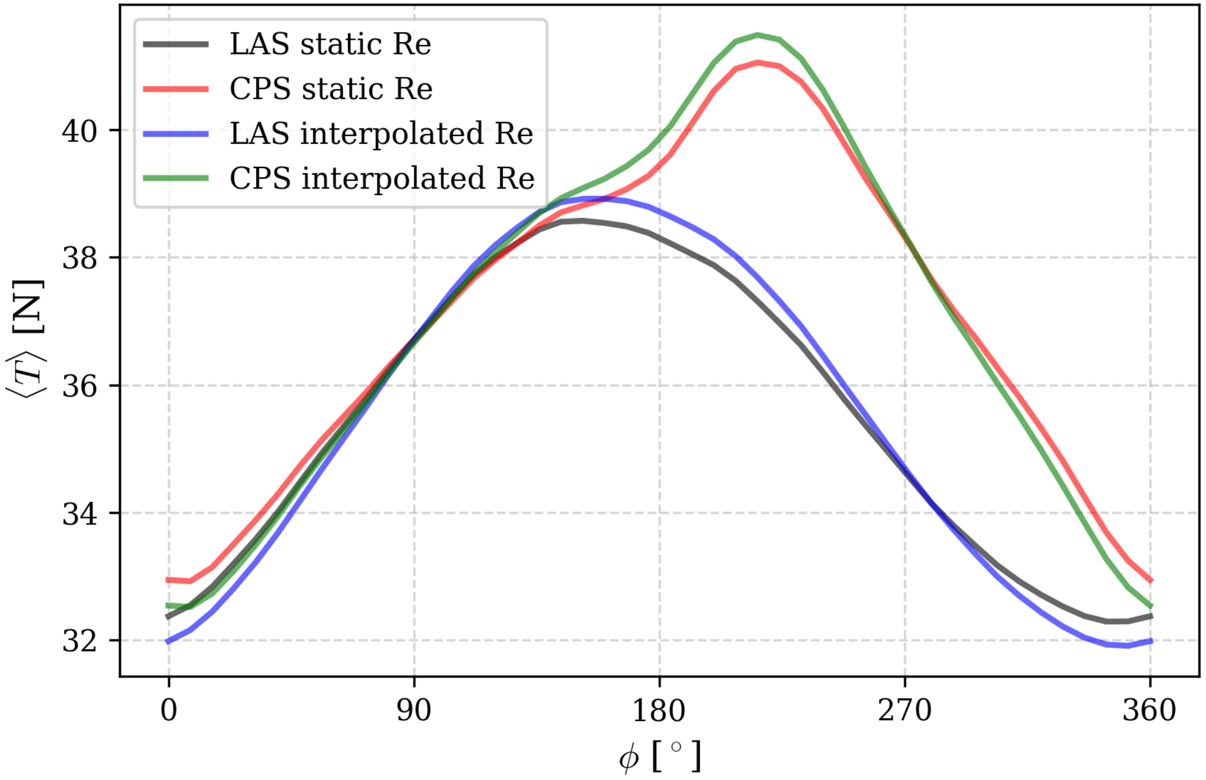


Experimental (floating)

