POLITECNICO MILANO 1863

Laboratory of Fluid Machines

Comparative assessment of actuator line modelling of FOWT rotor aerodynamics to wind tunnel experiments

Andrea G. Sanvito, Giacomo Persico, Paolo Schito, Vincenzo Dossena, Alberto Zasso

Andrea G. Sanvito

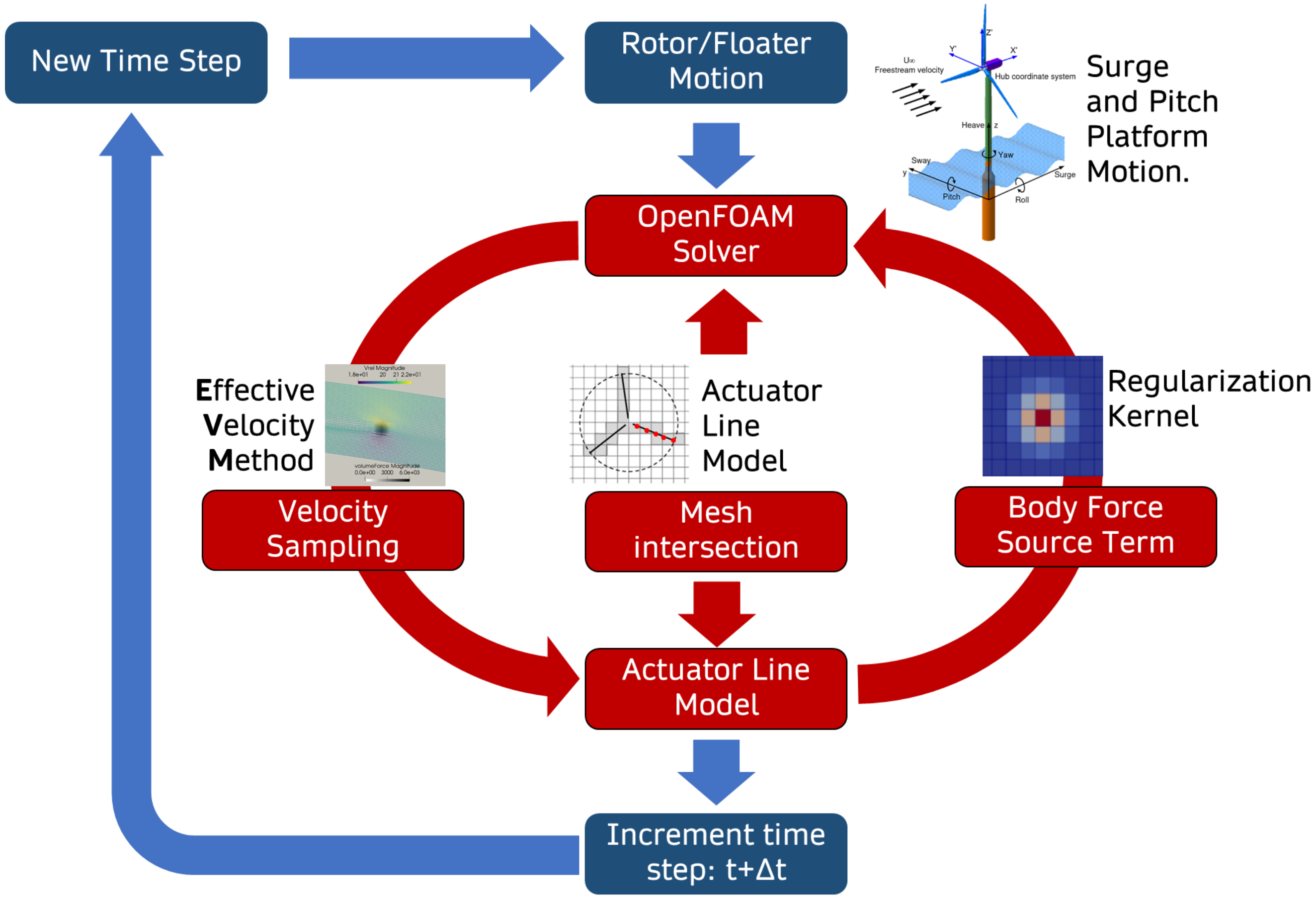
PhD Candidate

andreagiuseppe.sanvito@polimi.it

Taken from: Bergua R. et al. "OC6 Project Phase III: Validation of the Aerodynamic Loading on a Wind Turbine Rotor Undergoing Large Motion Caused by a Floating Support Structure." Wind Energy Science Discussions. 2022

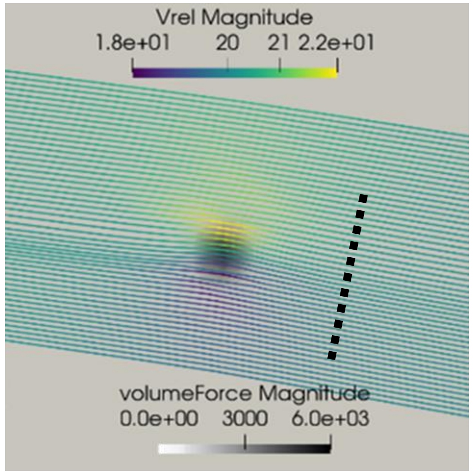
What is the level of accuracy of a medium-fidelity model in FOWT simulation?

Actuator Line Model (ALM)



- Reduced computational cost with respect to fully-resolved CFD simulations: the boundary layer is not solved.
- The actuator line replaces the blades: reliable airfoil polars are required.
- Good resolution of the wake according to the refinement level. The flow field is solved with a finite volume approach.
- Imposed surge and pitch platform motion is implemented in the in-house ALM solver.
- **Verification of FOWTs with ALM against wind tunnel experiments.**

Actuator Line Model (ALM)

