Advanced Offshore Wind Aerodynamics and Rotor Design

Advanced Design of Offshore Rotors

Funded by the European Union

University of Cyprus
Università degli Studi Firenze
NEEST New Energy & Environmental Solutions and Technologies
Aarhus BSS

Speakers

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Outlook of the Webinar

- Part 1: Advanced Design of Offshore Rotors
  - Blade design basics recap
  - Wind Turbines are not static machines
  - Advanced aeroelastic blade design

- Part 2: Recent understanding on floating wind turbine aerodynamics and wakes
  - Are our aeroleastic codes up to the task?
  - Recent insights from experiments and numerical simulations

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Agenda

01 Recap of Basics

How to determine pitch and twist?

02 Basics of WT operation

Recap: Variable speed – variable pitch

03 "Dynamic" wind turbines

Aeroelastic Tailoring

04 Low specific power

A large and slender rotor

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01

Recap of Basics

How to determine pitch and twist?

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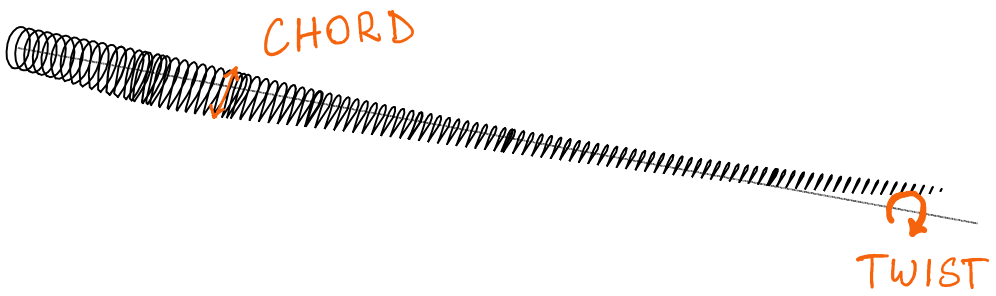
Design Objectives

#1: Optimal rotor force is achived for a=1/3: $F = \frac{4}{9}\rho A U_1^2$

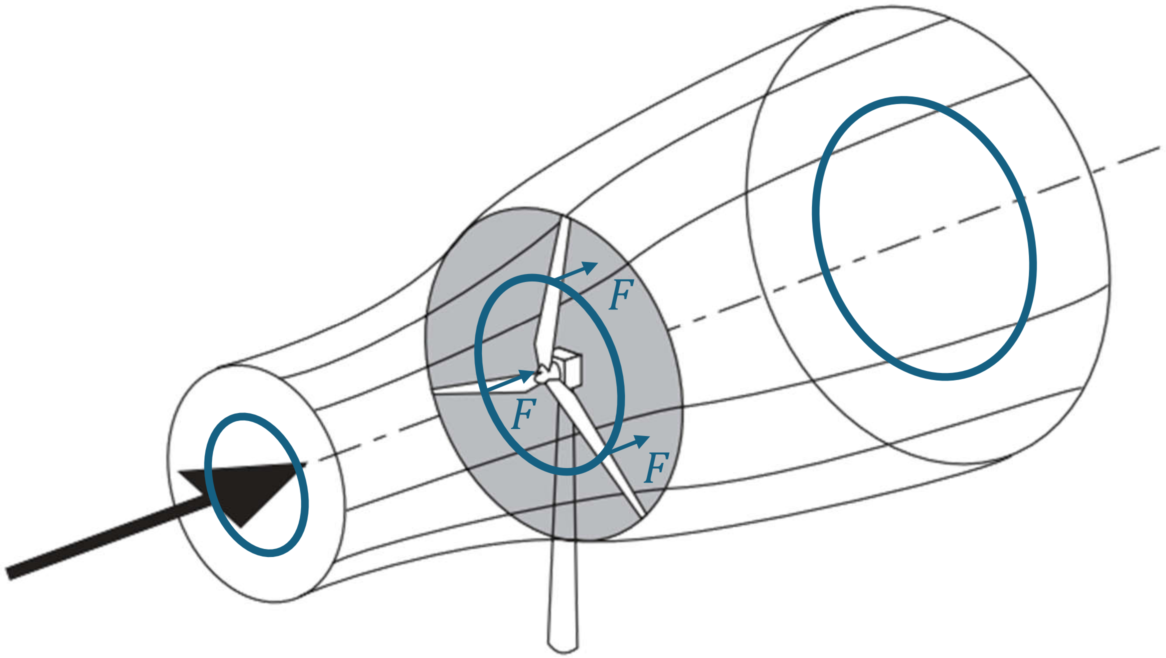
#2: Lift (useful force) to Drag (negative effect) ratio must be maximised

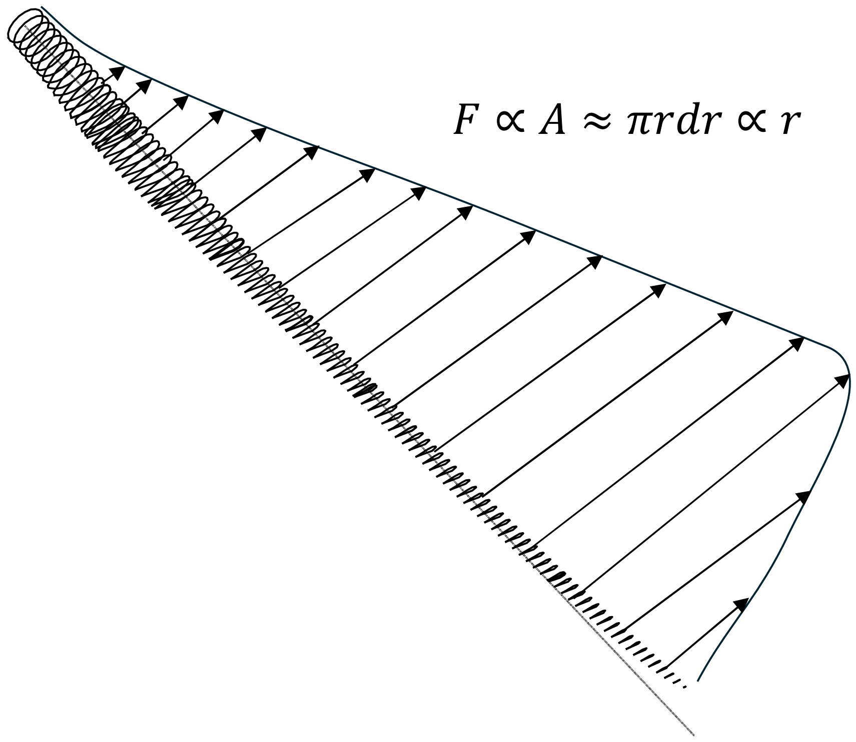
These objectives are applied on a sectional basis to obtain the optimal blade shape



Design Objectives

#1: Optimal rotor force is achived for a=1/3: $F = \frac{4}{9}\rho A U_1^2$

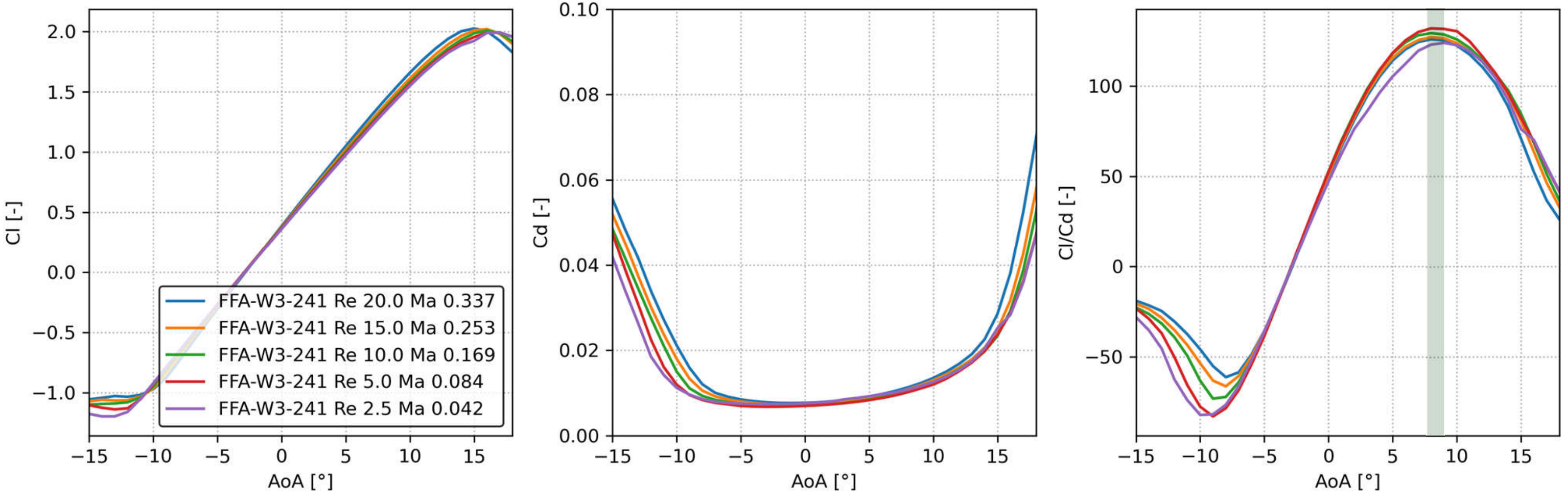




Design Objectives

#2: Lift (useful force) to Drag (negative effect) ratio must be maximised

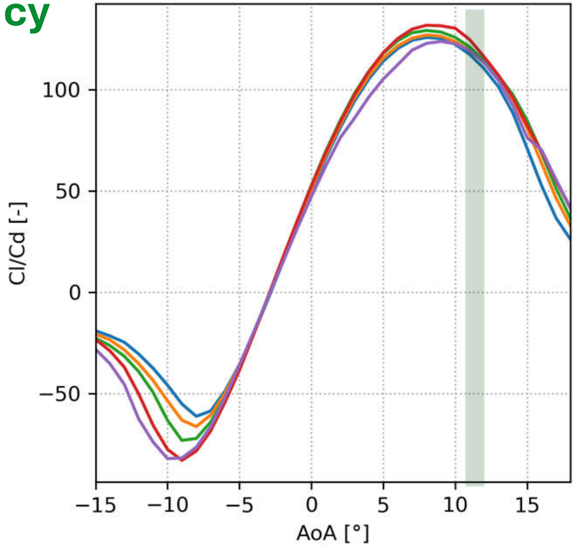
each blade section should operate at the «optimal» AoA for **maximum efficiency**

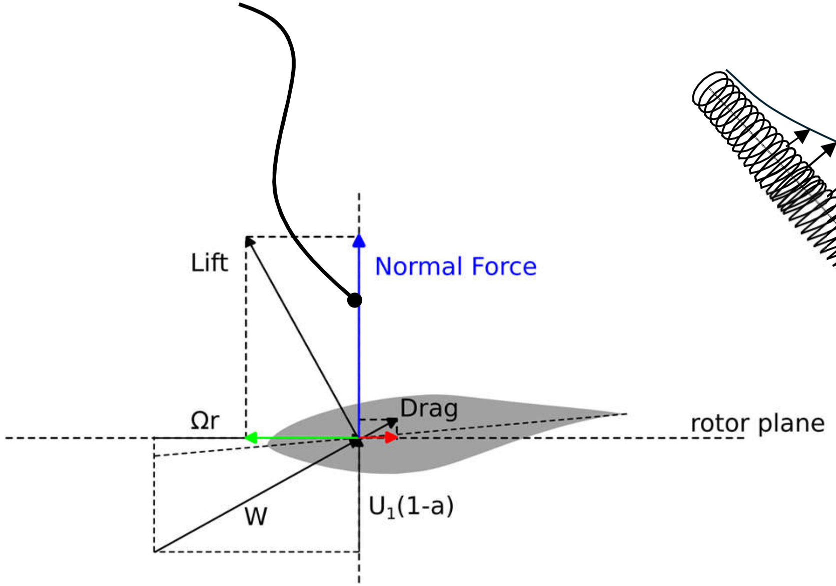


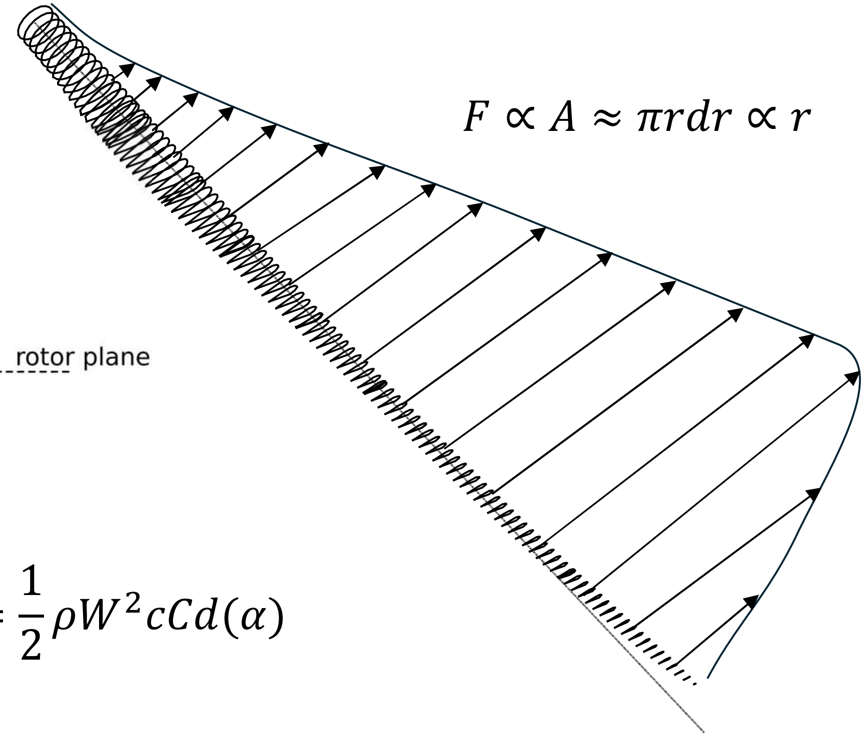
Design Objectives

$$Fn = \frac{1}{2}\rho c W^2 (Cl(\alpha)\cos(\phi) + Cd(\alpha)\cos(\phi))$$

each blade section should operate at the «optimal» AoA for **maximum efficiency**







$$F \propto A \approx \pi r dr \propto r$$

$$Lift = \frac{1}{2}\rho W^2 c Cl(\alpha) \qquad Drag = \frac{1}{2}\rho W^2 c Cd(\alpha)$$

02

Basics of WT operation

Recap: Variable speed – variable pitch

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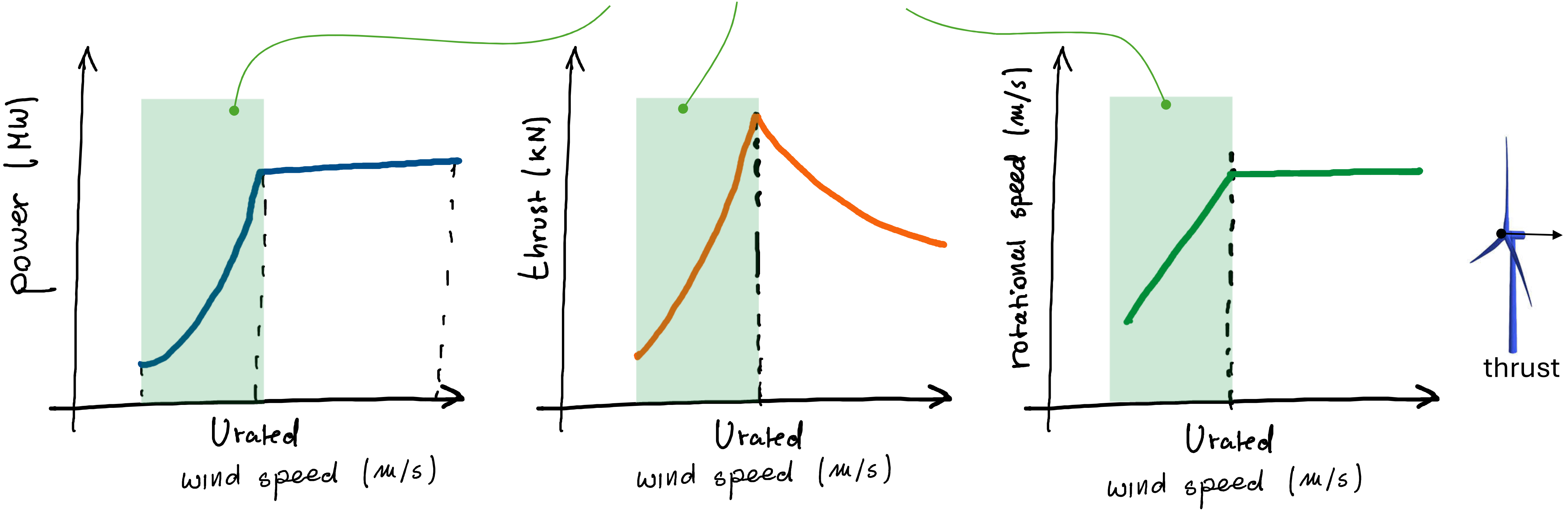
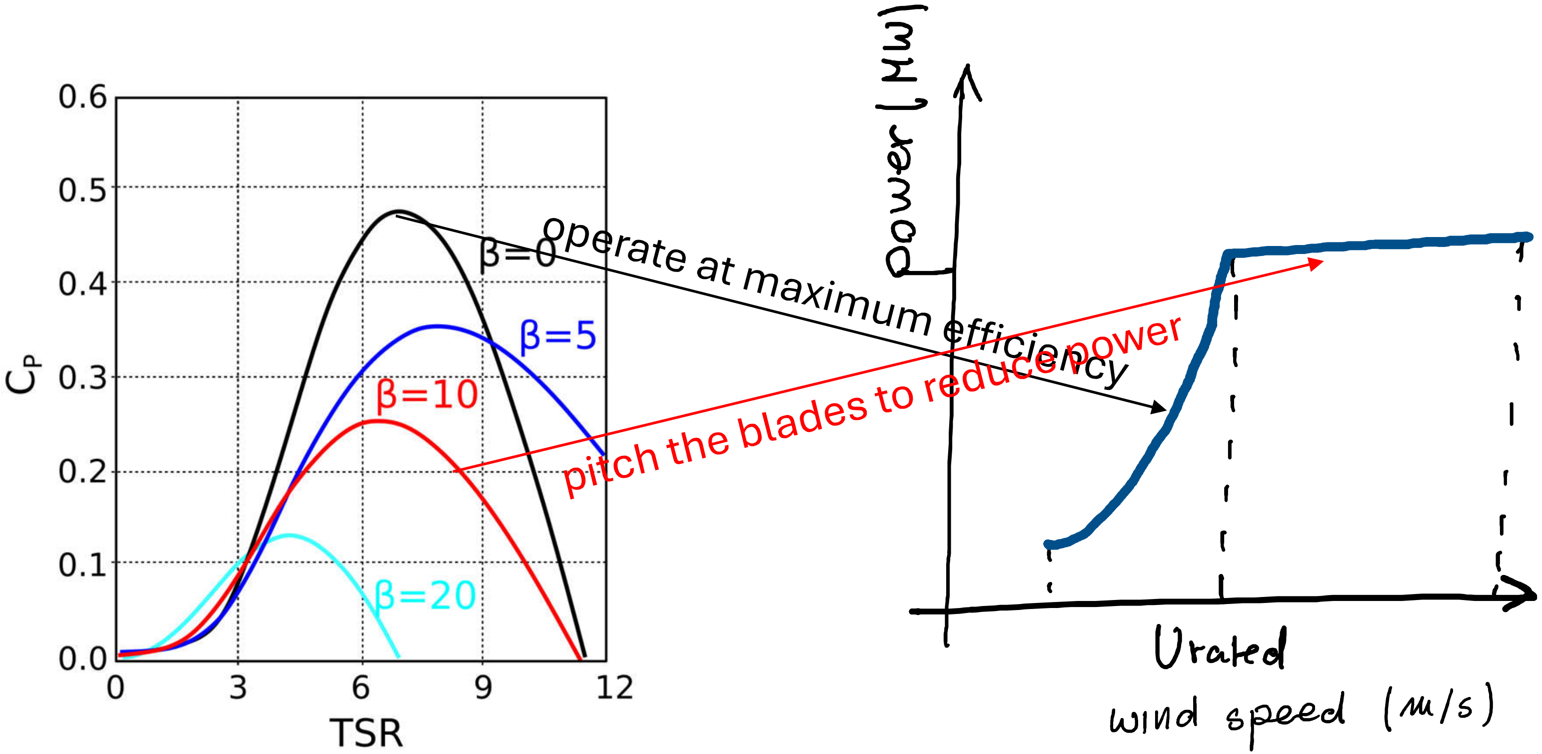
Operational Curves