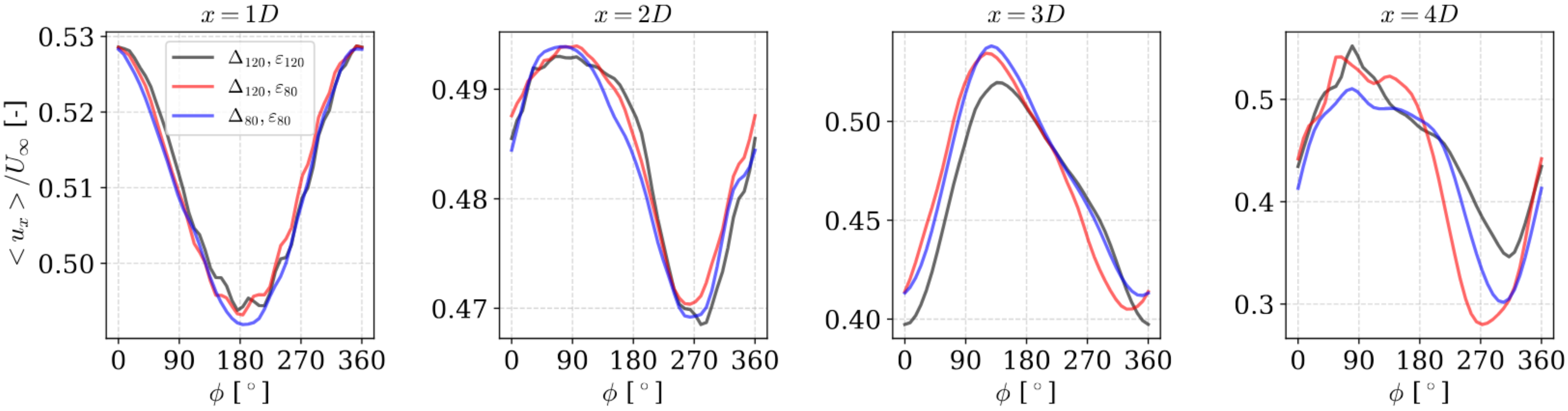
Surging Turbine Wake



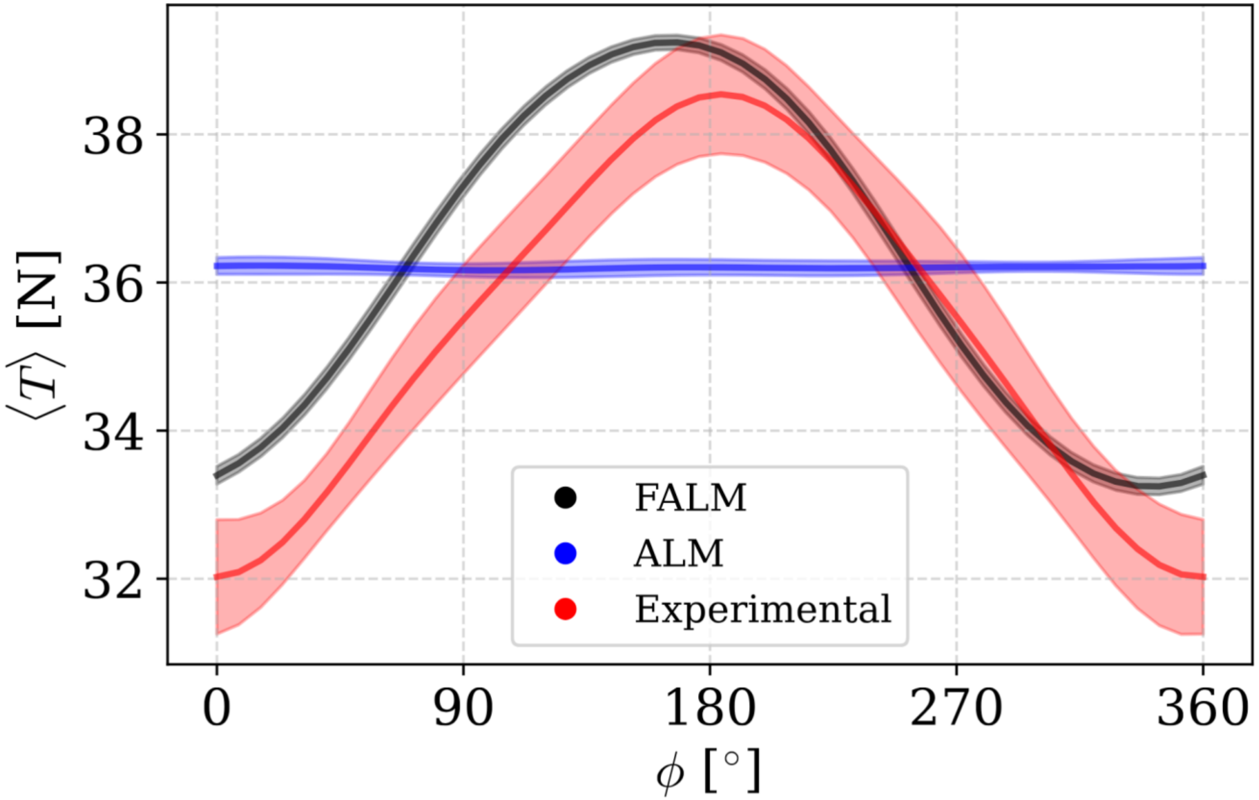
Reynolds Number Interpolation



Sensitivity to Smearing & Spatial Resolution



Pitching Turbine Phase Averaged Thrust



Sensitivity to Sampling Method

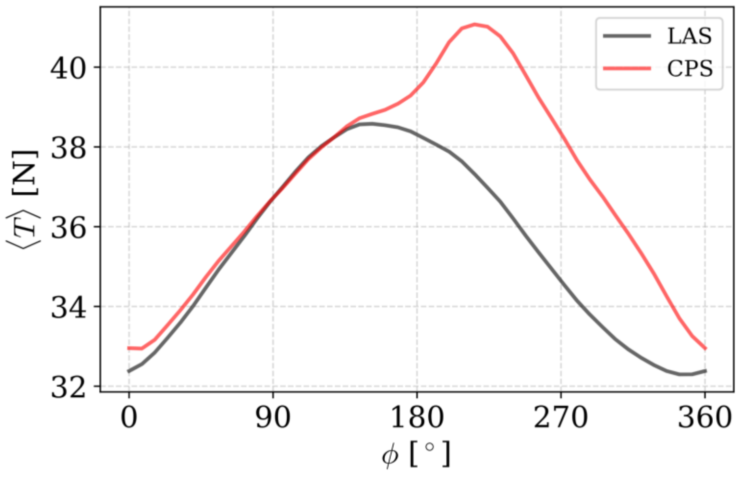