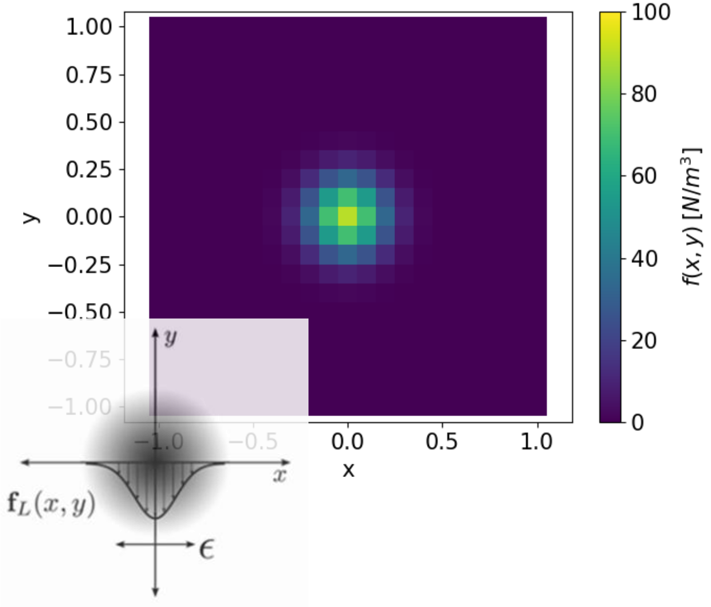


▪▪▪▪ velocity sampling line

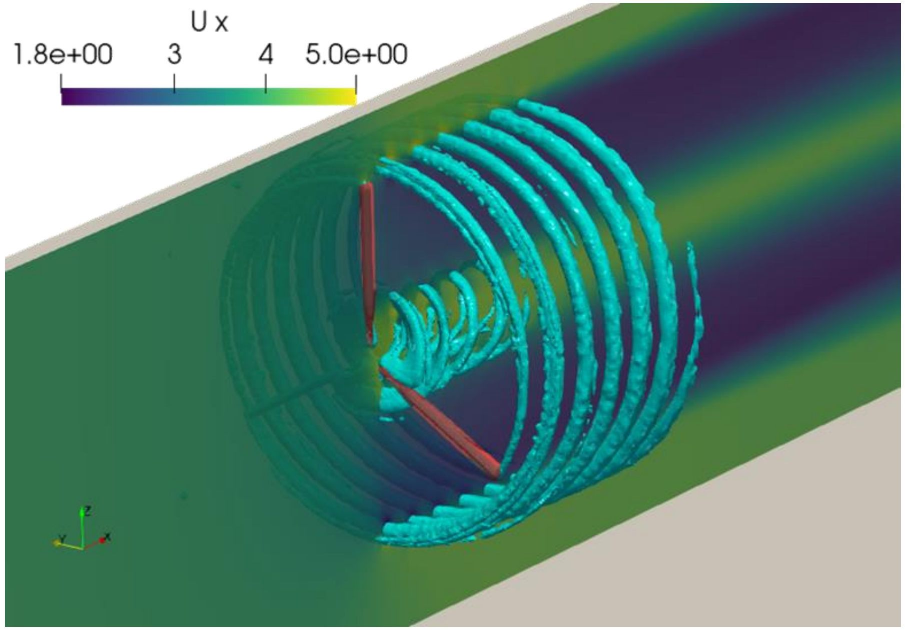
- **Effective velocity method** to calculate the angle of attack and the aerodynamic coefficients.
- Correction of the angle of attack to mimic the downwash produced by the force

$$\Delta\alpha = f(\mathrm{C_l}, \mathrm{C_d})$$

- Forces are applied in the numerical domain
- 2D Gaussian spreading function with **regularization kernel** width ε



- ALM is implemented in OpenFOAM CFD solver: body forces provide the source term for Navier-Stokes momentum equation.



ALM simulation in steady wind: tip and root vortices are visualised with Q-criterion (cyan) and the body forces (red).

Experimental Setup

DTU 10-MW RWT	Exp.1 UNAFLOW[1]	Exp.2 OC6 Phase III[2]
Rotor diameter [m]	2.38	
Hub diameter [m]	0.178	
Rotor overhang [m]	0.09467	0.139
Tilt angle [°]	5	
Rotational speed [rpm]	240	
Freestream wind speed [m/s]	4	
Hub height from ground [m]	2.086	2.188

Geometrical scale 1:75

Velocity scale 1:3

Low-Reynolds arifoil series SD7032 tested in 2D Wind Section at DTU[1]

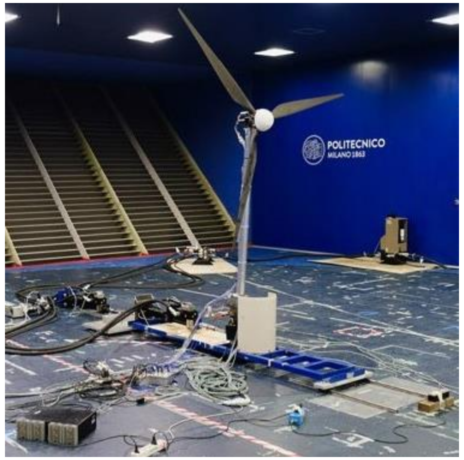
[1] Fontanella A. et al. "UNAFLOW: a holistic wind tunnel experiment about the aerodynamic response of floating wind turbines under imposed surge motion." Wind Energy Science. 2021

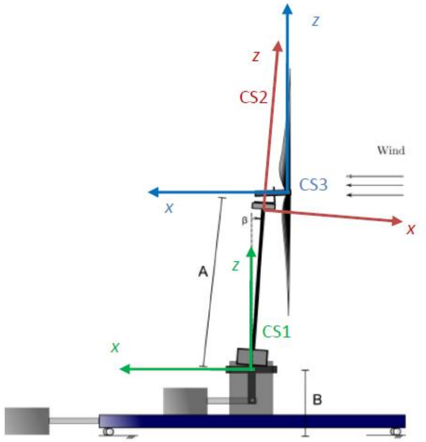
[2] Bergua R. et al. "OC6 Project Phase III: Validation of the Aerodynamic Loading on a Wind Turbine Rotor Undergoing Large Motion Caused by a Floating Support Structure." Wind Energy Science Discussions. 2022

Experiment setup

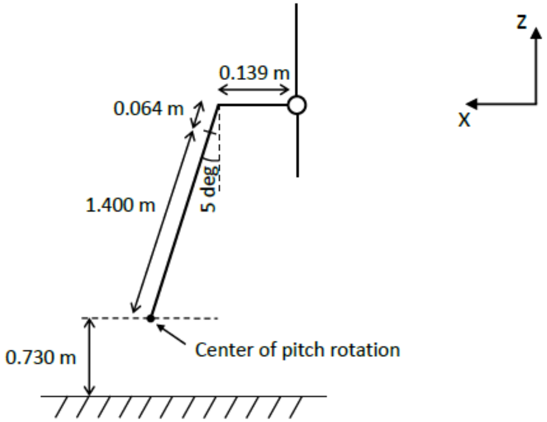
Conceptual layout

Experiment 1





Experiment 2



Load Cases

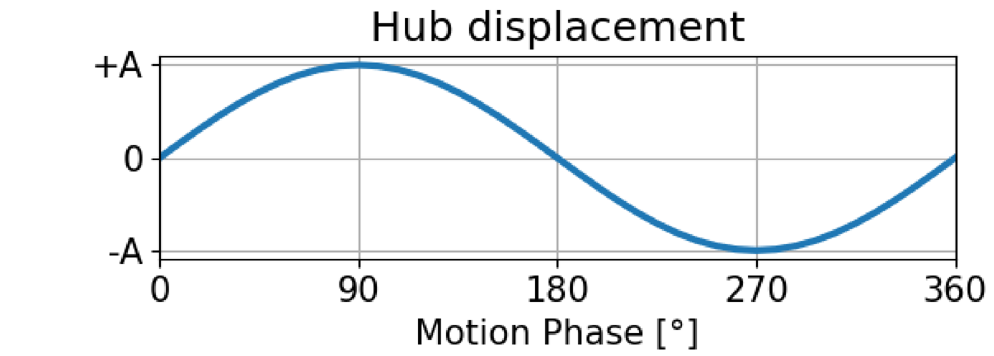
Unsteady aerodynamics parameter: $k = \frac{D \cdot f}{U_0}$