Efficiency is important between cut-in and rated



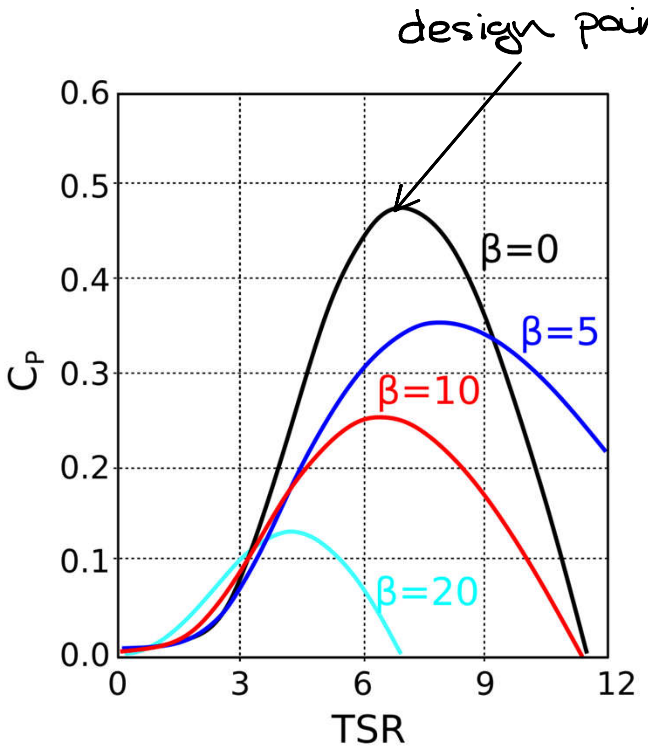
Operational & Performance Curves

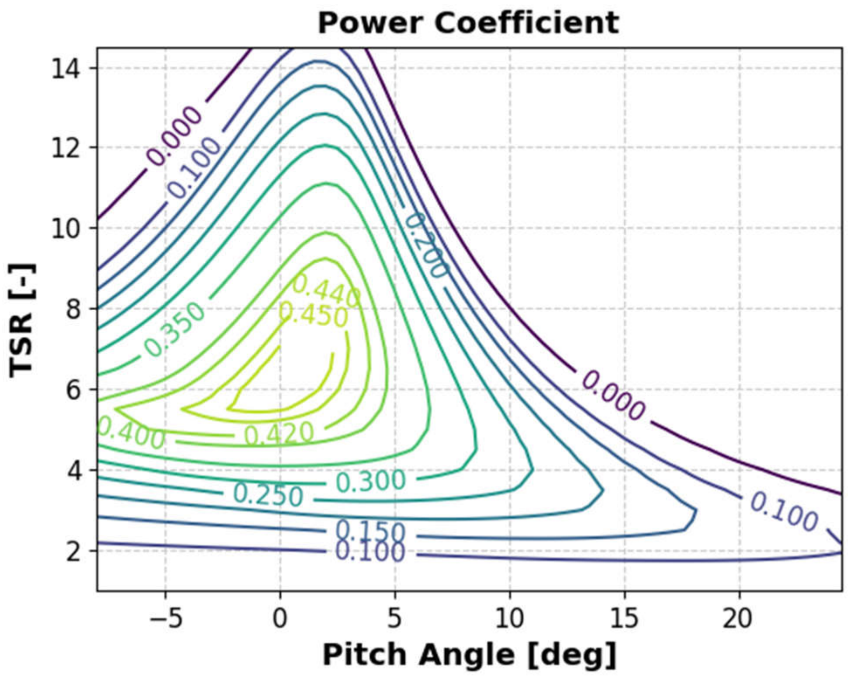
Beyond rated power we pitch the blades to **purposely reduce efficiency**



Performance Curves

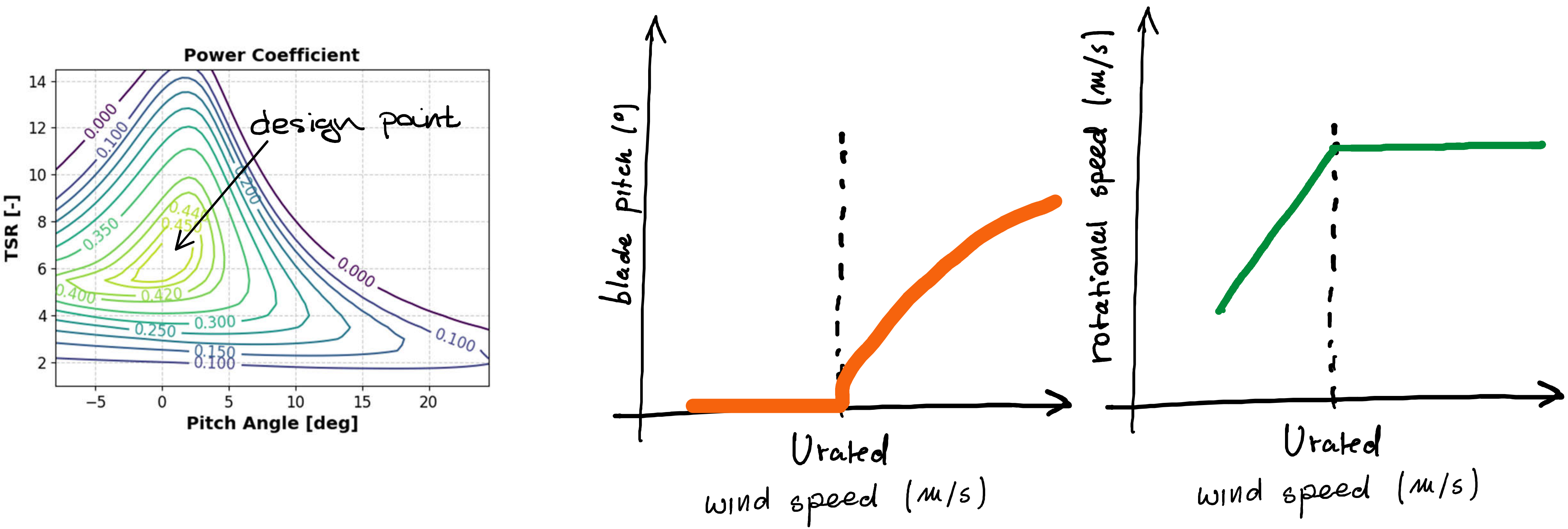
Wind turbine efficiency depends on the tip speed ratio (TSR) and the blade pitch angle (β)





Performance Curves

We operate at constant TSR and blade pitch below rated to stay at the optimal design point



03

“Dynamic” wind turbines

Aeroelastic Tailoring

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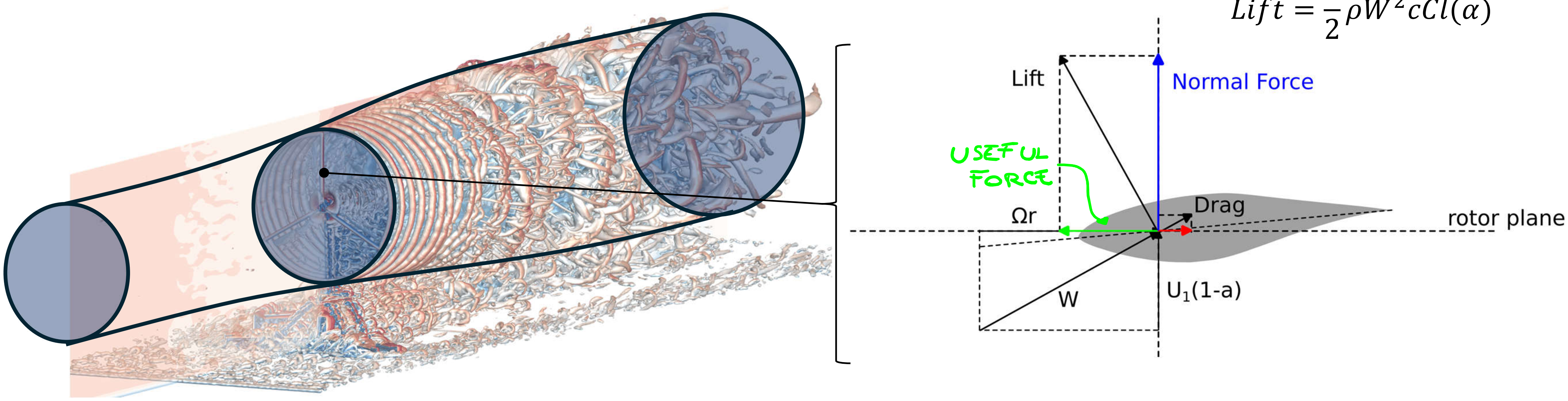
Aeroelasticity

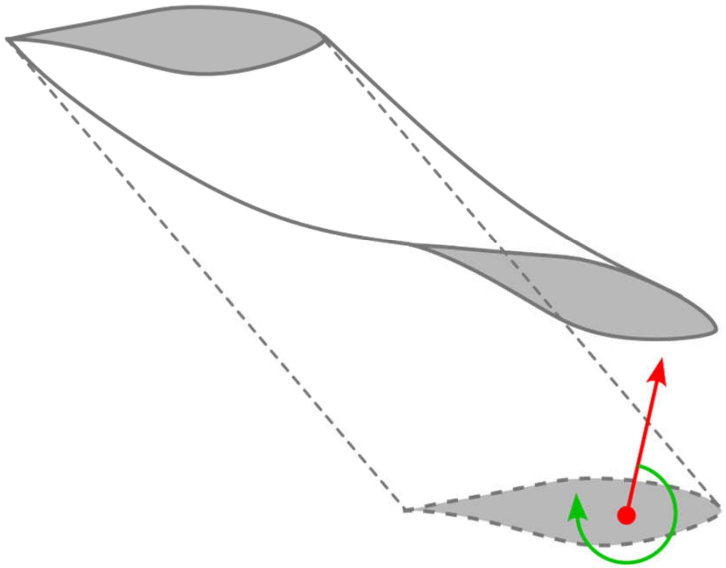
Lift generates an axial force **normal to the rotor**

$$Drag = \frac{1}{2}\rho W^2 c C d(\alpha)$$

$$Lift = \frac{1}{2}\rho W^2 c C l(\alpha)$$



Aeroelasticity

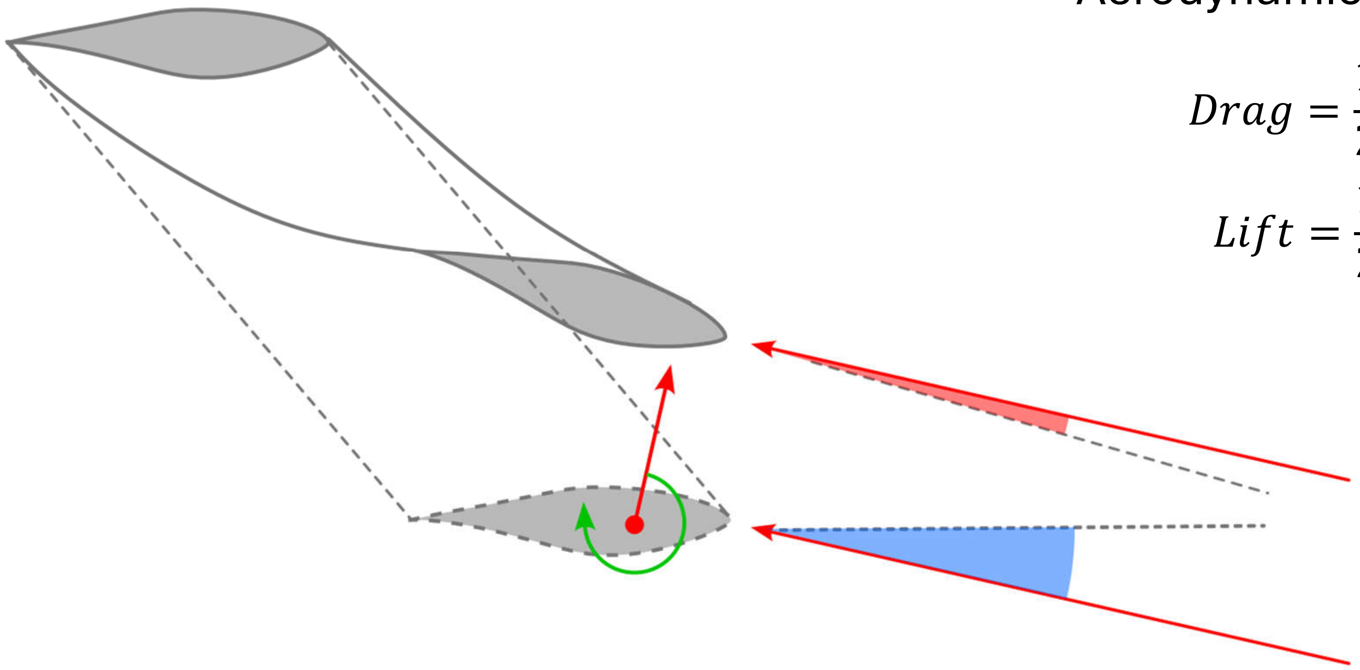


Under the influence of the aerodynamic forces a wind turbine blade is subject to bending and twisting

- lift generated out-of-plane bending
- pitching moment generates twisting

Deformation magnitude depends on aerodynamic load

Effects of Aeroelasticity



If the blade sections twist the flow incidence changes

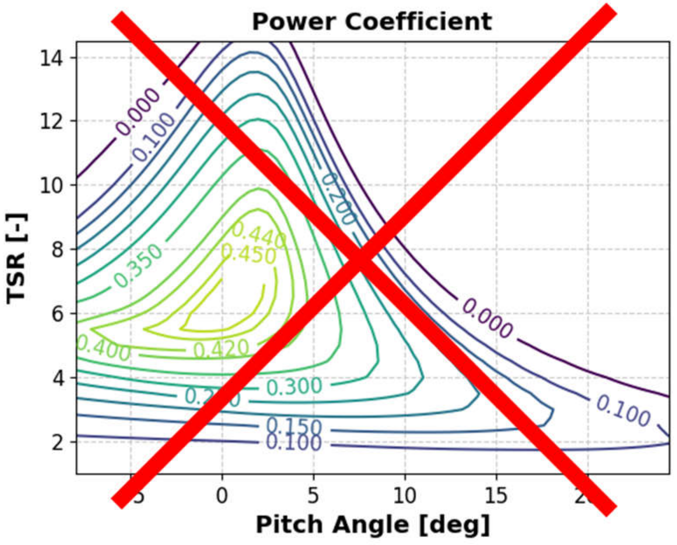
- Aerodynamic forces depend on AoA

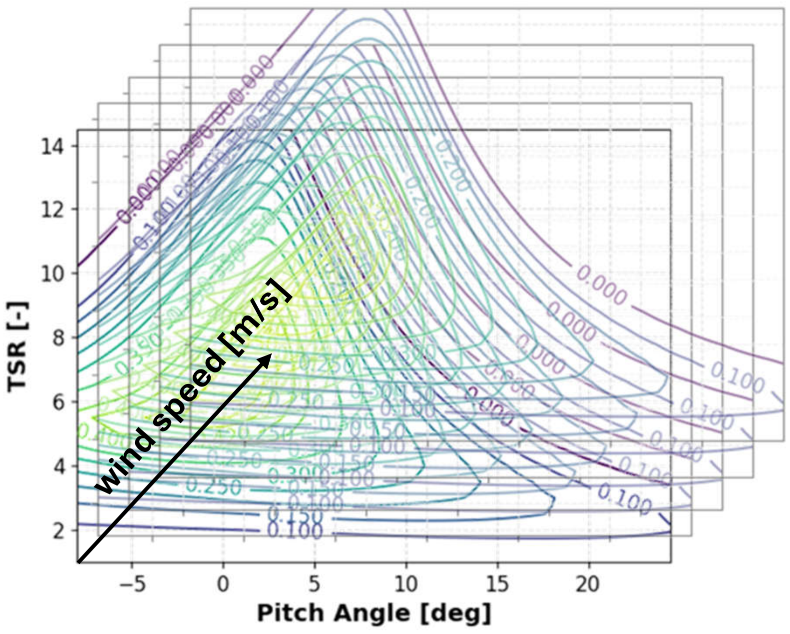
$$Drag = \frac{1}{2}\rho W^2 c Cd(\boldsymbol{\alpha})$$

$$Lift = \frac{1}{2}\rho W^2 c Cl(\boldsymbol{\alpha})$$

Effects of Aeroelasticity

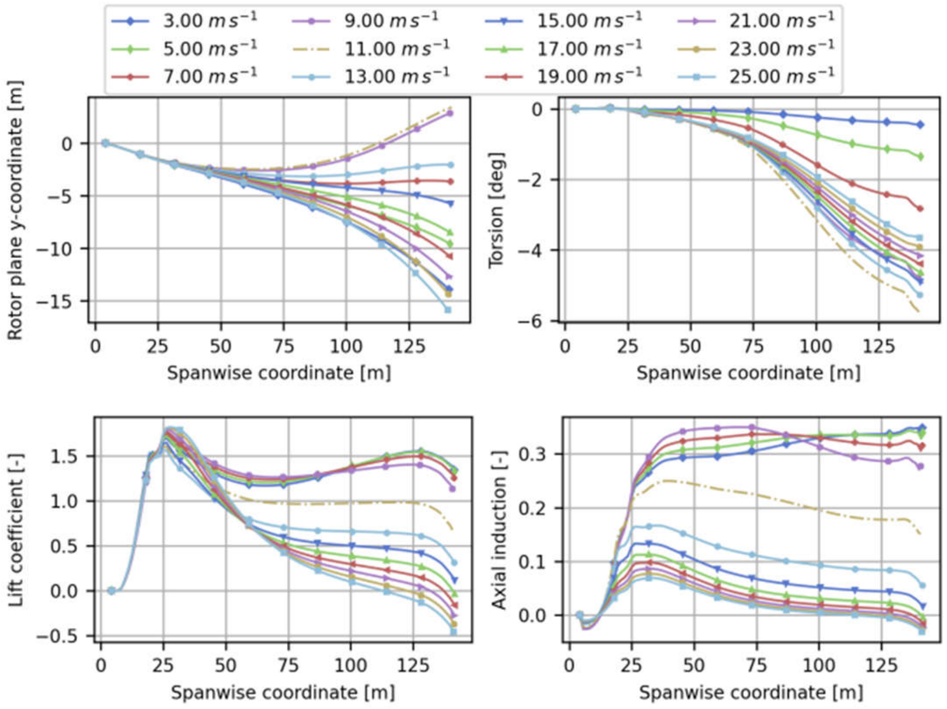
The performance map changes as a function of the aerodynamic load