Velocity Sampling Method:

- LAS = Line Average Sampling
- CPS = Collocation Point Sampling

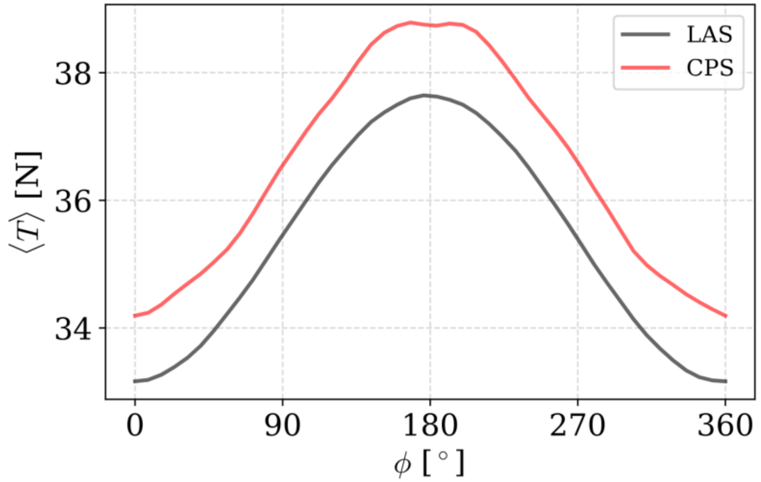
Remarks:

- **Significant sensitivity to sampling method.**
- Suggests **platform motion-sampling method coupling**.
- Requires further characterisation if method is to become widely used.