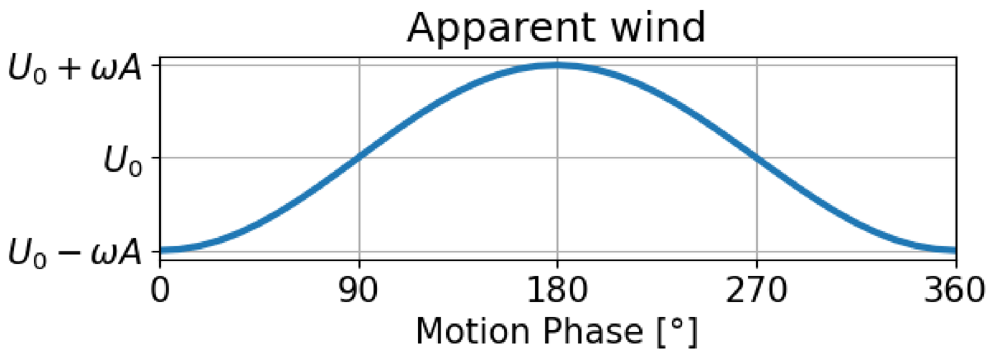
- f, ω platform motion frequency [Hz] [rad/s]
- D rotor diameter [m]
- U_0 mean wind speed [m/s]
- A platform motion amplitude [m] [°]

	Load Case	f [Hz]	A [m],[°]
Steady	LC1.1	-	-
Surge	LC2.1	0.125	0.125
	LC2.5	1	0.035
	LC2.7	2	0.008
Pitch	LC3.1	0.125	3
	LC3.5	1	1.4
	LC3.7	2	0.3

Prescribed sinusoidal surge displacement:

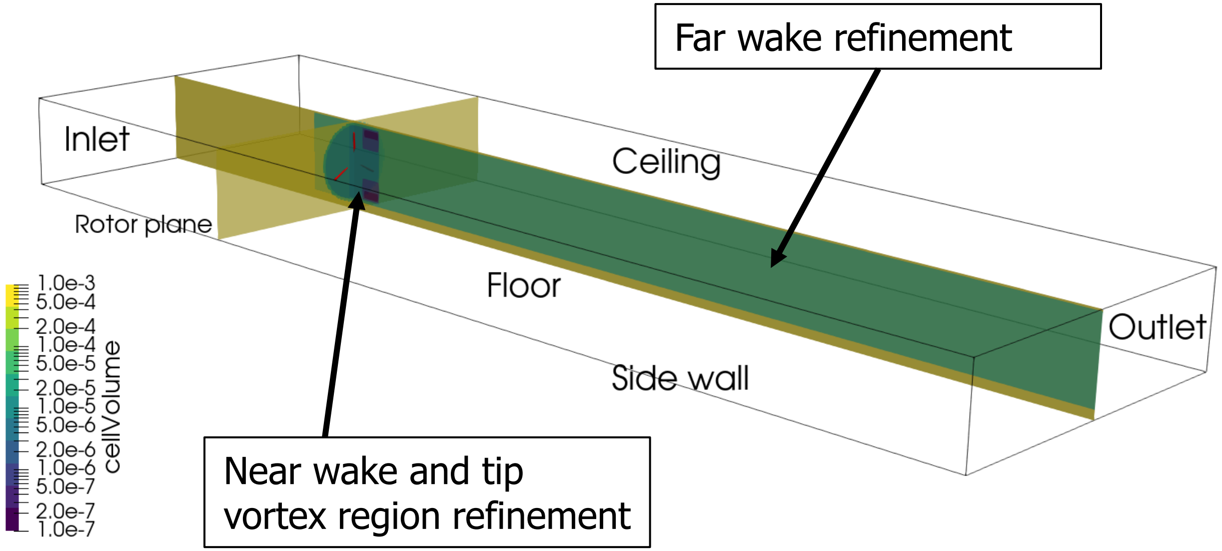
$$x_{surge} = A \sin(\omega t + \phi) \qquad \dot{x}_{surge} = A\,\omega \cos(\omega t + \phi)$$





Pitch platform motion is also implemented with rigid body kinematics, velocities are obtained by time derivation of the displacements.

CFD Setup and validation



- Rotor is modelled, no tower nor nacelle
- Tip and root losses not implemented
- Numerical domain with wind tunnel dimensions
- Blockage effect due to confined environment
- Wind tunnel boundary layer (BL) not modelled: slip-wall condition on lateral boundaries. The domain height is reduced by BL displacement thickness.
- Constant inflow velocity U_0=4 m/s
- Inflow Turbulence intensity TI=2%

ALM-CFD parameters:

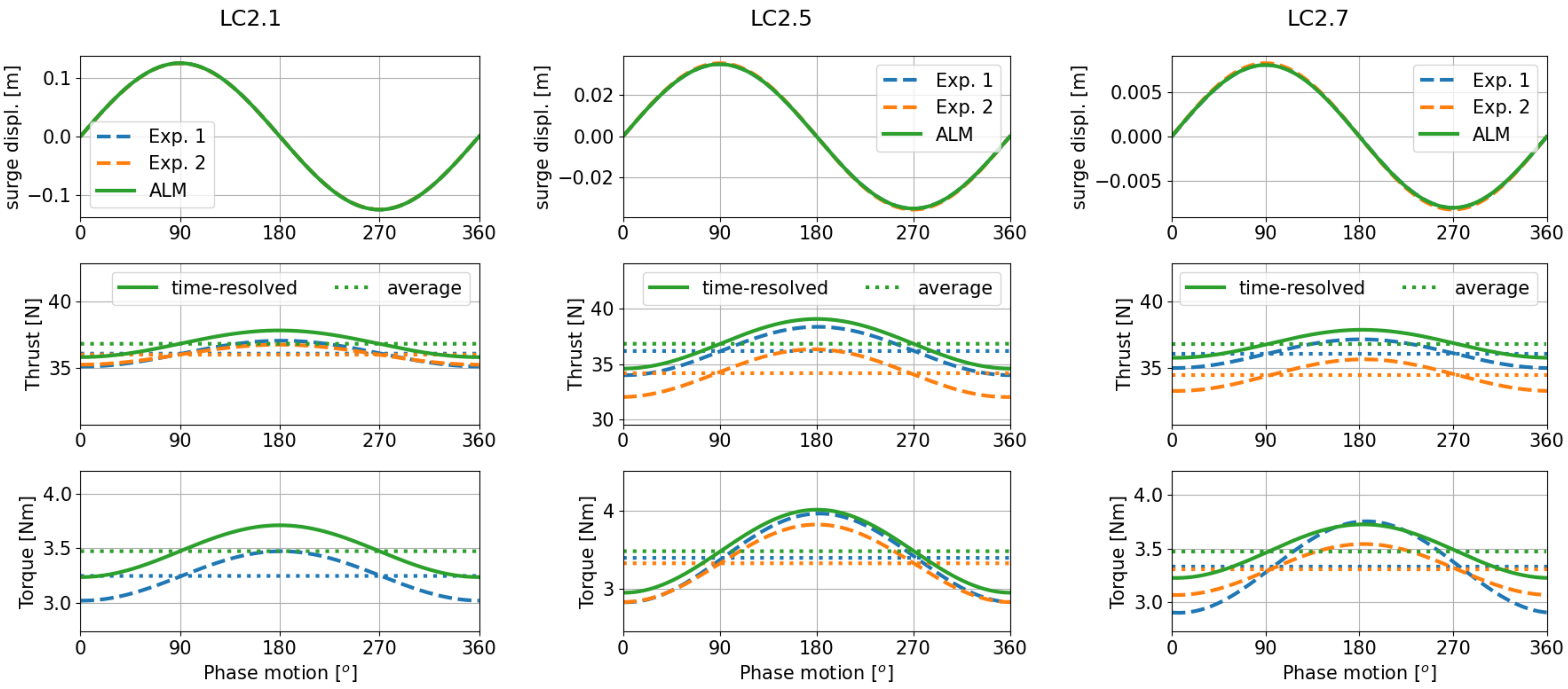
- ε/Δx =2 to avoid numerical instability[3]
- average number of actuator line points 75
- time-marching U-RANS with time step Δt=$5 \cdot 10^{-4}$ s
- Runtime of 10 s (40 revolutions) simulated time: 26 clock hours