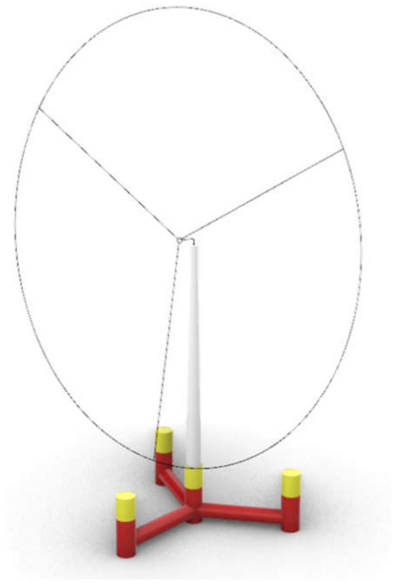




Effects on large modern rotors

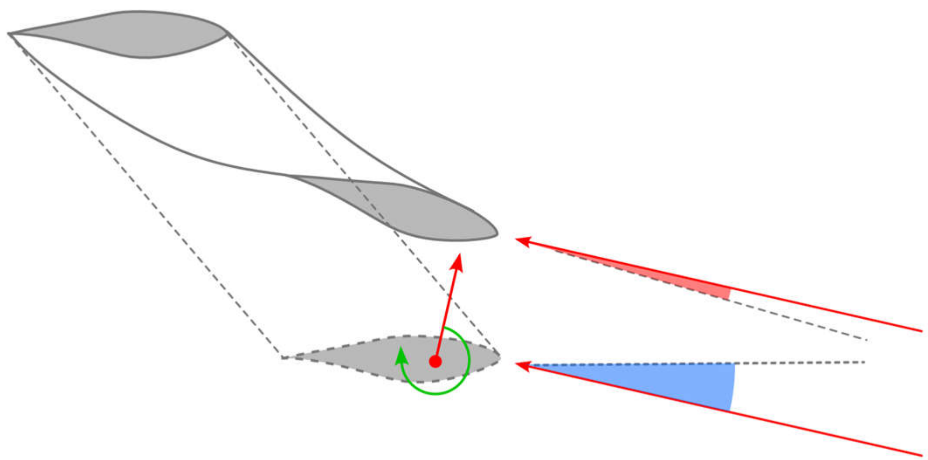
Modern blades can be very slender and very flexible





Zahle, F., Barlas, A., Lønbæk, K., Bortolotti, P., Zalkind, D., Wang, L., Labuschagne, C., Sethuraman, L., & Barter, G. (2024). Definition of the IEA Wind 22-Megawatt Offshore Reference Wind Turbine. Technical University of Denmark. https://doi.org/10.11581/DTU.00000317

Aeroelastic tailoring

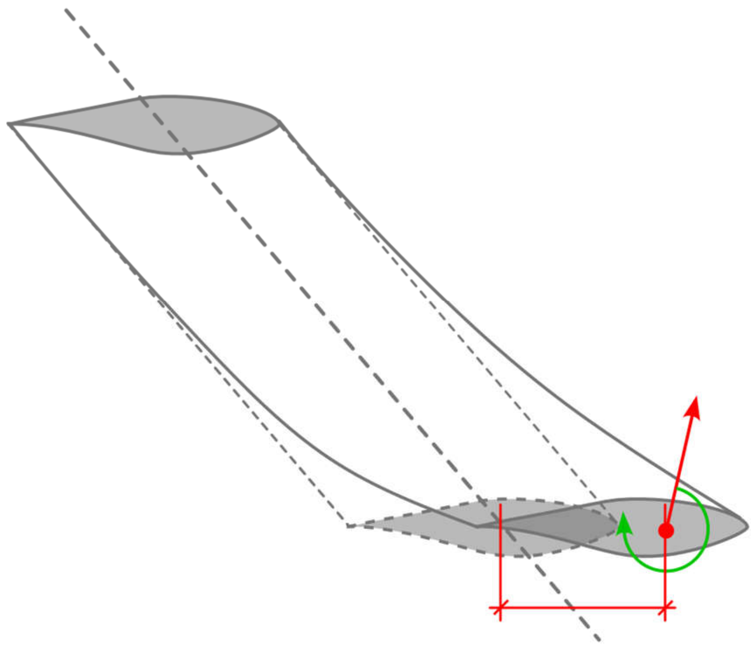


The change in AoA is clearly an **aeroelastic effect**

- It depends on blade deformation

Controlling the deformation to one's desire is aeroelastic tailoring

Aeroelastic tailoring

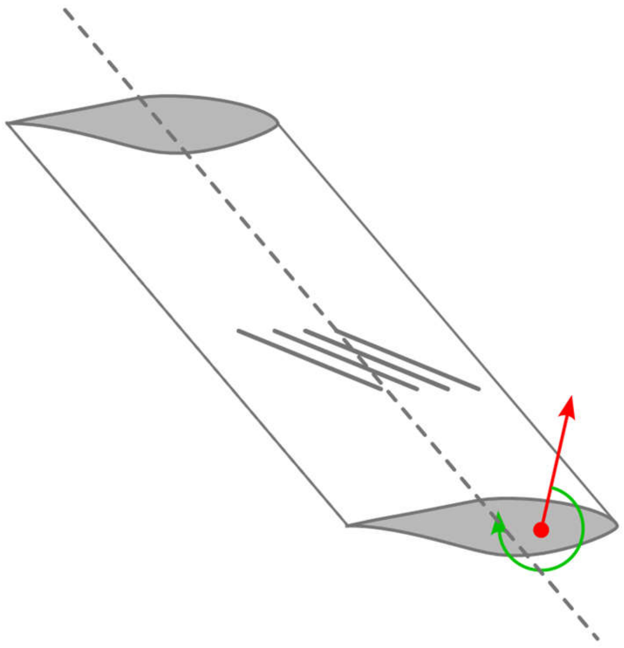


Introducing sweep is a way to influence torsional behavior

- Forward twist pitches the blade towards stall
- Backward twist pitches the blade towards feather

Controlling the deformation to one's desire is aeroelastic tailoring

Aeroelastic tailoring

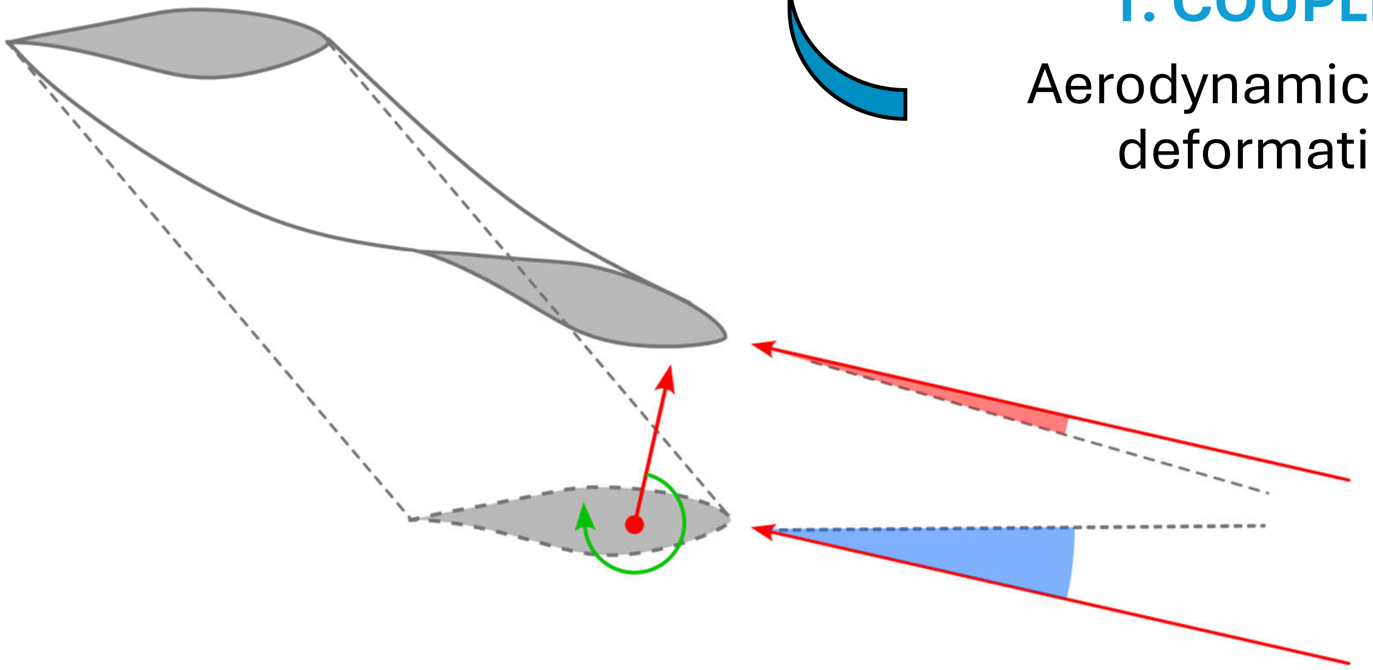


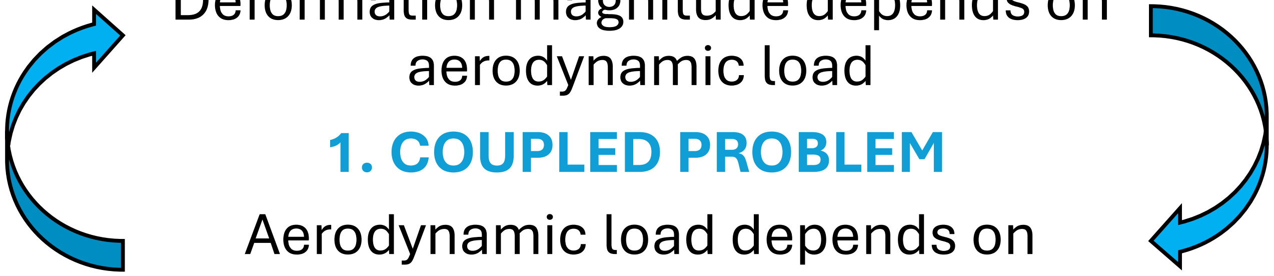
Changing the beam elastic properties also influences the aeroelastic response

- Changing fiber direction in anisotropic composite materials introduce couplings between DOFs
- Changing the position of structural elements inside the blade section introduces couplings between DOFs

Controlling the deformation to one's desire is aeroelastic tailoring

Aeroelastic tailoring





Deformation magnitude depends on aerodynamic load

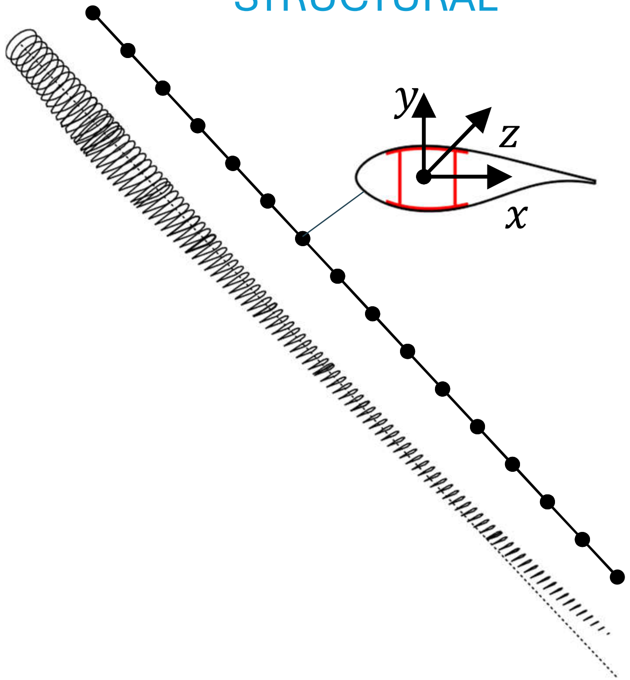
1. COUPLED PROBLEM

Aerodynamic load depends on deformation magnitude

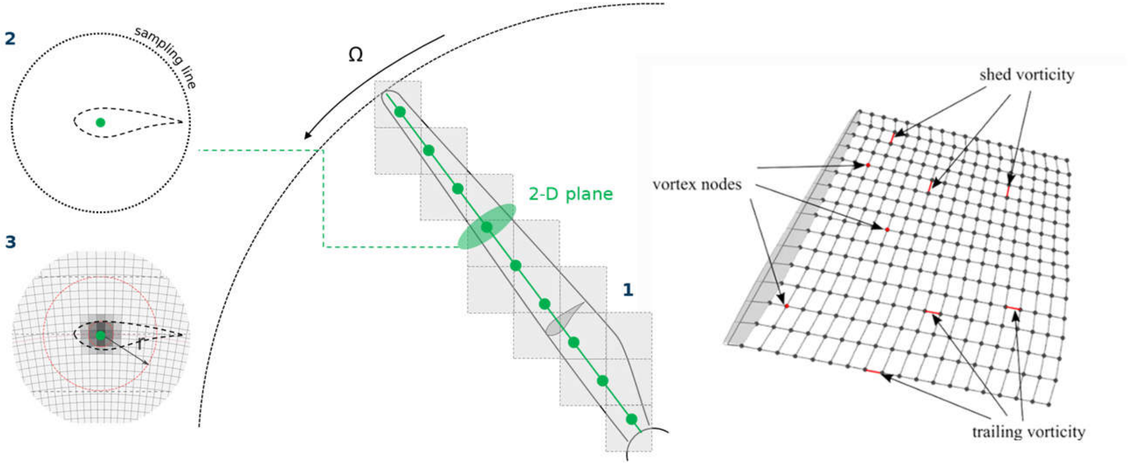
Aeroelastic modelling

- Because WT blades are long and slender they are often modelled as 1D objects
  - A series of “2D” properties are supplied to the 1D beams
  - This is the case for most **aerodynamic models** and **structural models**

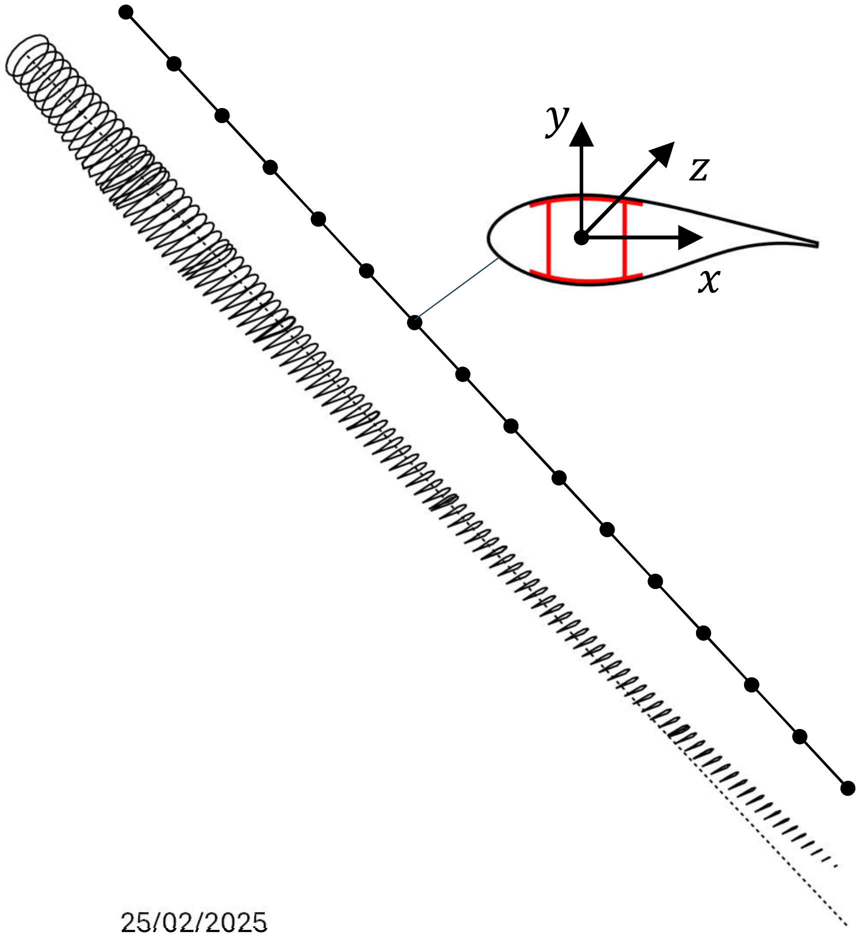
STRUCTURAL



AERODYNAMIC



Beam model



$$M = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & M_{15} & M_{16} \\ & M_{22} & M_{23} & M_{24} & M_{25} & M_{26} \\ & & M_{33} & M_{34} & M_{35} & M_{36} \\ & & & M_{44} & M_{45} & M_{46} \\ & sym & & & M_{55} & M_{56} \\ & & & & & M_{66} \end{bmatrix}$$