Pitching turbine



Surging turbine



Phase Averaging Bin Size

Larger bins → Faster temporal convergence

Smaller bins → Better phase resolution

Reynolds stresses polluted by mean flow $O(\Delta\phi^2)$

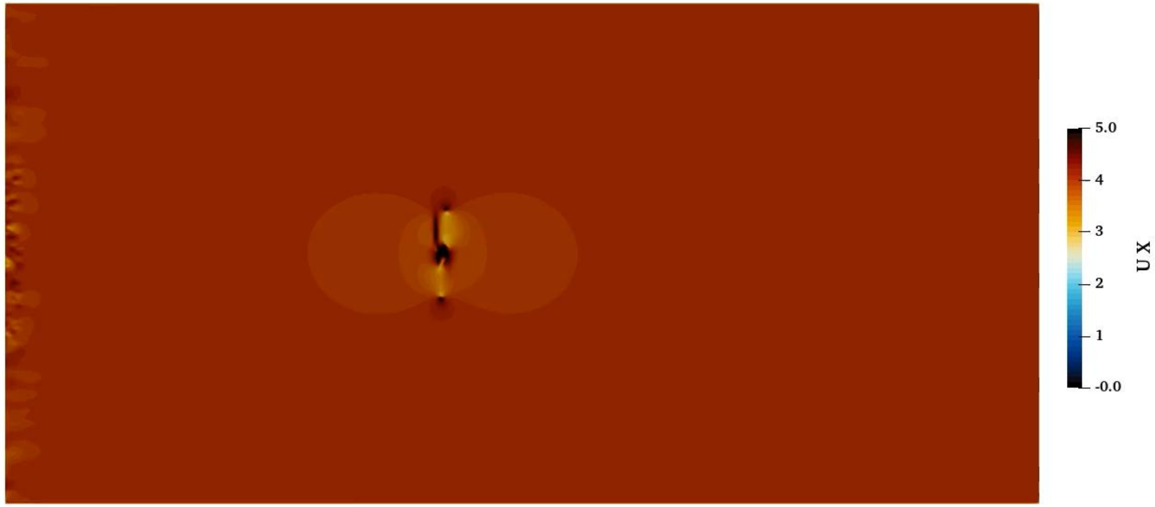
$$\langle u_i' u_j' \rangle(\phi_i) \approx \underbrace{\frac{1}{\Delta\phi} \int_{\phi_i - \frac{\Delta\phi}{2}}^{\phi_i + \frac{\Delta\phi}{2}} (u_i - \langle u_i \rangle)(u_j - \langle u_j \rangle)\, \mathrm{d}\phi}_{\text{Pseudo-turbulence}} + \underbrace{\frac{1}{12} \frac{\partial u_i}{\partial \phi} \frac{\partial u_j}{\partial \phi} \Delta\phi^2}_{\text{Mean flow pollution}}$$

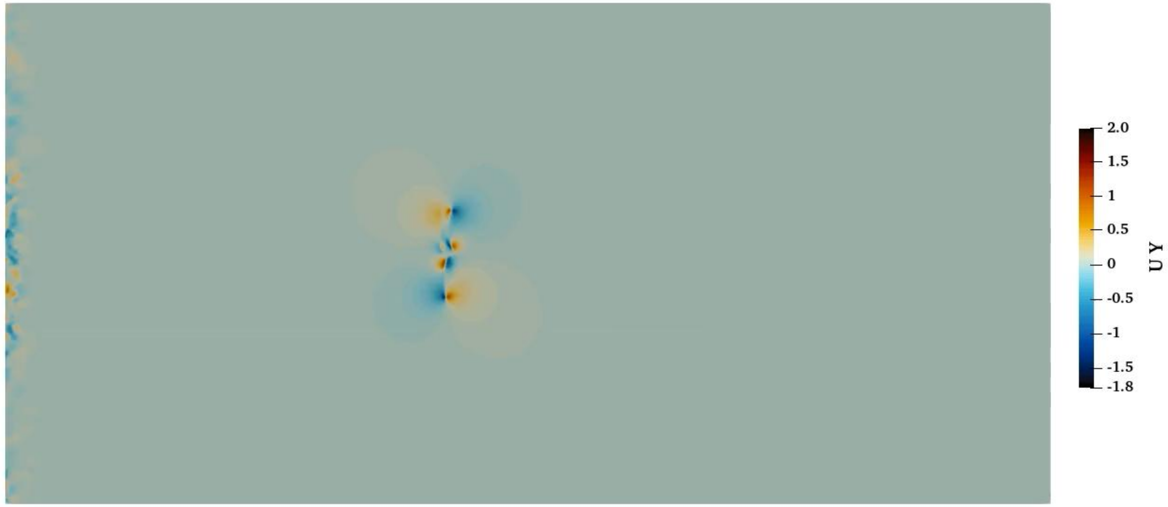
The Solver

- OpenFOAM v2212
- Custom in-house (F)ALM code
- $\frac{D}{Dt}$: Backward Euler
- ∇: Linear Gauss
- $\mathrm{div}(\cdot)$: Limited Linear
- ∇^2: Linear Gauss
- PIMPLE velocity-pressure coupling
- U: PBiCGStab, p: GAMG