LC1.1	ALM	Exp. 1	%error Exp.1	Exp. 2	%error Exp.2
Thrust [N]	36.89	35.91	+2.72	33.68	+9.52
Torque [Nm]	3.49	3.32	+5.14	3.23	+8.17

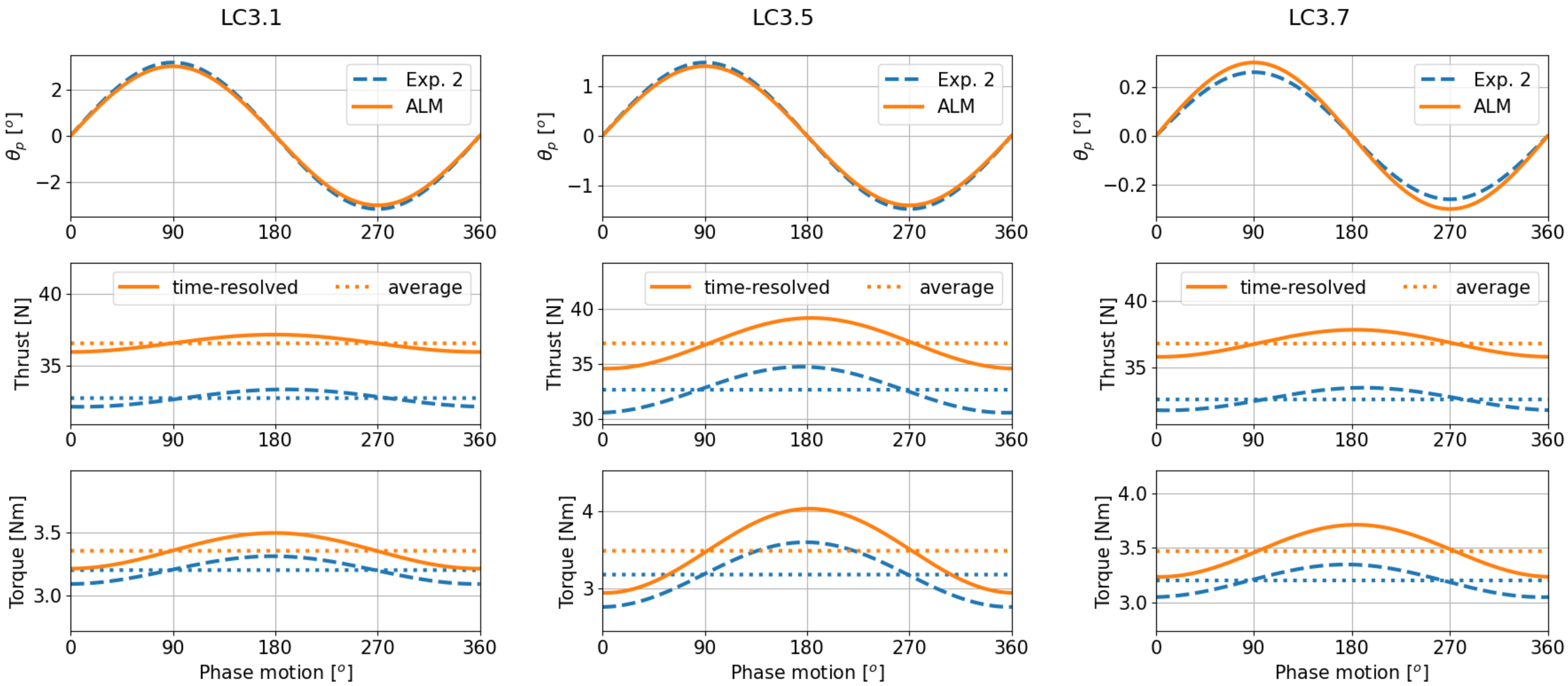
Higher discrepancies for torque: the tip losses are impactful.

[3] Troldborg, N., "Actuator Line Modeling of Wind Turbine Wakes", PhD Thesis, Technical University of Denmark, Lyngby, Denmark, 2008.