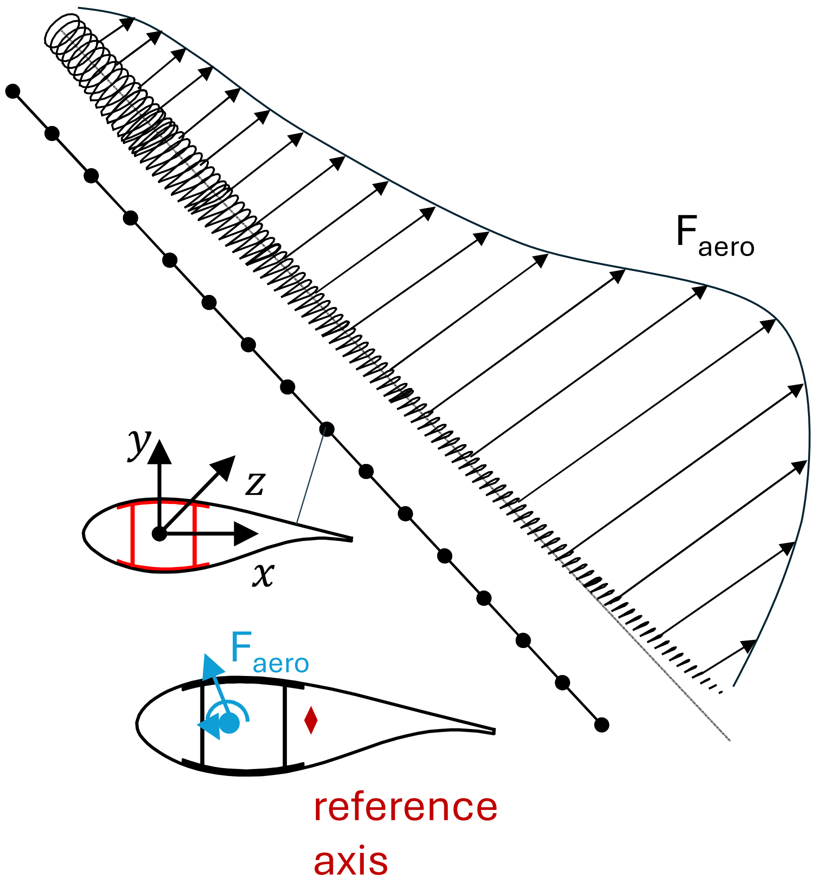
$$K = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} & K_{15} & K_{16} \\ & K_{22} & K_{23} & K_{24} & K_{25} & K_{26} \\ & & K_{33} & K_{34} & K_{35} & K_{36} \\ & & & K_{44} & K_{45} & K_{46} \\ & sym & & & K_{55} & K_{56} \\ & & & & & K_{66} \end{bmatrix}$$

- Euler-Bernoulli beam
- Timoshenko beam
- Fully-coupled beam

$$K\delta + C\dot{\delta} + M\ddot{\delta} = F$$

strains $(\delta_x, \delta_y, \delta_z, \delta_{\theta x}, \delta_{\theta y}, \delta_{\theta z})$

Beam model – coupled effects



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- shear-twist coupling
- bend-twist couping

$$K\delta + C\dot{\delta} + M\ddot{\delta} = F$$

strains

04

Low specific power

A large and slender rotor

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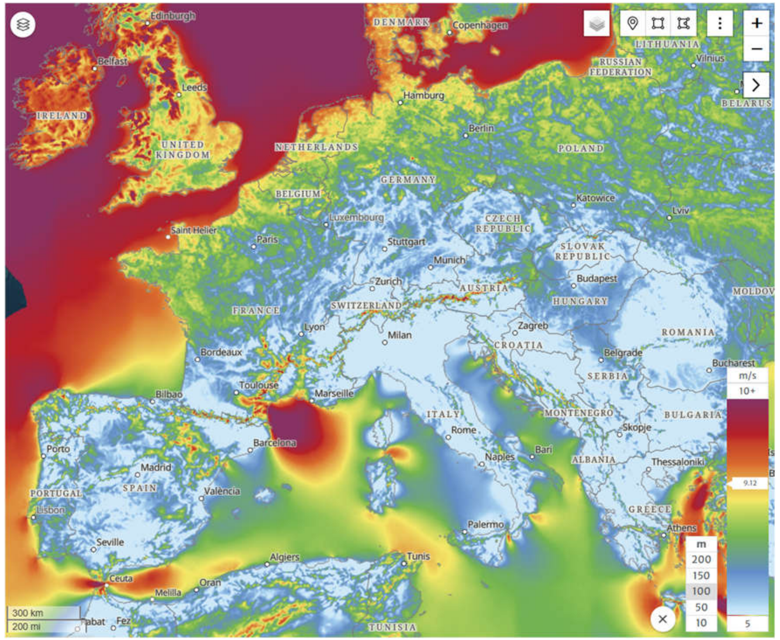
Not all offshore sites are perfect

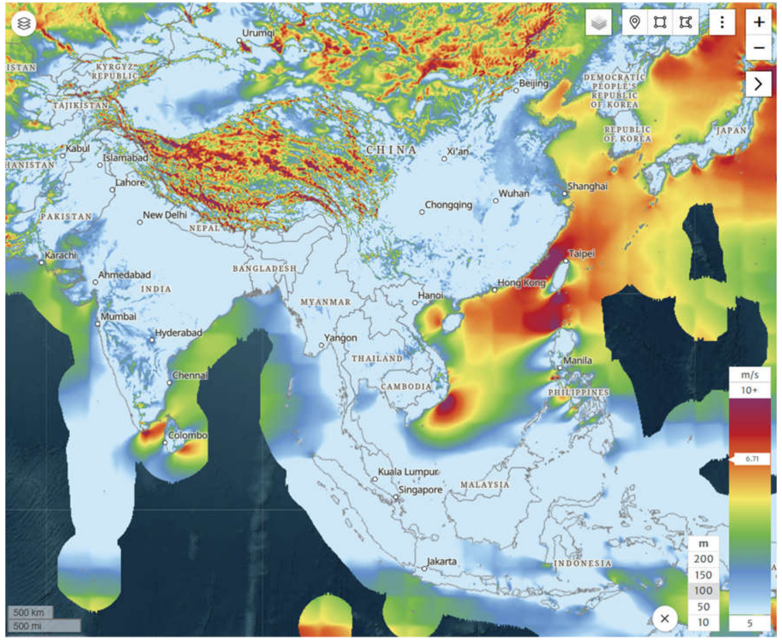
...but the best winds are still offshore!

Floating wind can help decarbonize countries where the wind resource is not ideal

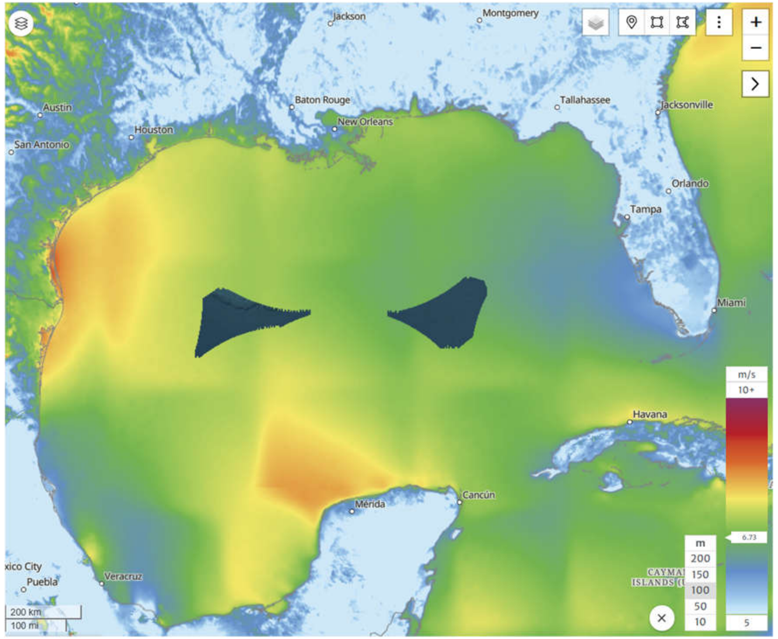
Europe



South-east Asia



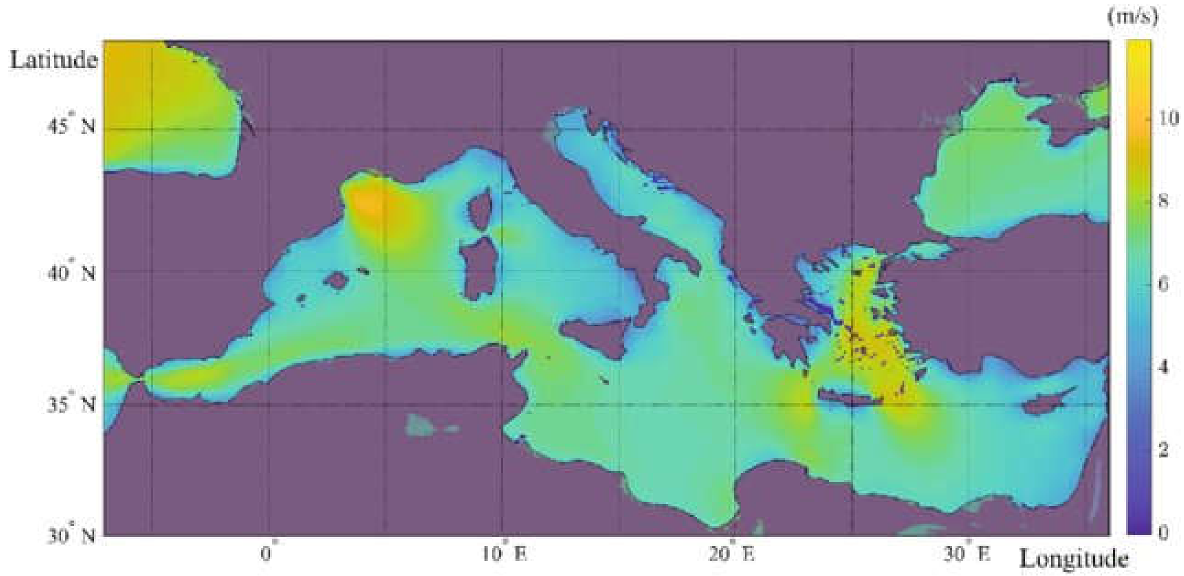
Florida & Gulf of Mexico



[Data/information/map] obtained from the Global Wind Atlas version 4.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU). The Global Wind Atlas version 4.0 is released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP). For additional information: https://globalwindatlas.info

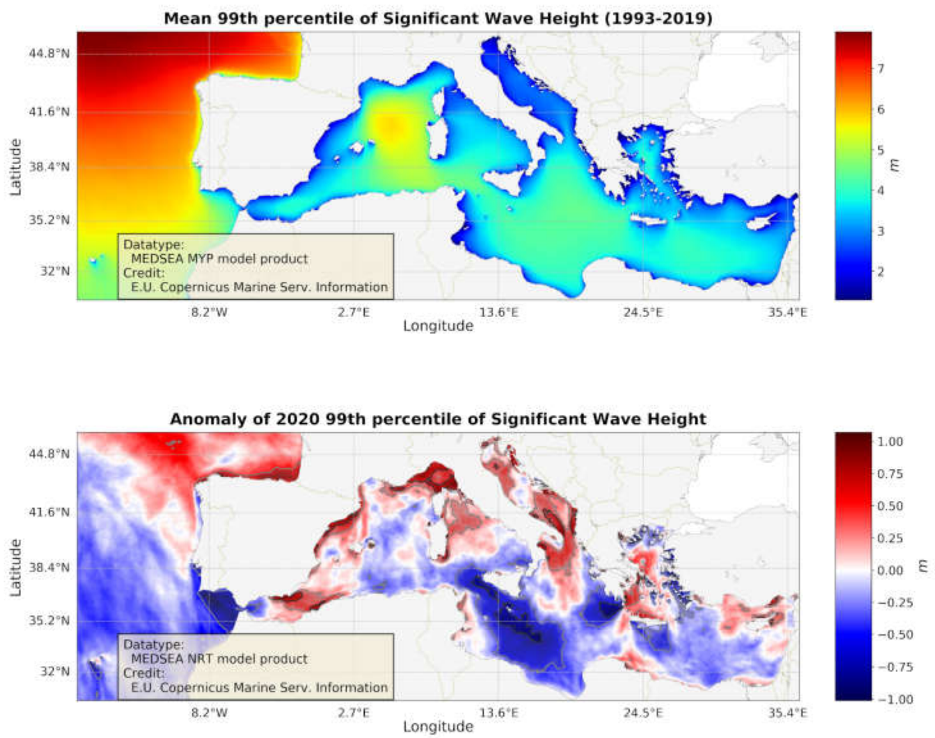
With lower winds also come lower waves?

a spotlight on the Mediterranean Sea



DOI: 10.1016/j.enconman.2021.114416

Mediterranean Sea wave height extreme variability mean and anomaly.

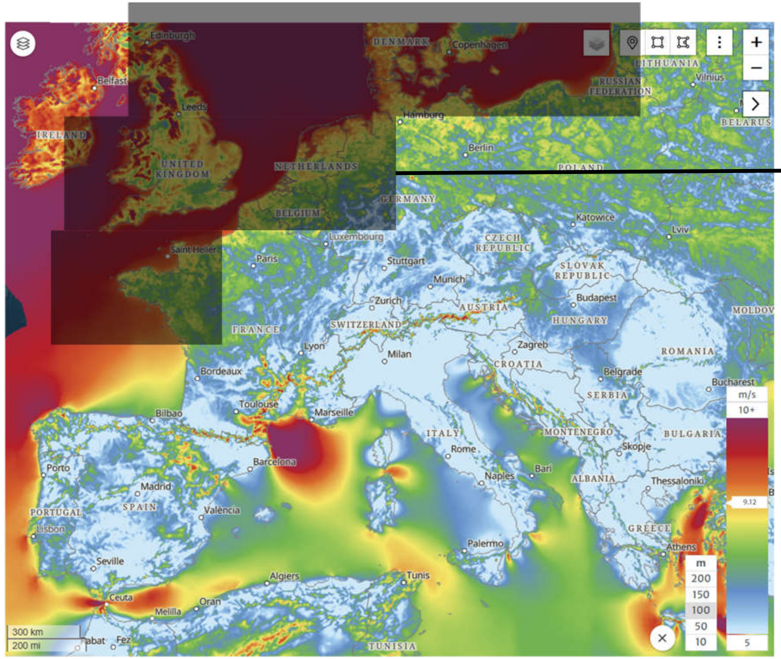


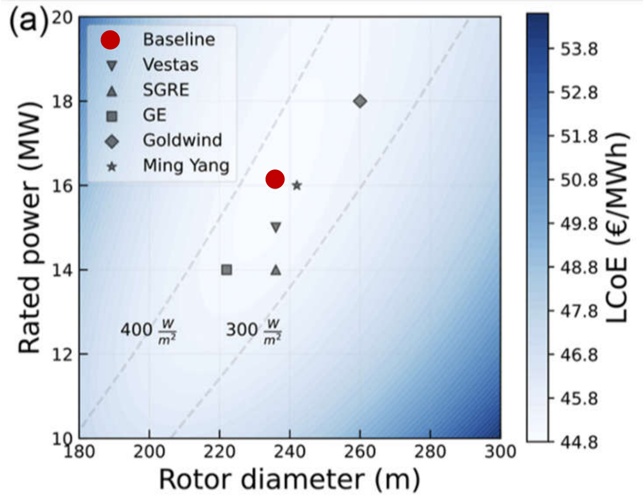
What do offshore turbines look like?

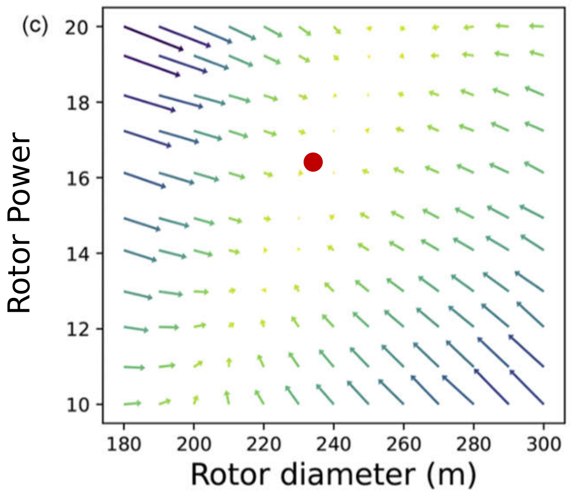
Generally very large

Generally very Powerful

High specific power



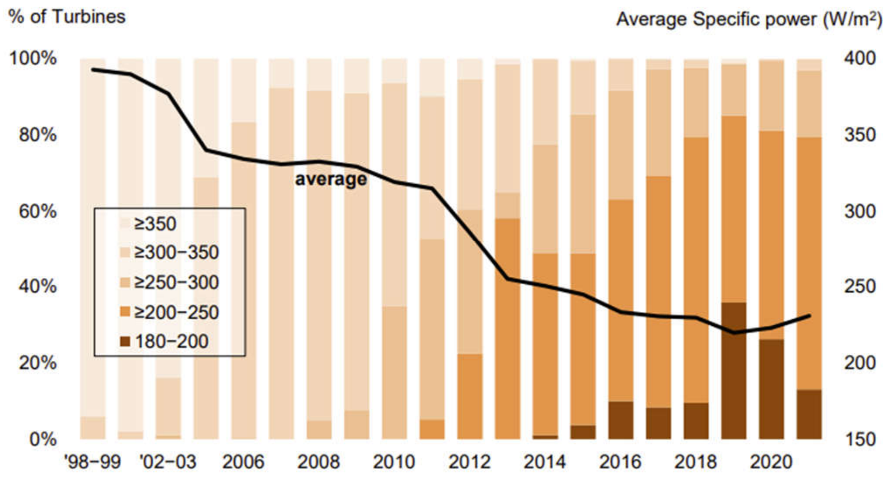




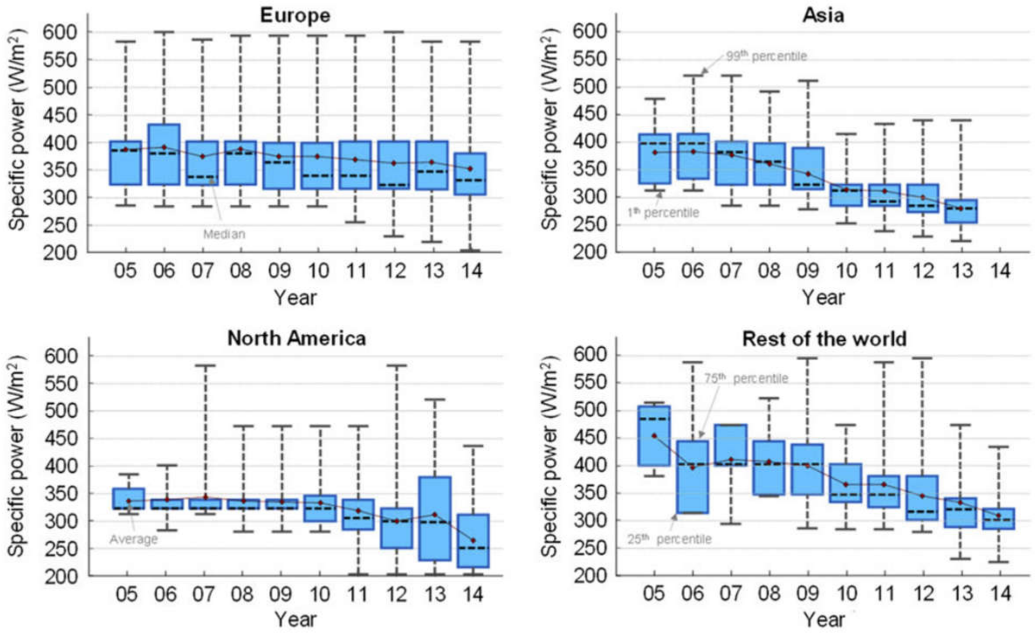
Mehta, M., Zaaijer, M., and von Terzi, D.: Drivers for optimum sizing of wind turbines for offshore wind farms, Wind Energ. Sci., 9, 141–163, https://doi.org/10.5194/wes-9-141-2024, 2024.