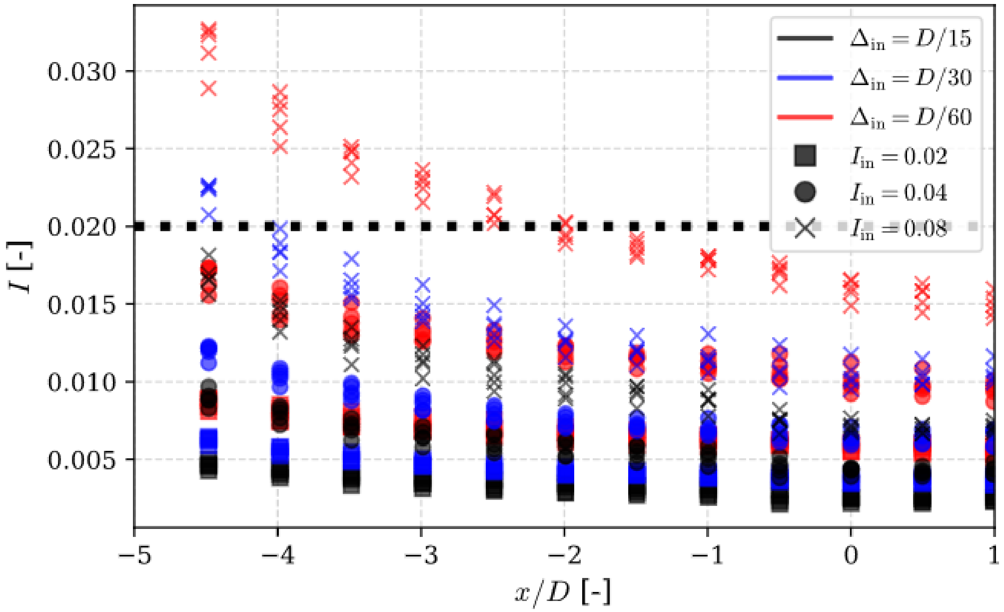
Roll: Transverse Velocity

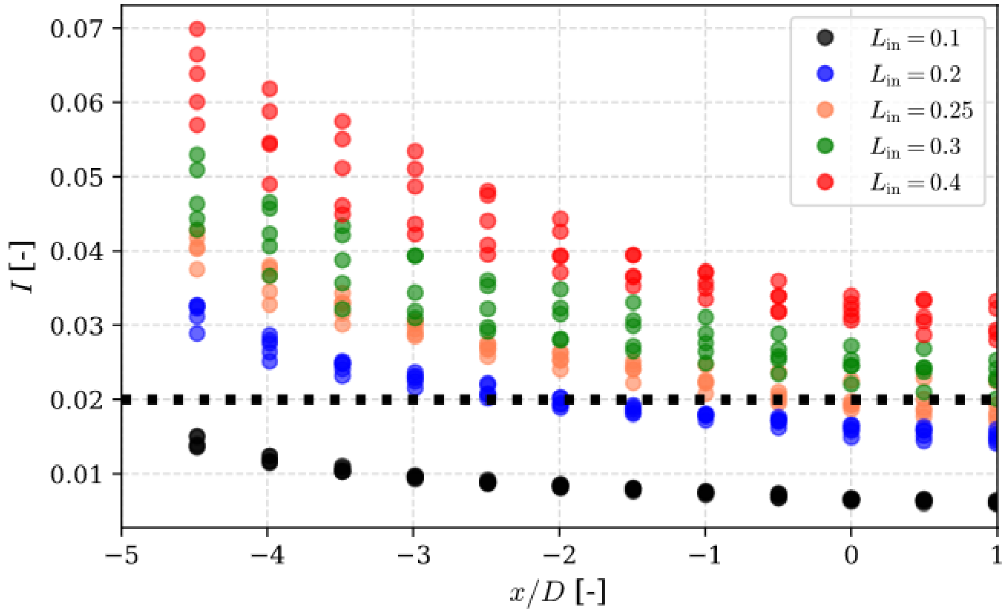
Roll A=1.9deg F=1Hz





Turbulent Inlet





Influence of Wind tunnel Blockage