FOWT – Surge Platform Motion



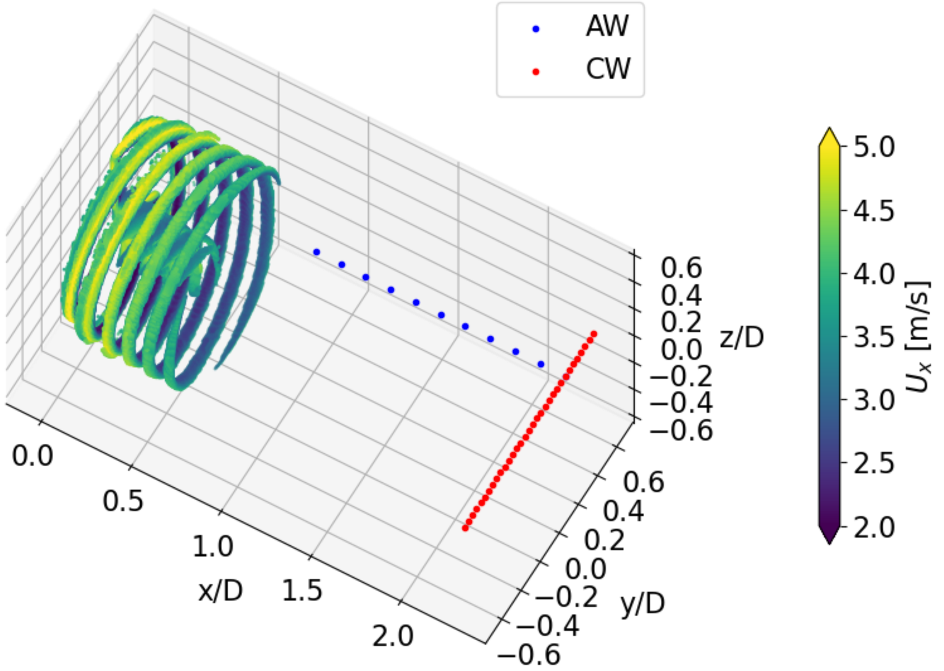
FOWT – Pitch Platform Motion



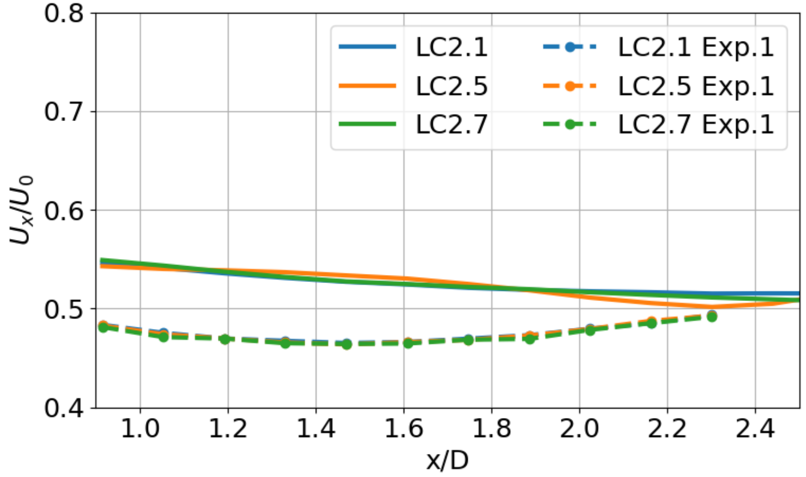
Wake analysis

$$wake\ deficit = \frac{1}{\sum_i^n |r_i|} \sum_{i=1}^{n} |r_i| (U_{x_i} - U_0)$$

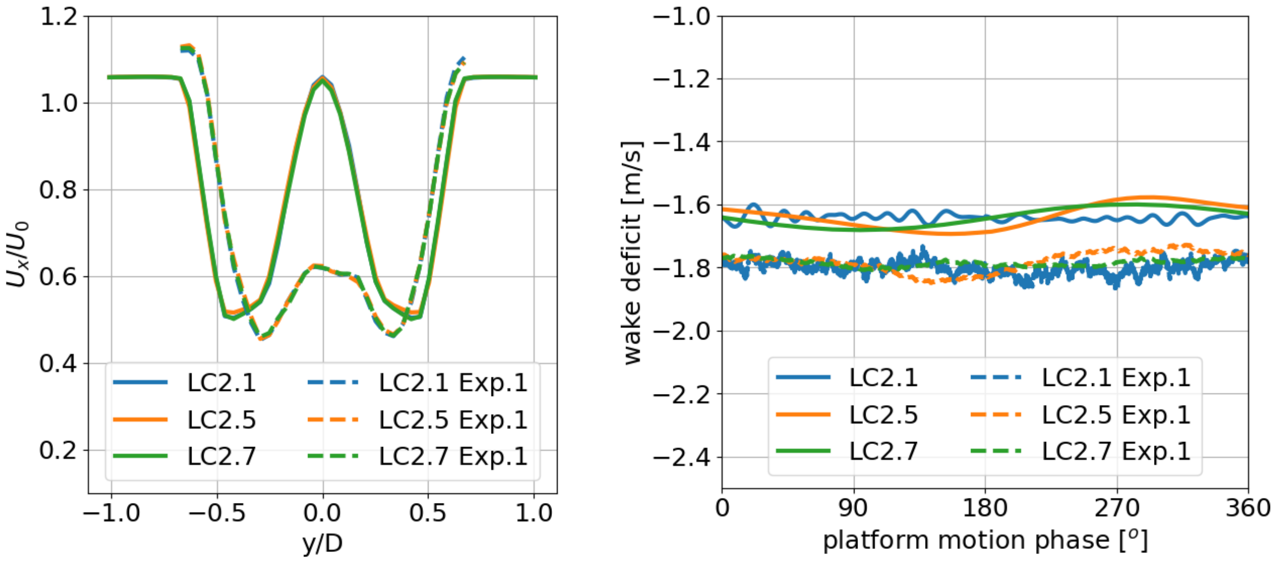
n = number of probes



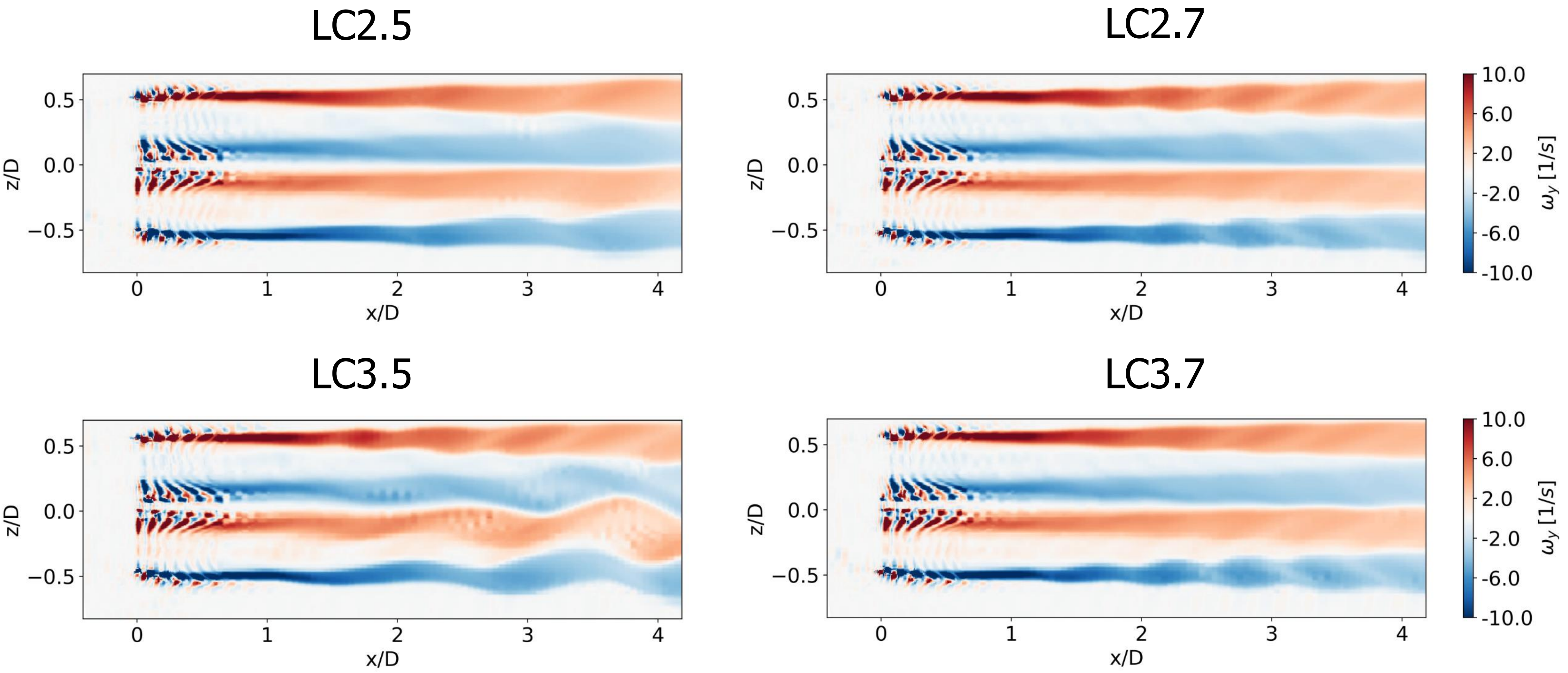
Hot wire Along-Wind (AW)