Specific power has been clearly decreasing offshore

Especially in Asia, where more low-wind-sites are exploited



[1]



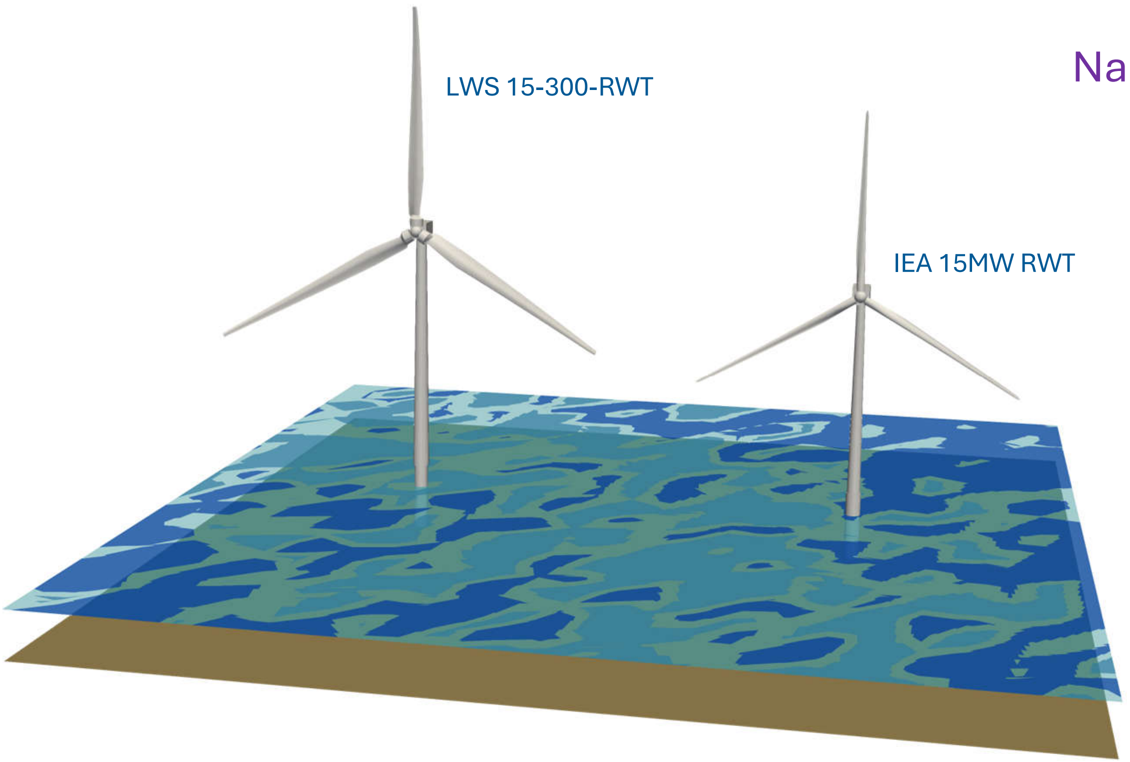
[2]

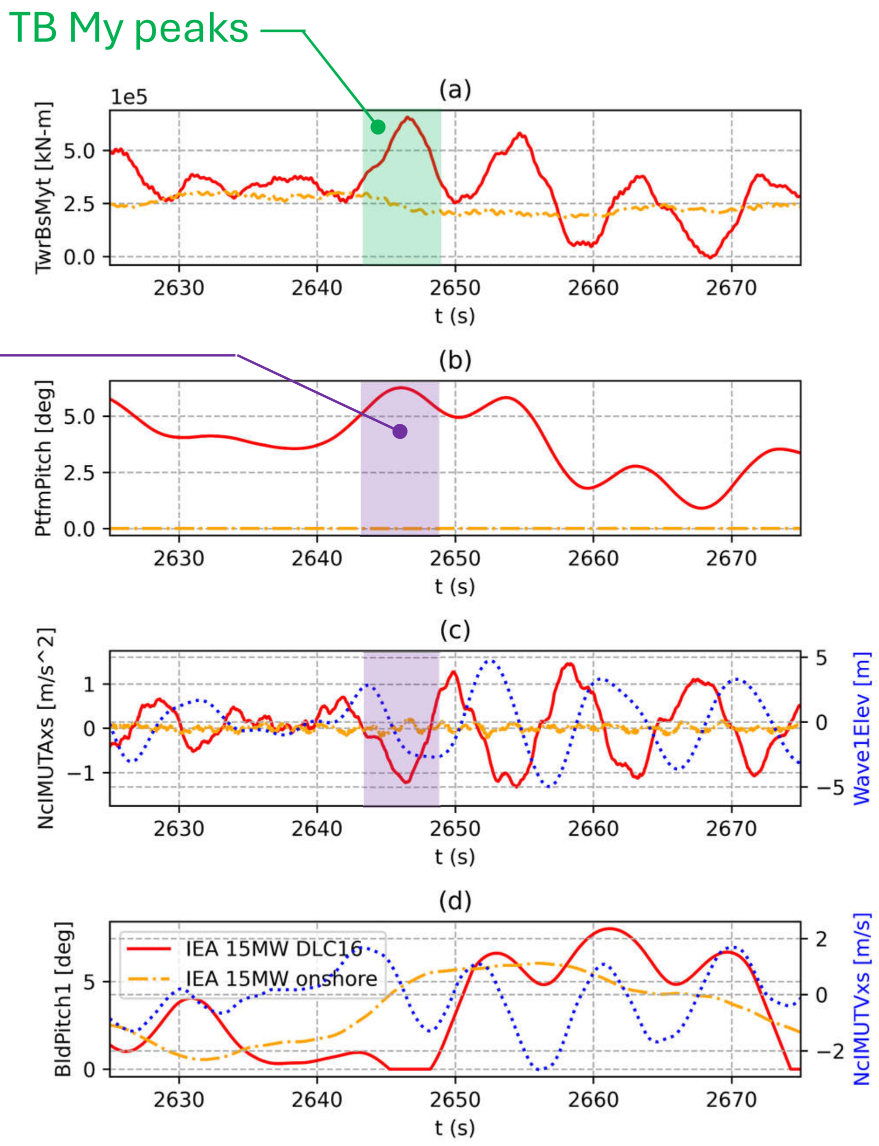
[1] **U.S. Department of Energy; Lawrence Berkeley National Laboratory** (2022). *Land-Based Wind Market Report: 2022 Edition*. Authors: Ryan Wiser, Mark Bolinger, et al. energy.gov
[2] **Serrano-González, J., & Lacal-Arántegui, R.** (2016). *Technological evolution of onshore wind turbines — a market-based analysis*. *Wind Energy*, **19**(12), 2171-2187.

Can this work for FOWTs?

Gravitational & inertial effects can amplify loads

- greater the higher the hub-height - extra material required

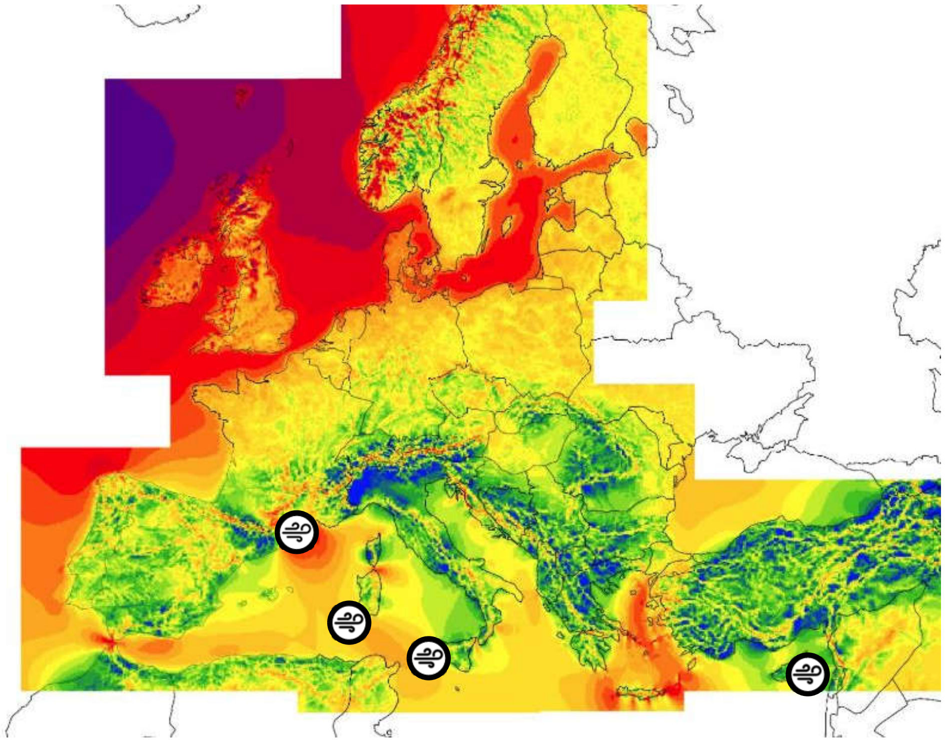




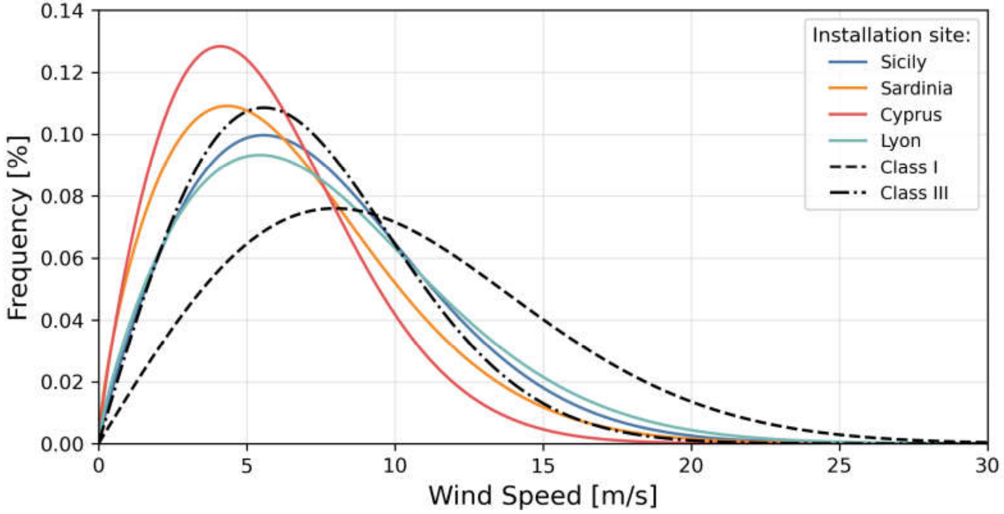
F. Papi, A. Bianchini: https://doi.org/10.1016/j.rser.2022.112489

Can this work for FOWTs?

Is there a techno-economic optimum?



source: ERA5 @ 100m mswl



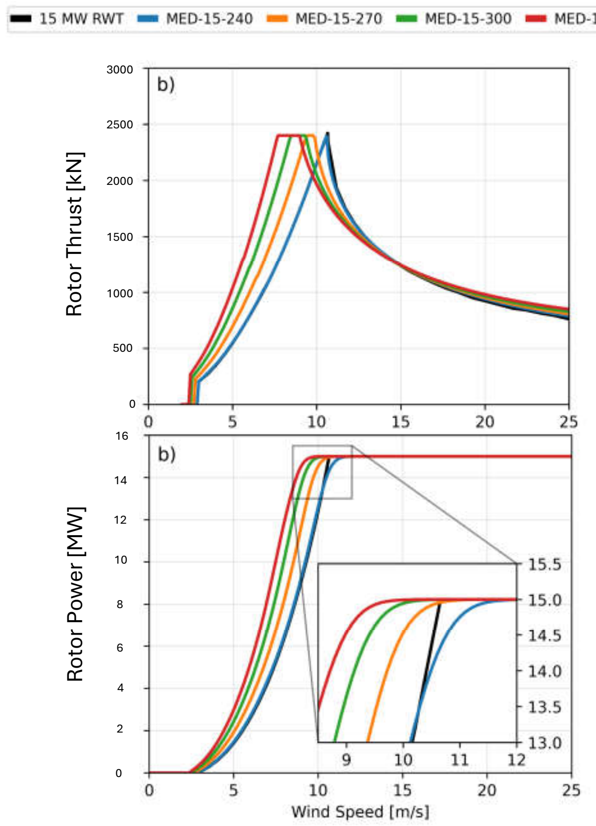
R. Travaglini, F. Papi, A. Bianchini: Floating wind farms in sea basins with moderate wind speeds: a critical assessment of the potential of low-specific-power turbines in reducing the LCoE, Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2025.115990

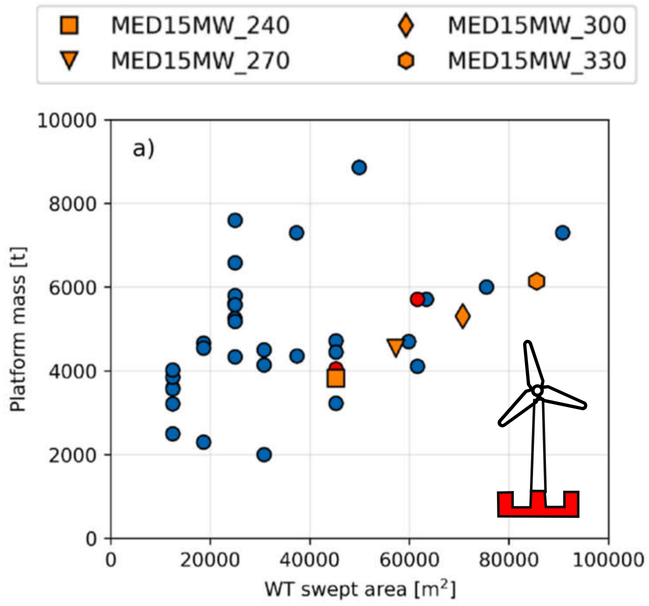
Can this work for FOWTs?

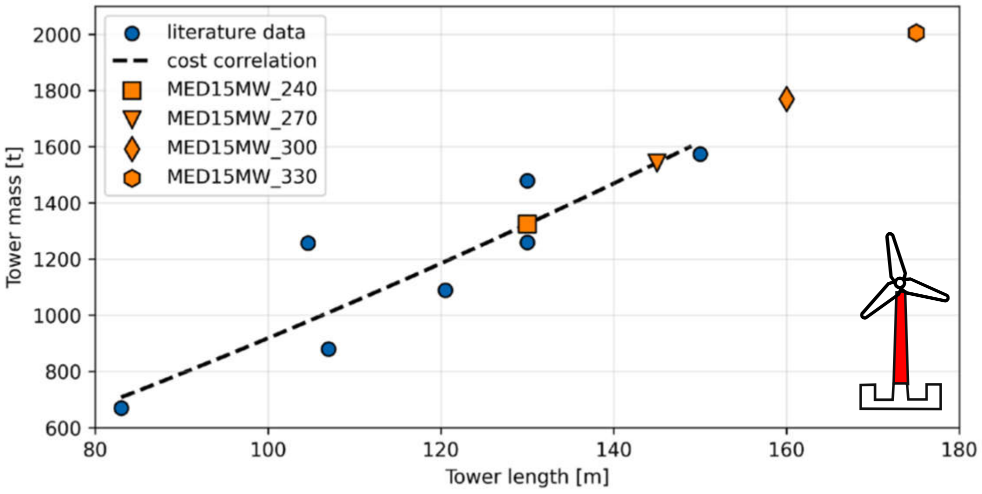
Four conceptual **15MW** FOWTs – **240 m to 330 m in diameter**

cost functions for all turbine components

aerodynamically-similar to IEA 15MW







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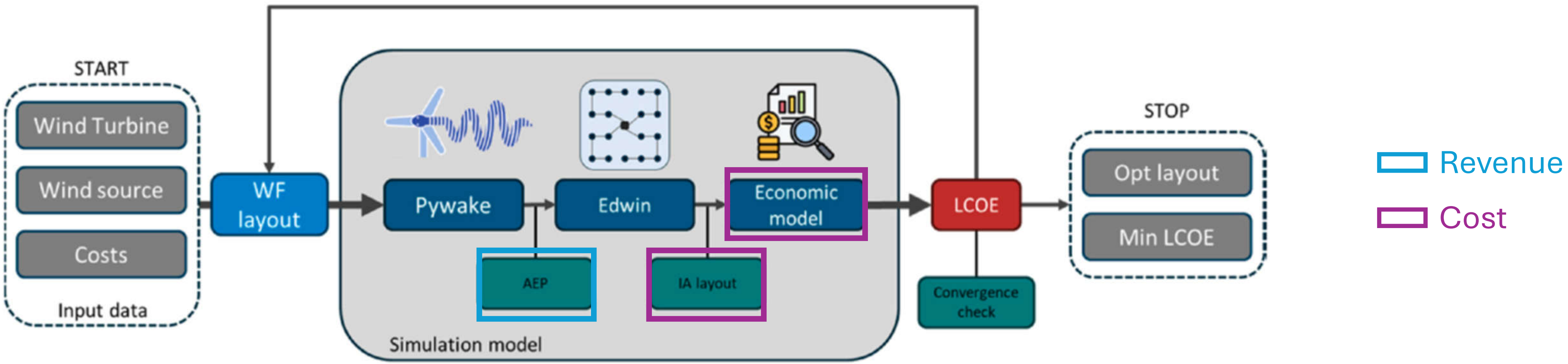
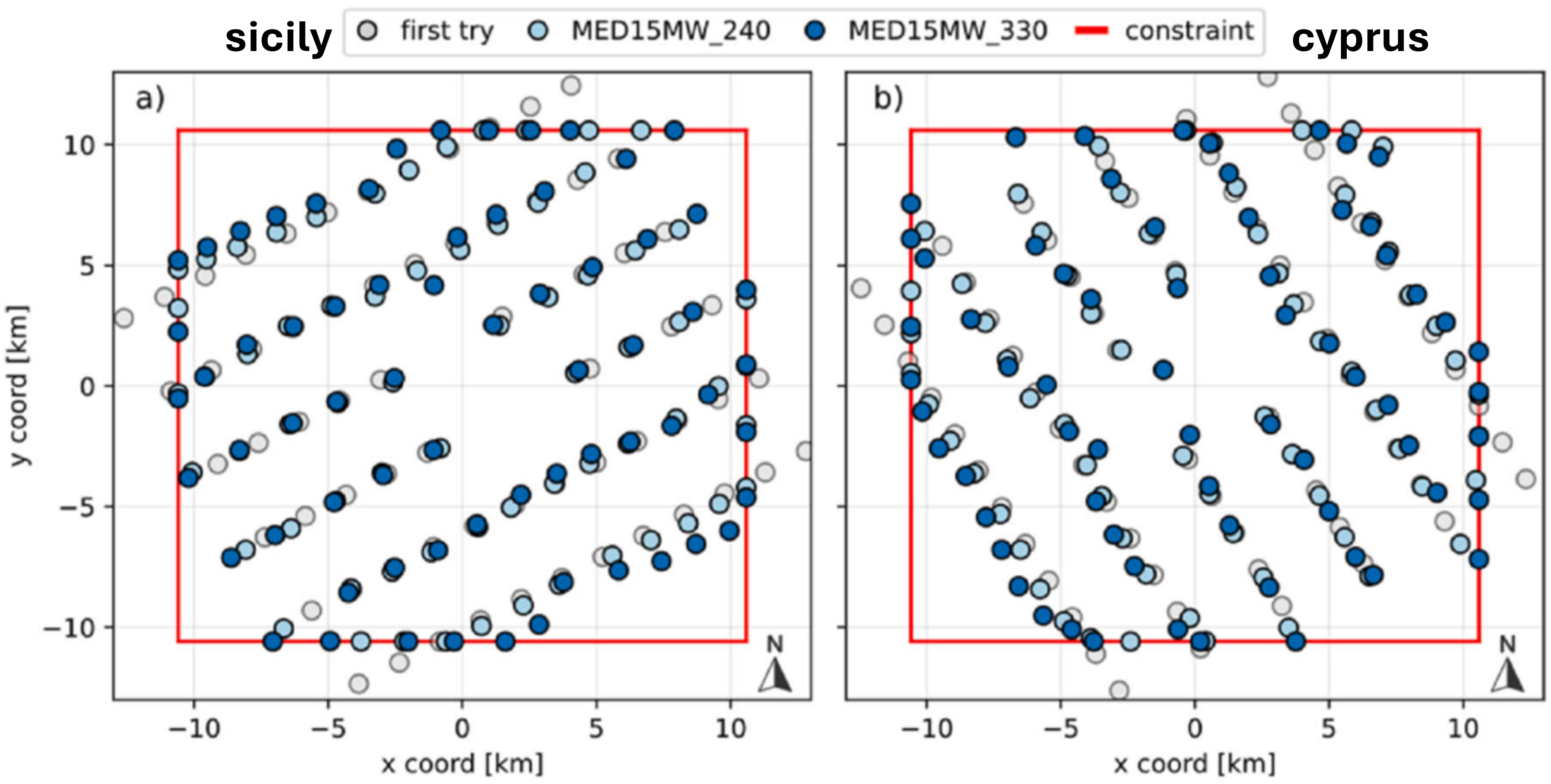
Can this work on FOWTs?

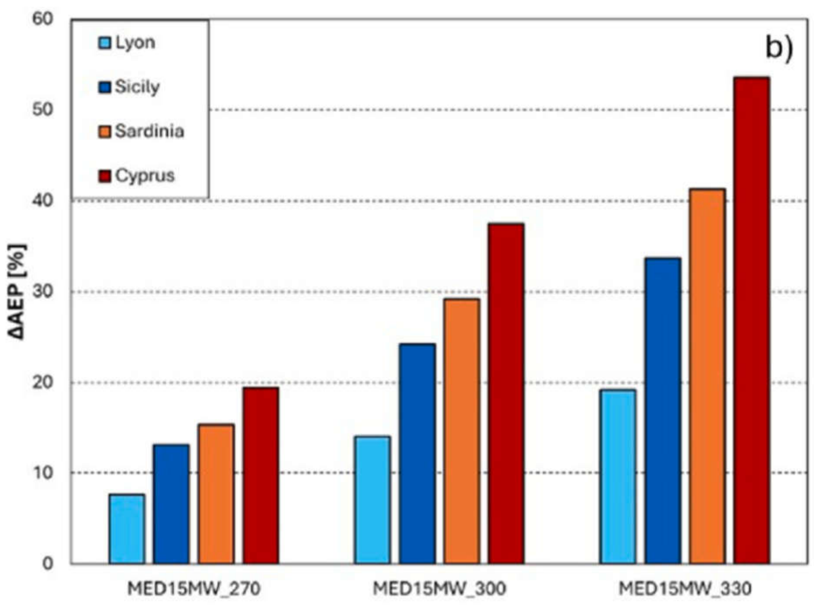


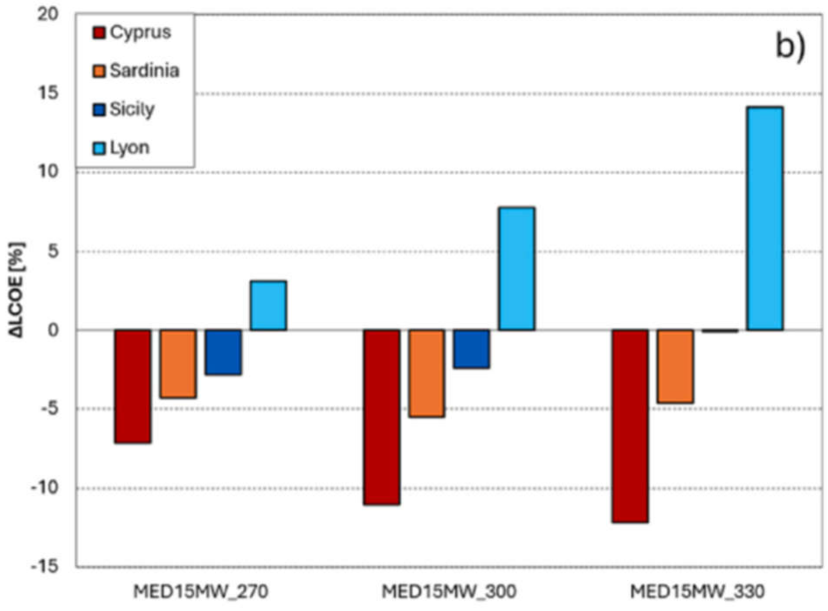
Can this work on FOWTs?

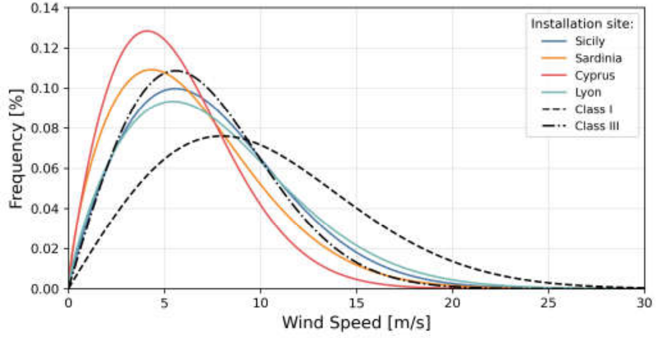


Can this work on FOWTs?

AEP increases in all cases, but it outpaces costs only if wind speed is low



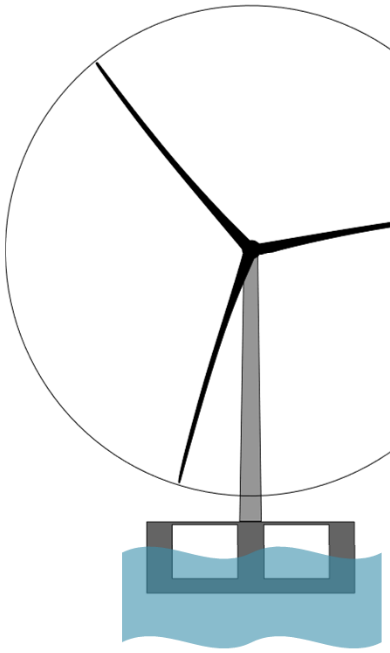




R. Travaglini, F. Papi, A. Bianchini: Floating wind farms in sea basins with moderate wind speeds: a critical assessment of the potential of low-specific-power turbines in reducing the LCoE, Renewable and Sustainable Energy Reviews, https://doi.org/10.1016/j.rser.2025.115990

Objective

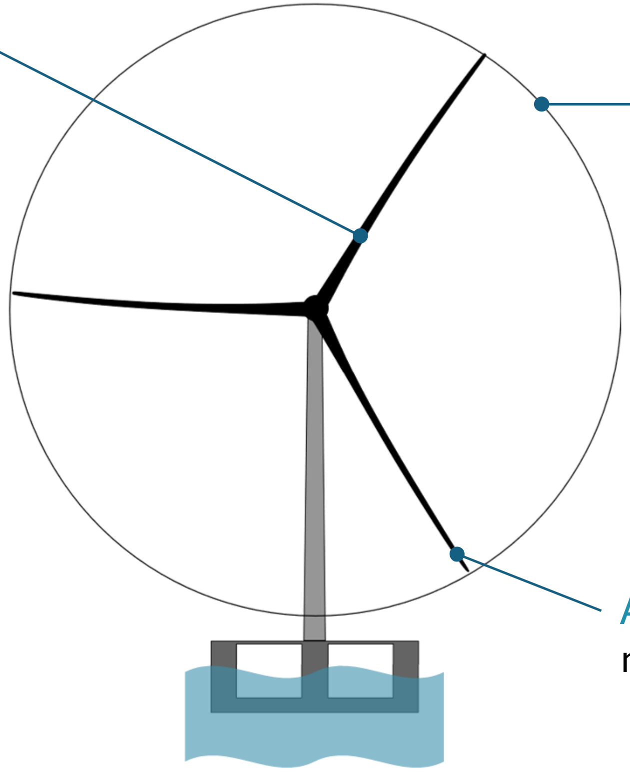
AEROELASTIC TAILORING
bend-twist coupling to alleviate loads in high winds



IEA 15MW

Current offshore turbines have around 330 W/m²

FLOATFARM



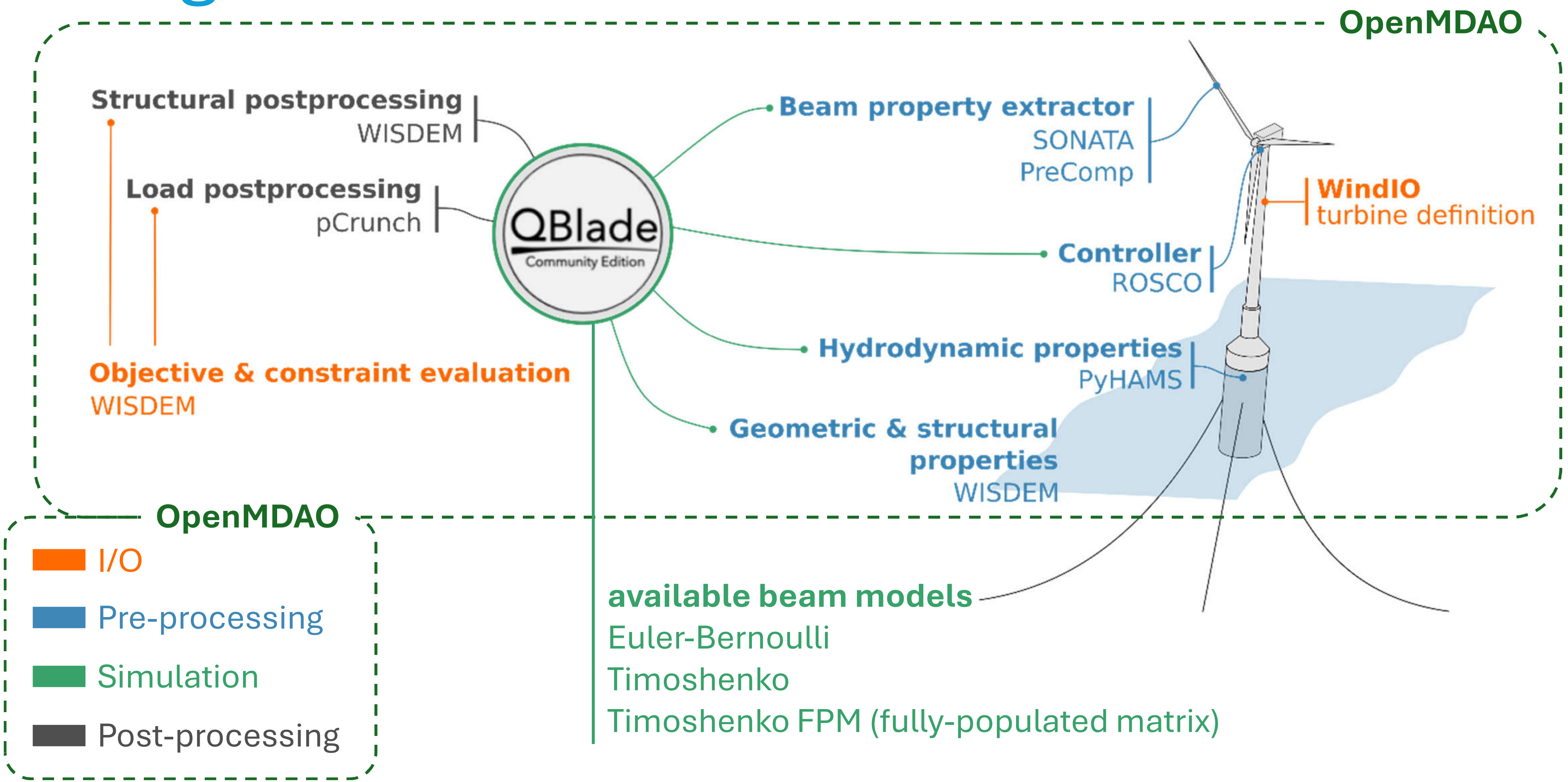
LOW WIND SPEED ROTOR

- 200 W/m² specific power
- 15MW
- 150 m blade
- low cut-in wind speed
- up to +20% AEP

MS1.1 aero-servo-elastic rotor design

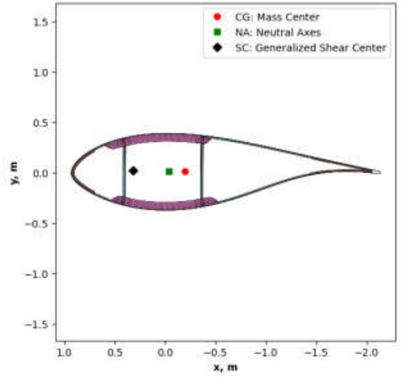
ADVANCED AERODYNAMICS
multi-fidelity optimization

Design framework



What is the influence of the beam model & pre-processing?

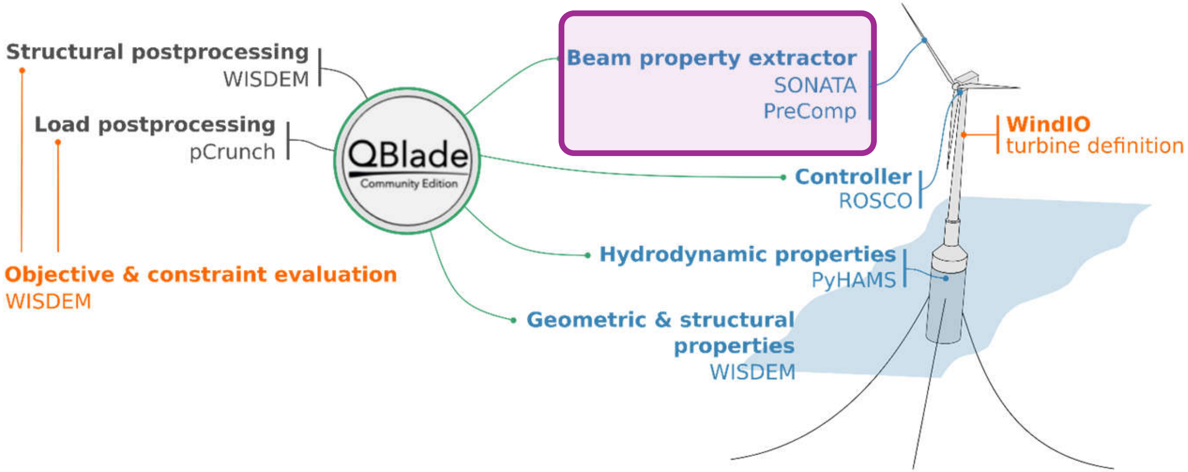
Timoshenko fully-coupled blade model ←



SONATA

- ✓ 1D cross-sectional analysis
- ✓ **anba –** determines Timoshenko matrix

$$\begin{bmatrix} \boldsymbol{K_{11}} & K_{12} & 0 & 0 & 0 & K_{16} \\ & \boldsymbol{K_{22}} & 0 & 0 & 0 & K_{26} \\ & & \boldsymbol{K_{33}} & K_{34} & K_{34} & 0 \\ & & & \boldsymbol{K_{44}} & K_{45} & 0 \\ & sym & & & \boldsymbol{K_{55}} & 0 \\ & & & & & \boldsymbol{K_{66}} \end{bmatrix}$$