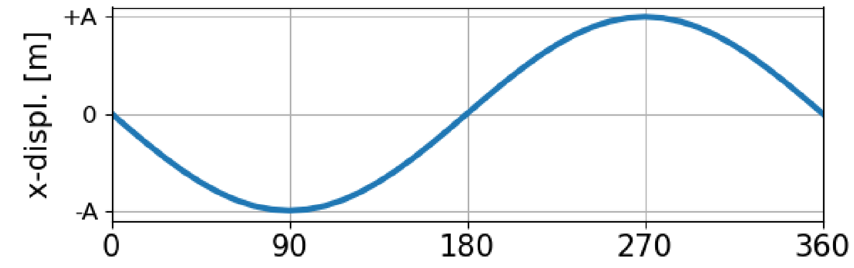
Hot wire Cross-Wind (CW)

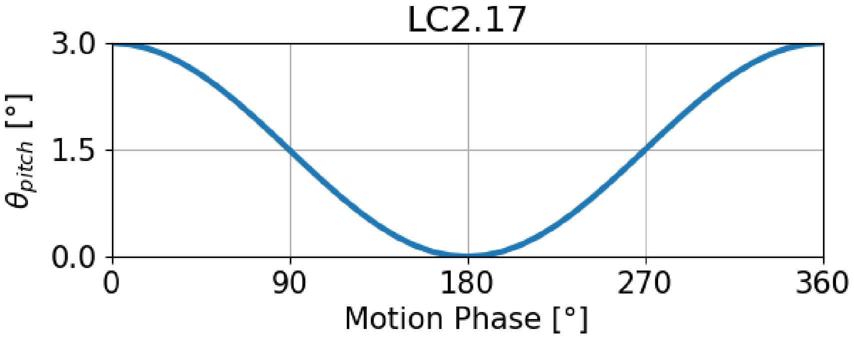


Flow Field – Vorticity



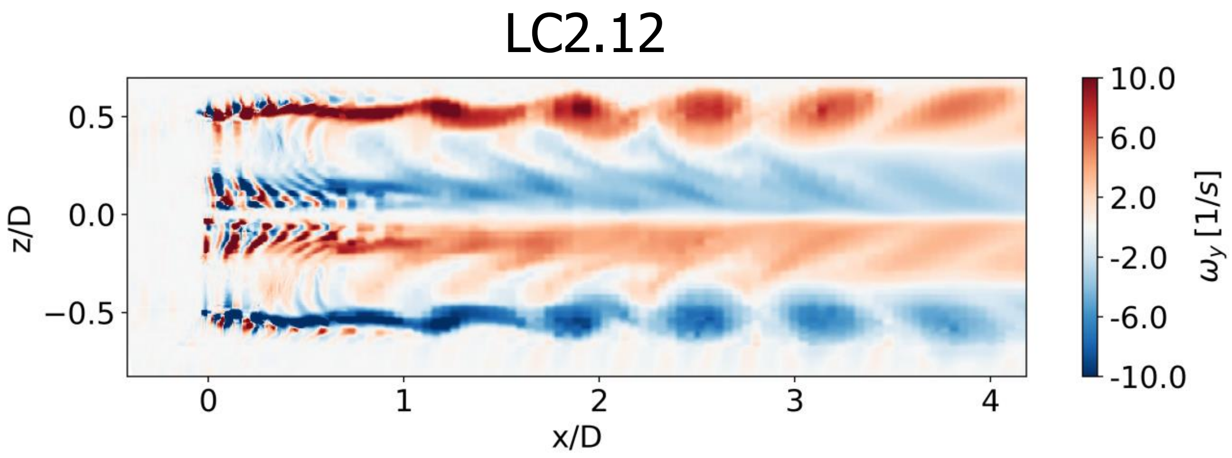
Dynamic Inflow

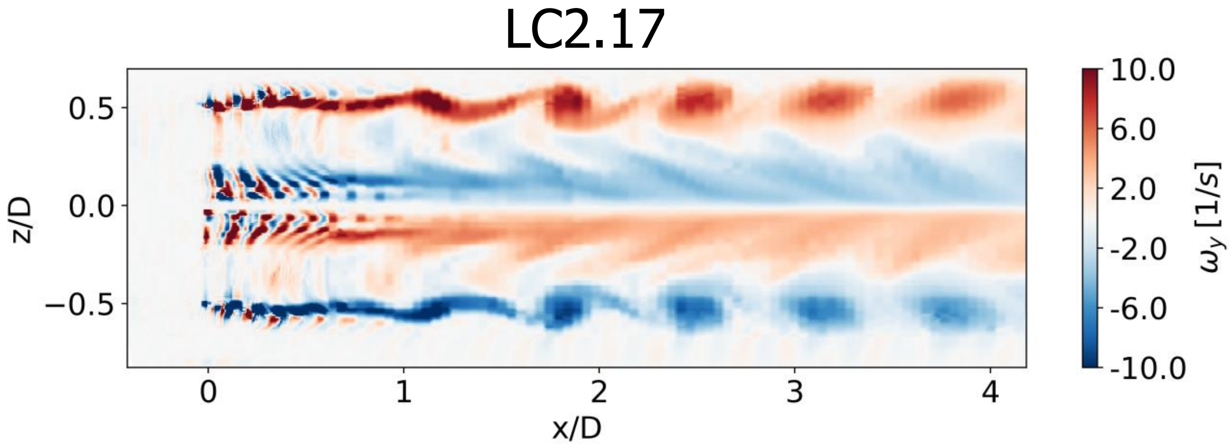


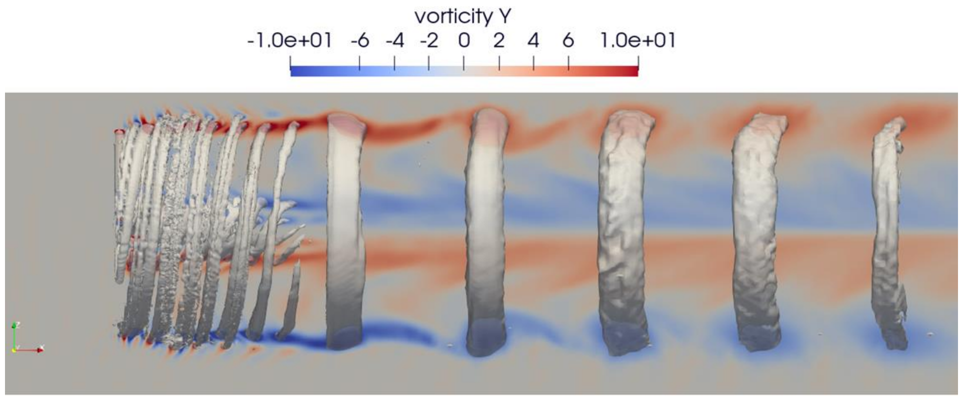


	Load Case	f [Hz]	A [m]	Ω [rpm]	θ_{pitch} [°]
Surge	LC2.12	2	0.08	240	0
	LC2.17	2	0.08	240	1.5±1.5