Euler-Bernoulli blade model ←

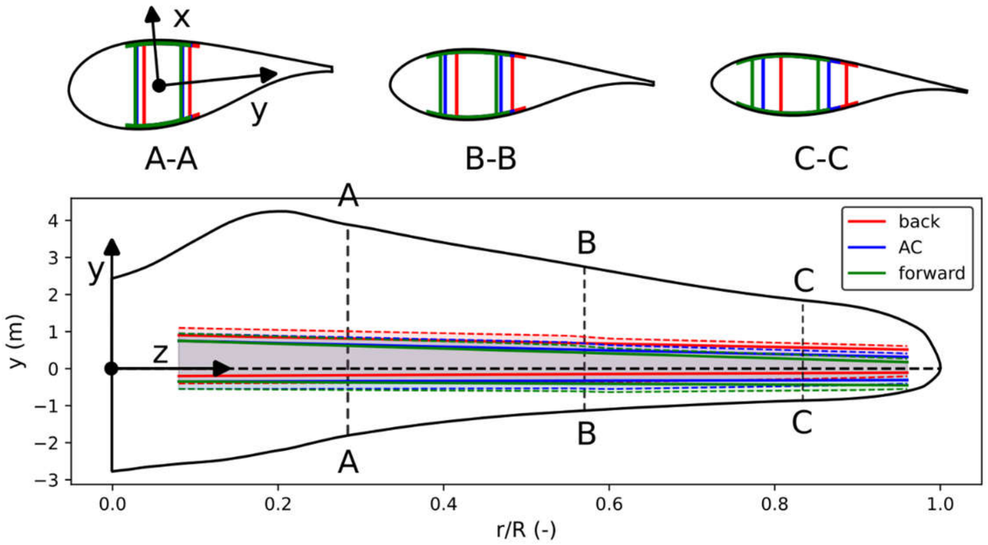
$$\begin{bmatrix} \boldsymbol{K_{11}} & 0 & 0 & 0 & 0 & 0 \\ & 0 & 0 & 0 & 0 & 0 \\ & & 0 & 0 & 0 & 0 \\ & & & \boldsymbol{K_{44}} & K_{45} & K_{46} \\ & sym & & & \boldsymbol{K_{55}} & K_{56} \\ & & & & & \boldsymbol{K_{66}} \end{bmatrix}$$

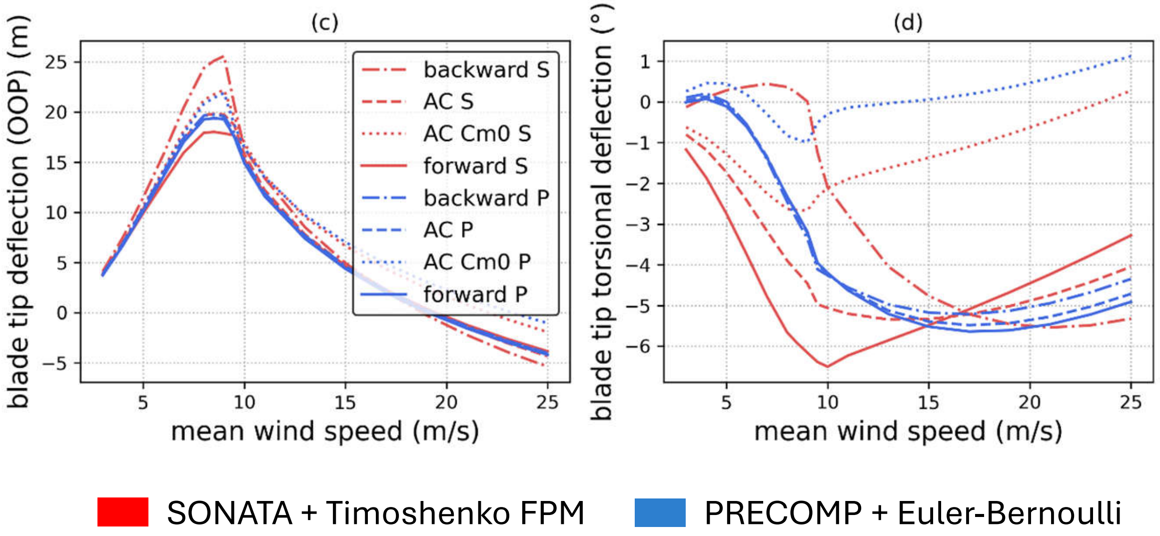
PRECOMP

- ✓ 1D cross-sectional analysis
- ✓ **neglects shear**

Effect of shear web position on performance

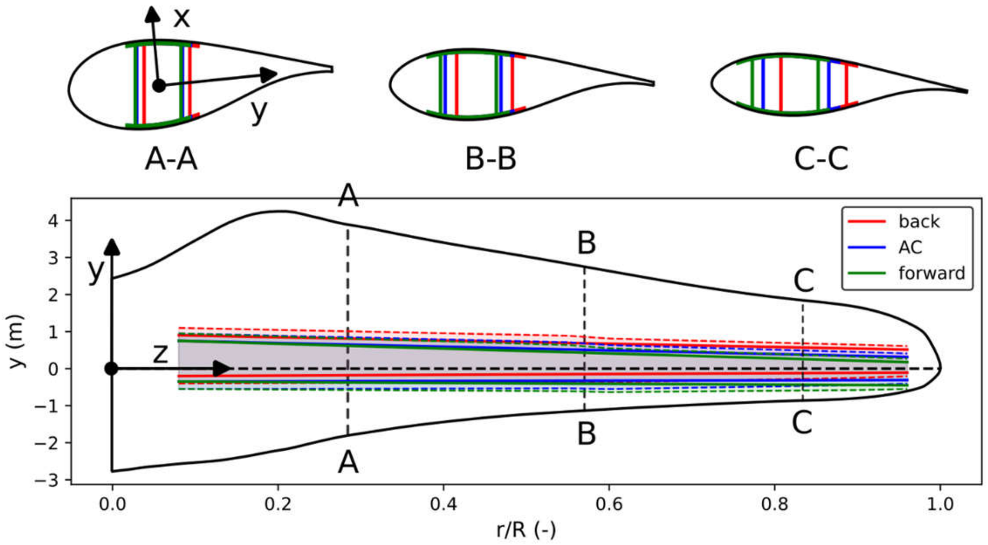
Only when using a **Timoshenko fully-coupled** blade model (& appropriate pre-processor) can we capture these effects

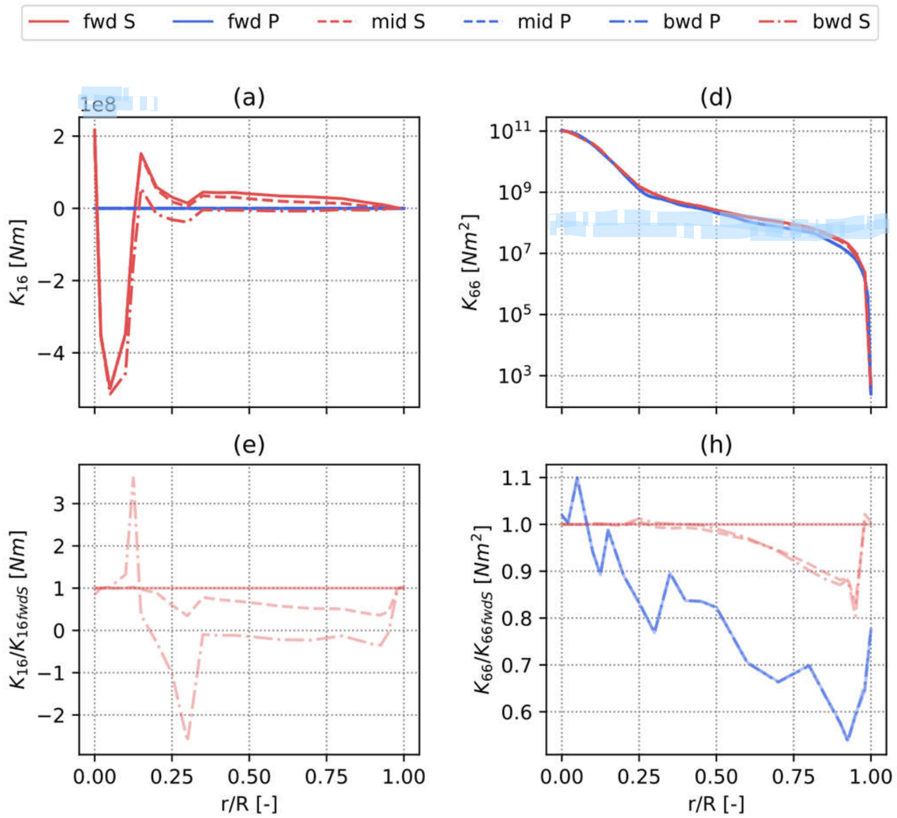




Effect of shear web position on performance

Only when using a **Timoshenko fully-coupled** blade model (& appropriate pre-processor) can we capture these effects



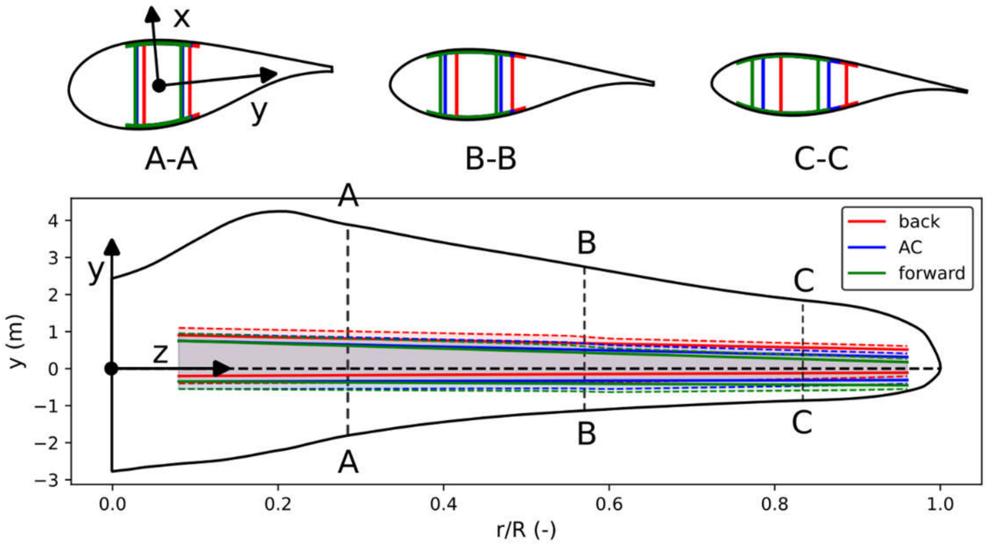


SONATA + Timoshenko FPM

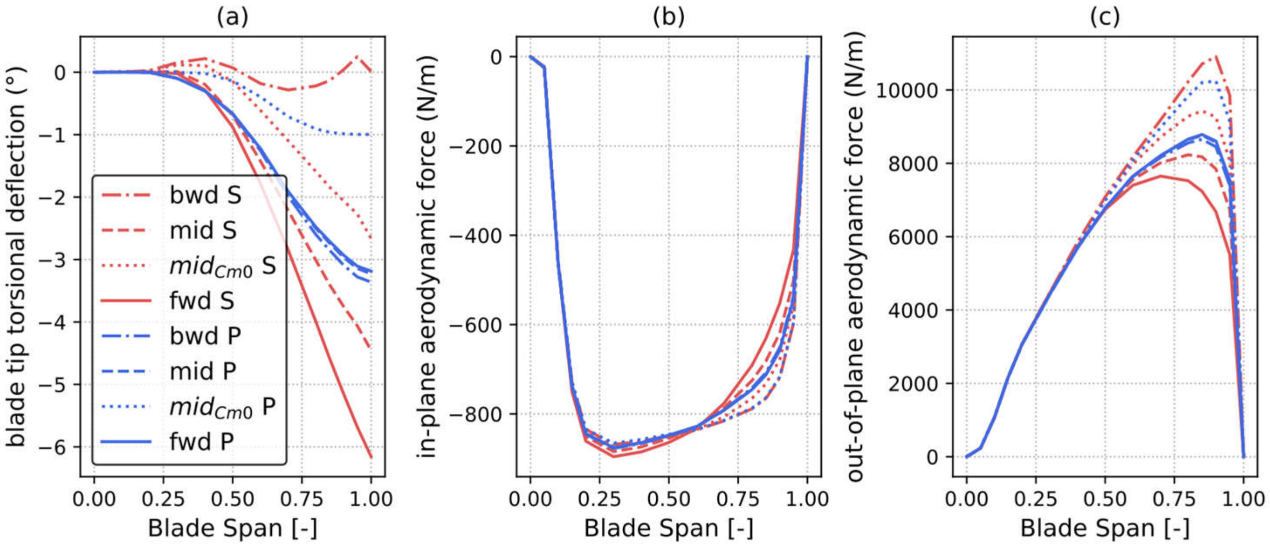
PRECOMP + Euler-Bernoulli

Effect of shear web position on performance

Only when using a **Timoshenko fully-coupled** blade model (& appropriate pre-processor) can we capture these effects



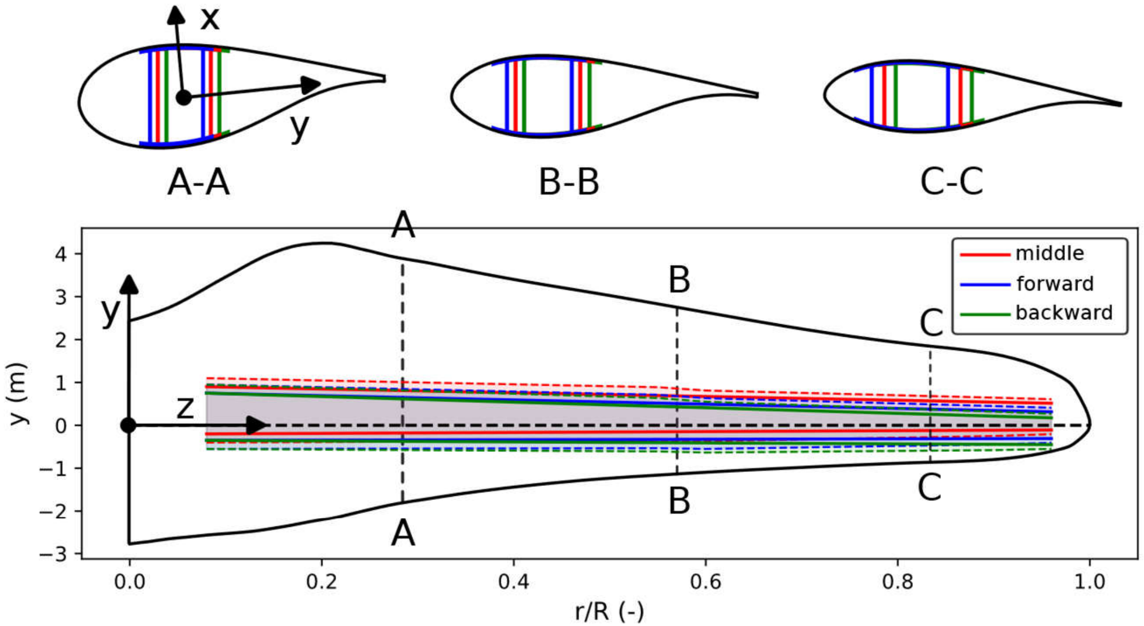
@ 10 m/s



SONATA + Timoshenko FPM   PRECOMP + Euler-Bernoulli

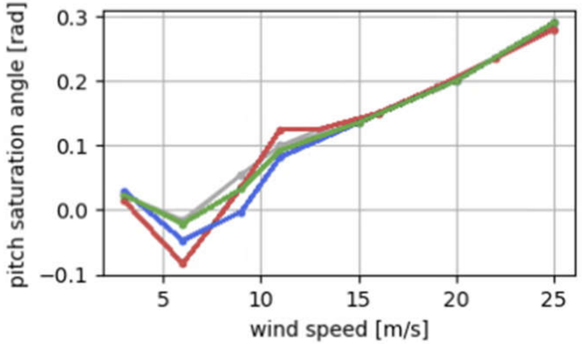
Blade design

- How does spar-cap position influence performance?
  - **Objective**: AEP
  - **DVs**: blade twist, blade chord, **collective pitch**
  - **Constraints**: maximum thrust
- Optimizations with **3 different spar-cap/shear-web positionings**
  - **10 cm** towards LE or TE @ tip
  - **5 cm** towards LE or TE @ root



System dynamics change dramatically

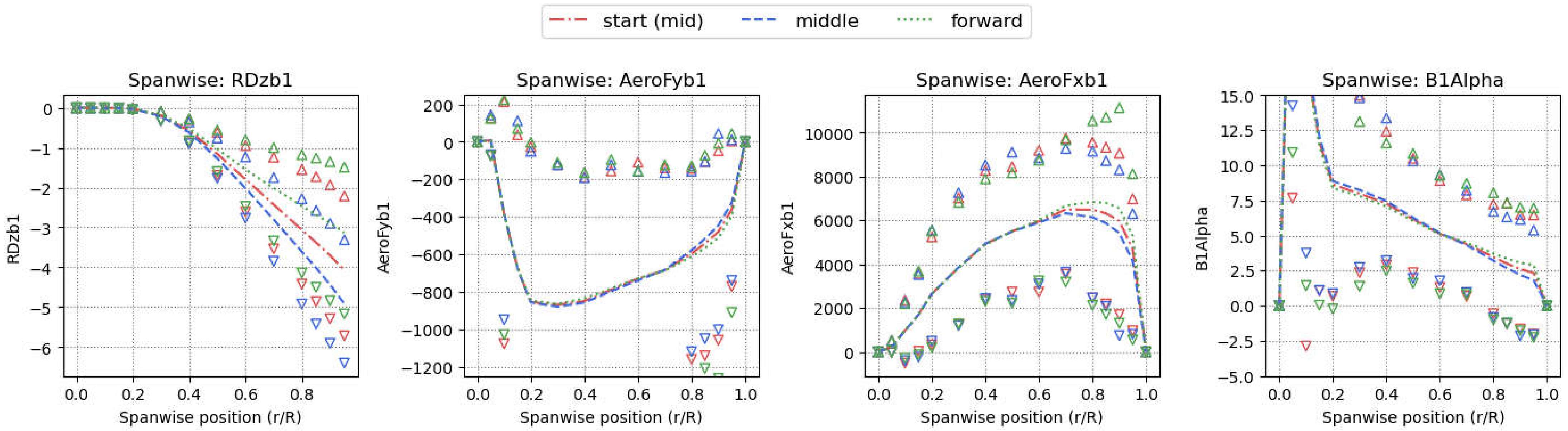
- the more forward the spar caps the more shear-twist coupling