Tip vortex pairing occurs at higher surge platform displacements





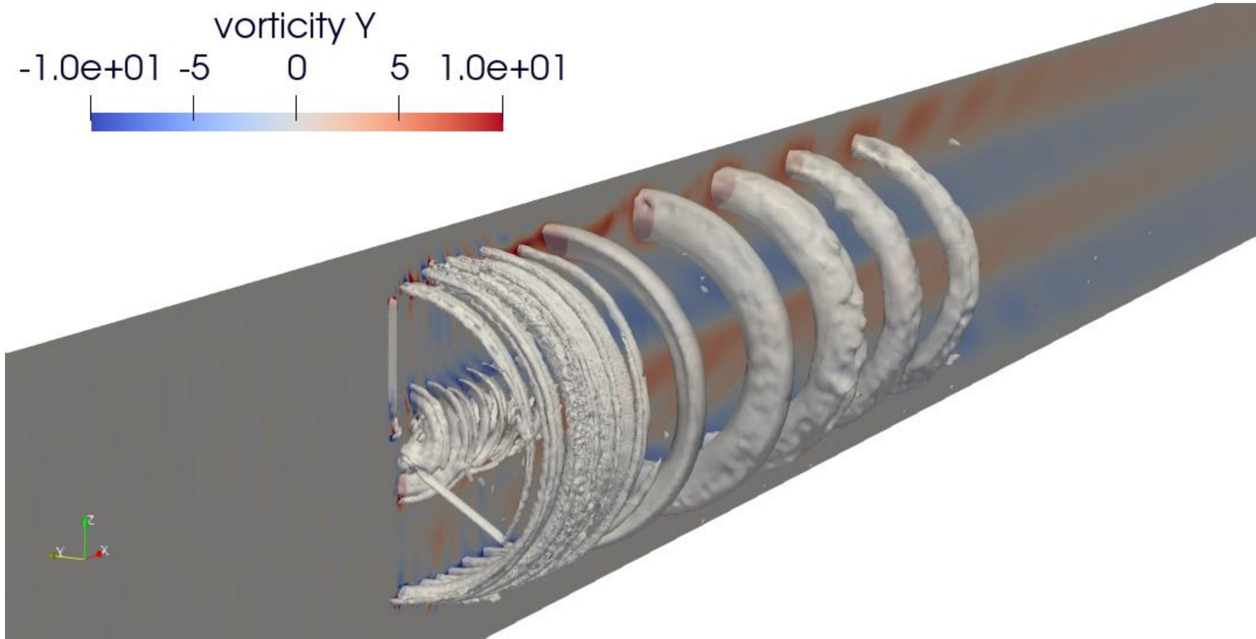


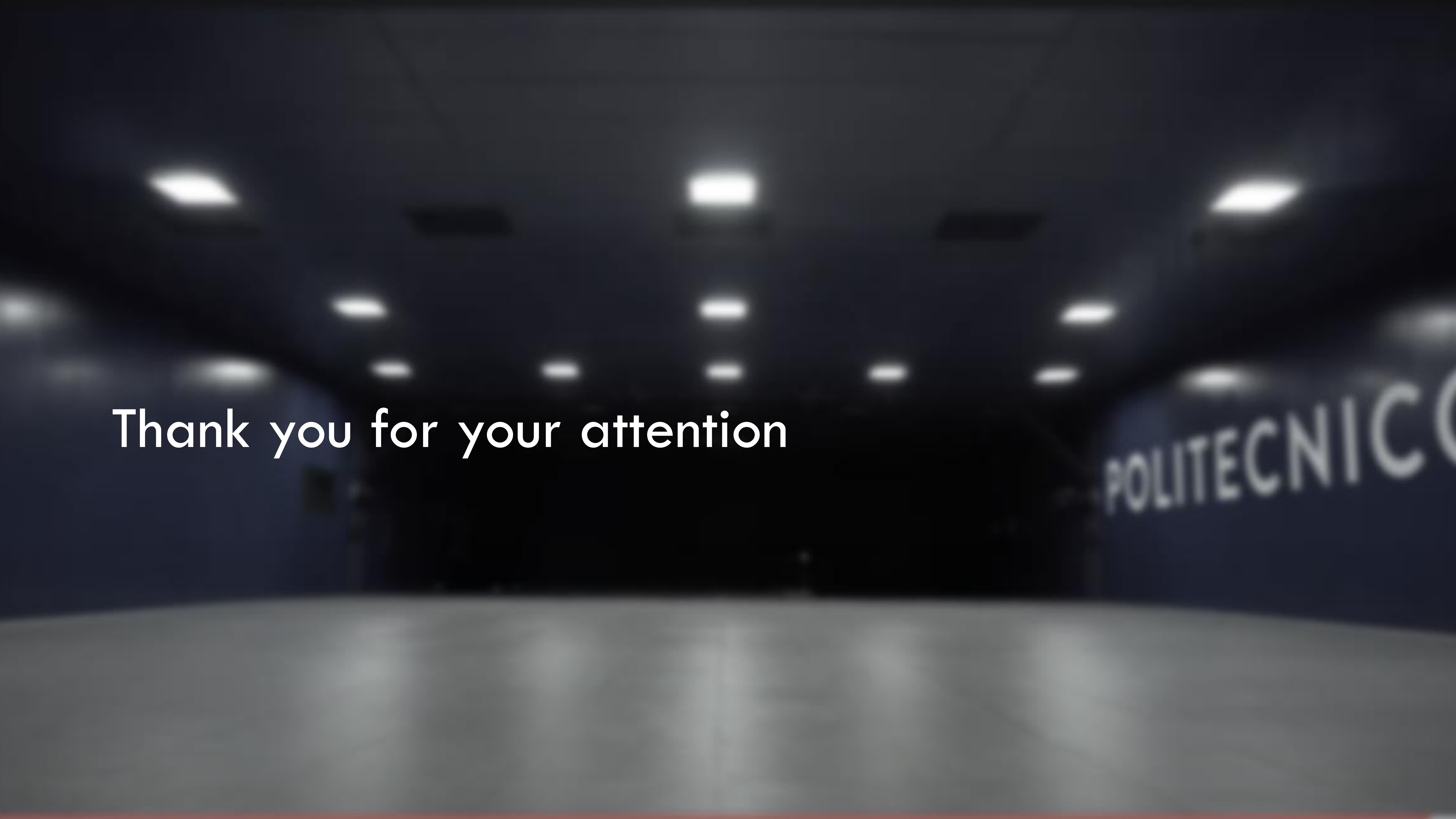
Conclusions

- The in-house ALM provides a reliable tool to simulate FOWTs
- Based on the EVM to assess the angle of attack, the level of mesh refinement at the rotor is limited.
- ALM capability to resolve the wake. ALM can be used for wind farm layout.
- ALM shows wake dynamic modes and mixing.

Future Work

- Development of a rigorous velocity sampling based on circulation designed for FOWTs (in progress).
- Tip and root loss model can improve ALM predictions.
- LES for wake investigations with POD.

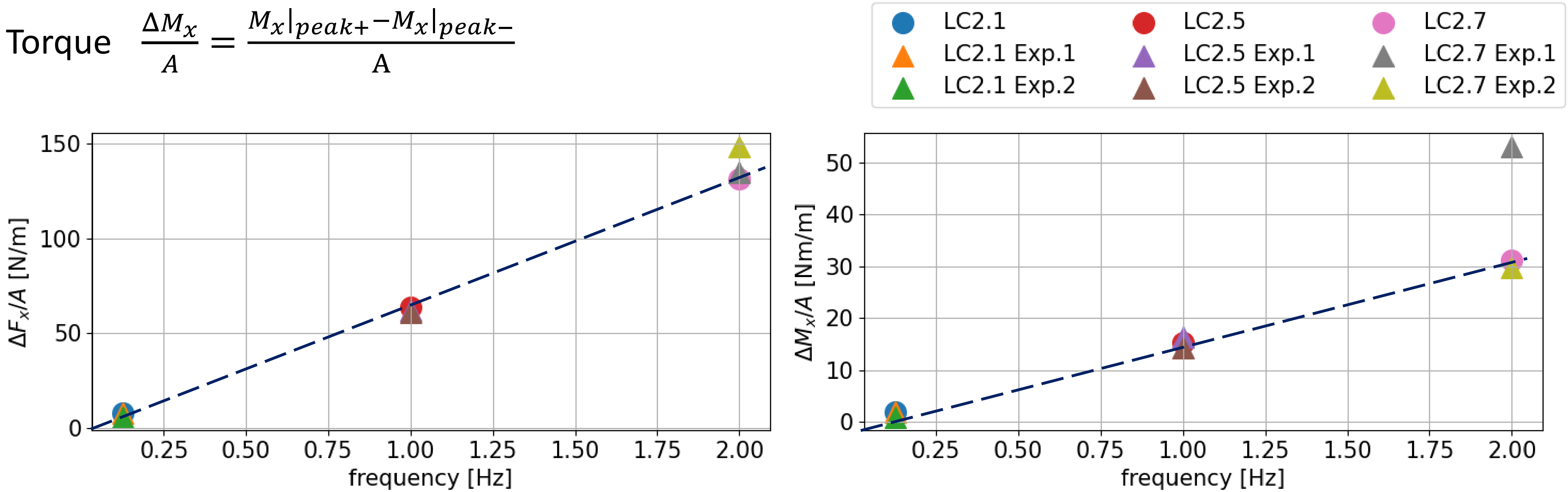



Thank you for your attention

Summary – Surge Load Cases

Thrust $\frac{\Delta F_x}{A} = \frac{F_x|_{peak+} - F_x|_{peak-}}{A}$

Torque $\frac{\Delta M_x}{A} = \frac{M_x|_{peak+} - M_x|_{peak-}}{A}$

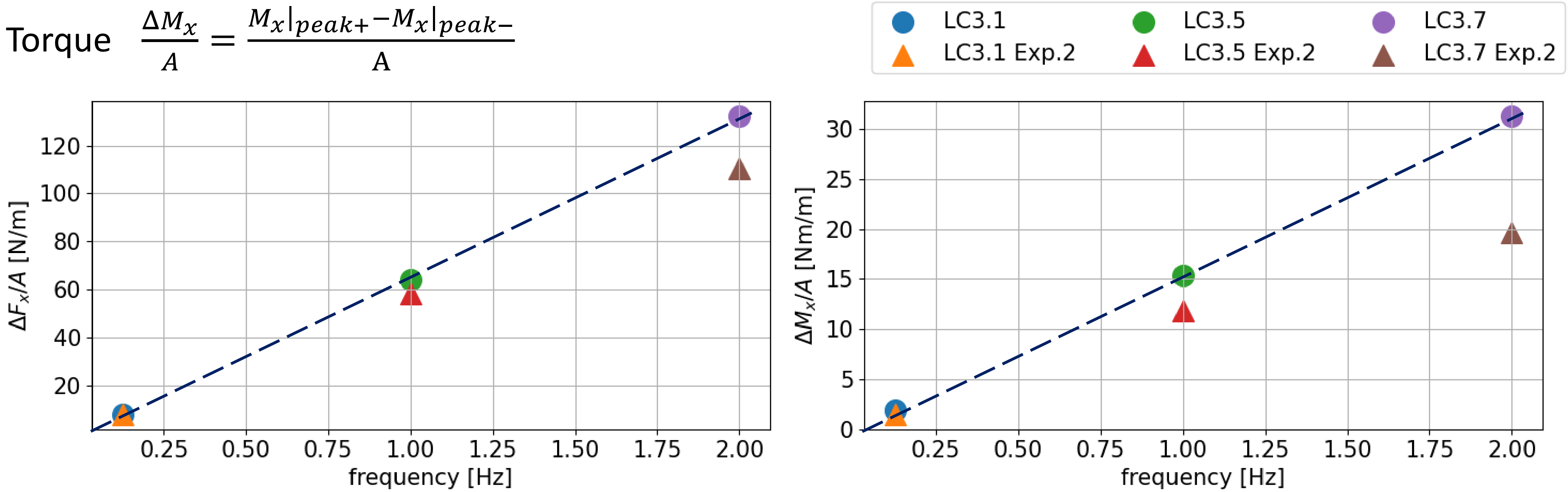


- Quasi-steady behaviour for surge motion.
- ALM agreement with thrust amplitudes of experiments, mean values overpredicted as in steady case LC1.1
- Torque amplitude discrepancies in experiments: mass imbalances during tests

Summary – Pitch Load Cases

Thrust $\frac{\Delta F_x}{A} = \frac{F_x|_{peak+} - F_x|_{peak-}}{A}$

Torque $\frac{\Delta M_x}{A} = \frac{M_x|_{peak+} - M_x|_{peak-}}{A}$



- Quasi-steady behaviour in pitch motion as expected, fit with experiments is lower as frequency increases
- ALM amplitudes in agreement with experiments, mean values overpredicted as in steady case LC1.1
- Torque amplitude discrepancies in experiments: mass imbalances during tests