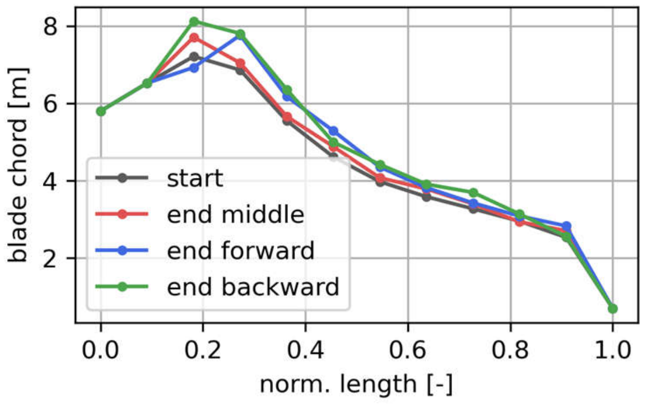
Blade design

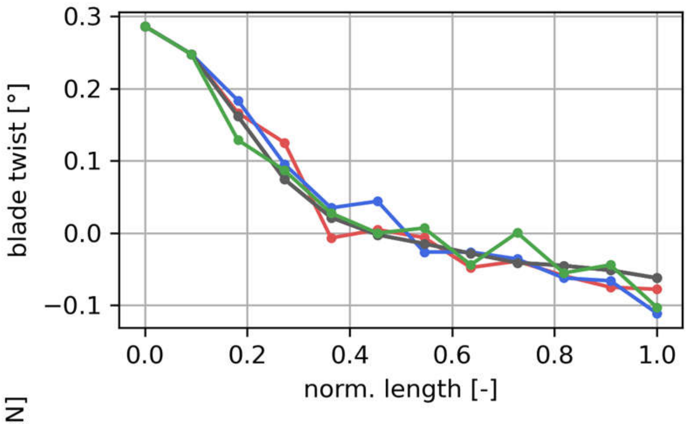
System dynamics change significantly

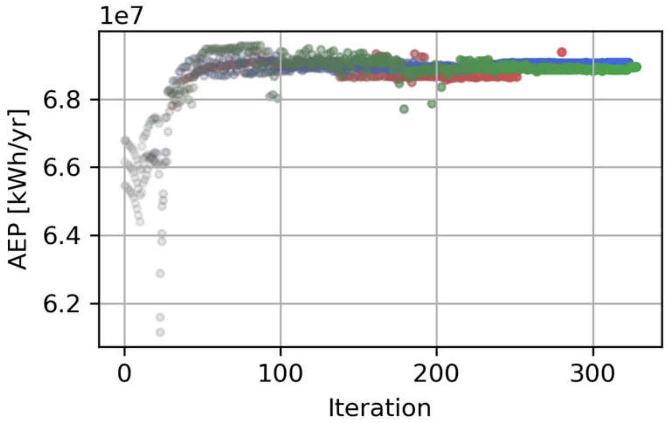
- the more forward the spar caps the more shear-twist coupling

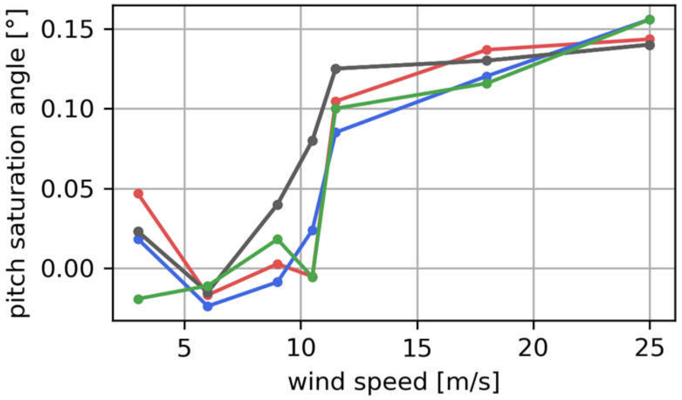


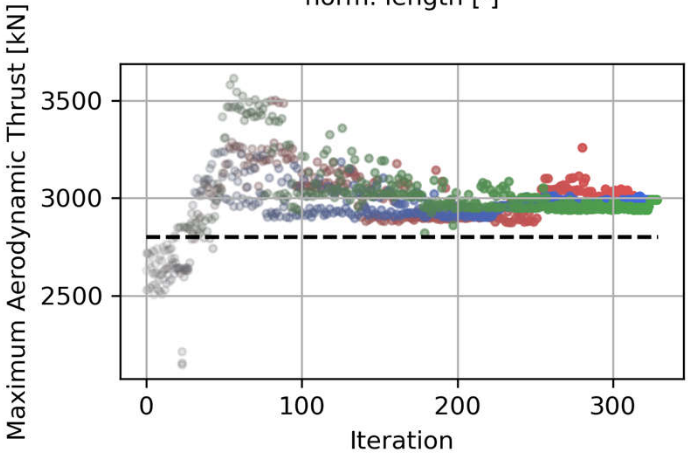
Optimization results – a global maximum?

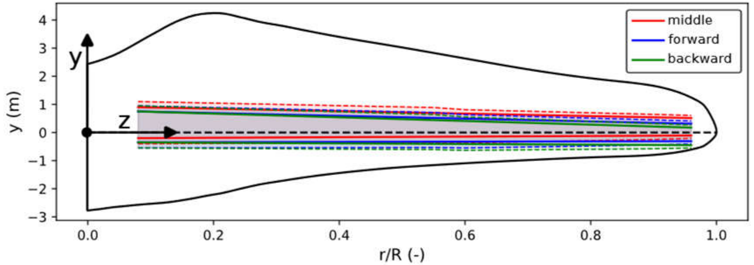




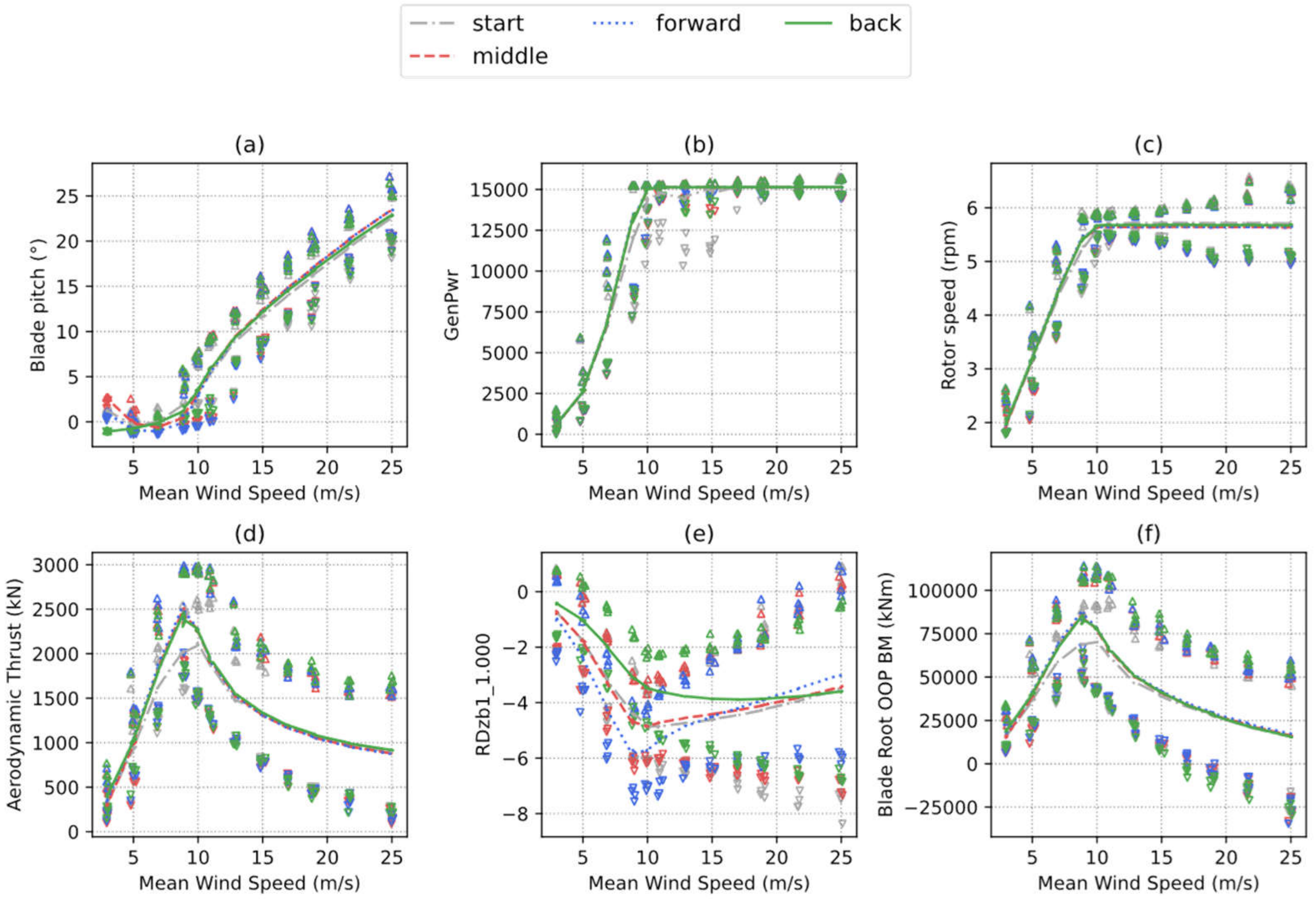






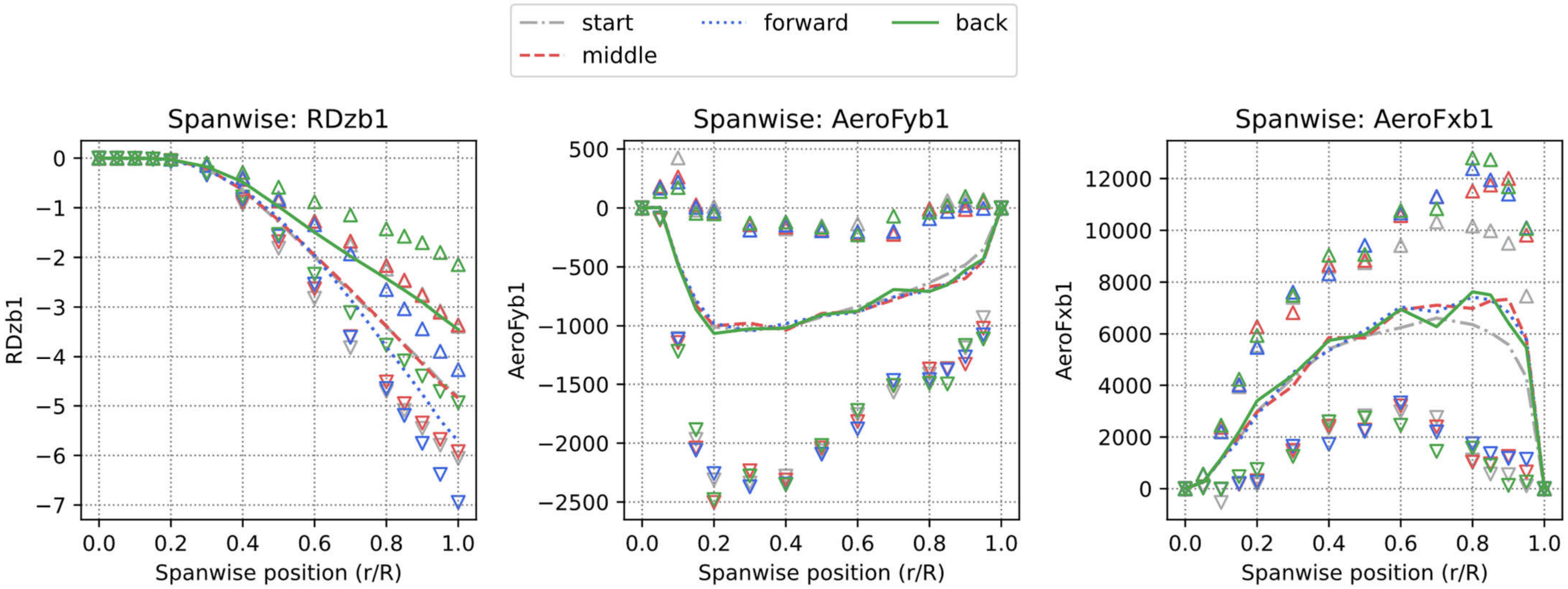


Optimization results – a global maximum?



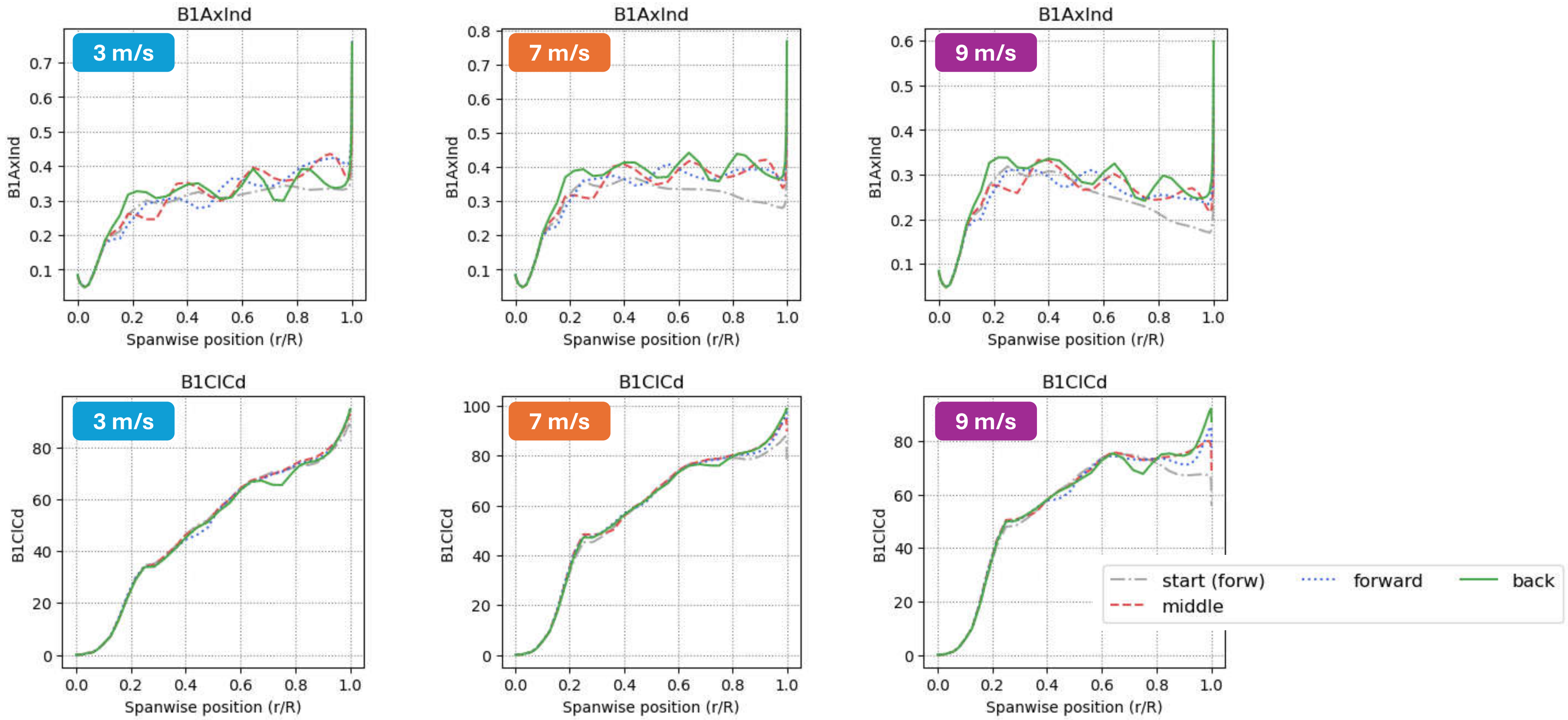
Optimization results – a global maximum?

Through the combination of collective **blade pitch**, **blade chord** and **blade twist** the optimizer can reach the same **spanwise force distribution**



Optimization results – a global maximum?

Very similar distribution of axial induction and efficiency – which generally both increase across the board



Recent understanding on floating wind turbine aerodynamics and wakes

Funded by the European Union

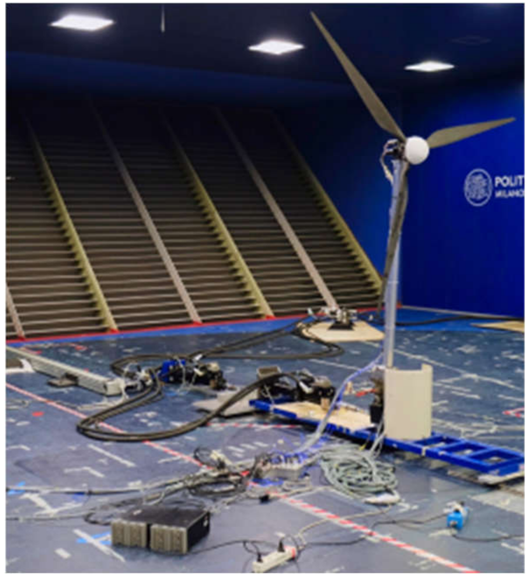
University of Cyprus
Università degli Studi Firenze
NEEST New Energy & Environmental Solutions and Technologies
Aarhus BSS

Latest research programmes: OC6 Phase III

The OC6 project was a research project under the **IEA Wind Task 30** focused on **validating tools** used for FOWT

OC6 Phase III focused on the aerodynamic response of a floating wind turbine under motion involving **29 academic and industrial partners** from 10 countries simulating the UNAFLOW test case

UNAFLOW campaign



TETHYS

NETTUNO – www.nettuno-project.it

Oct '23 — Oct '24 — Oct '25

phase I: **one** turbine

phase II: **two** turbines

Insight into FOWT wake development and loads on downwind turbines

Combined **experimental** and **numerical** approach

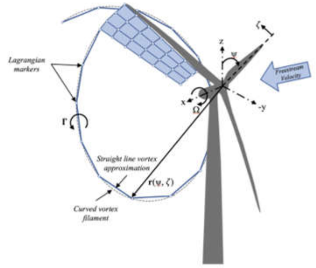
UNIVERSITÀ DEGLI STUDI FIRENZE

POLITECNICO MILANO 1863

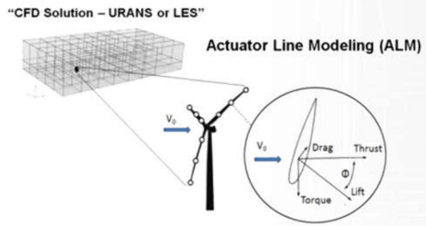
Finanziato dall'Unione europea NextGenerationEU

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

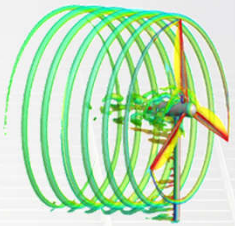
NETTUNO – Phase



free vortex wake



Actuator Line CFD

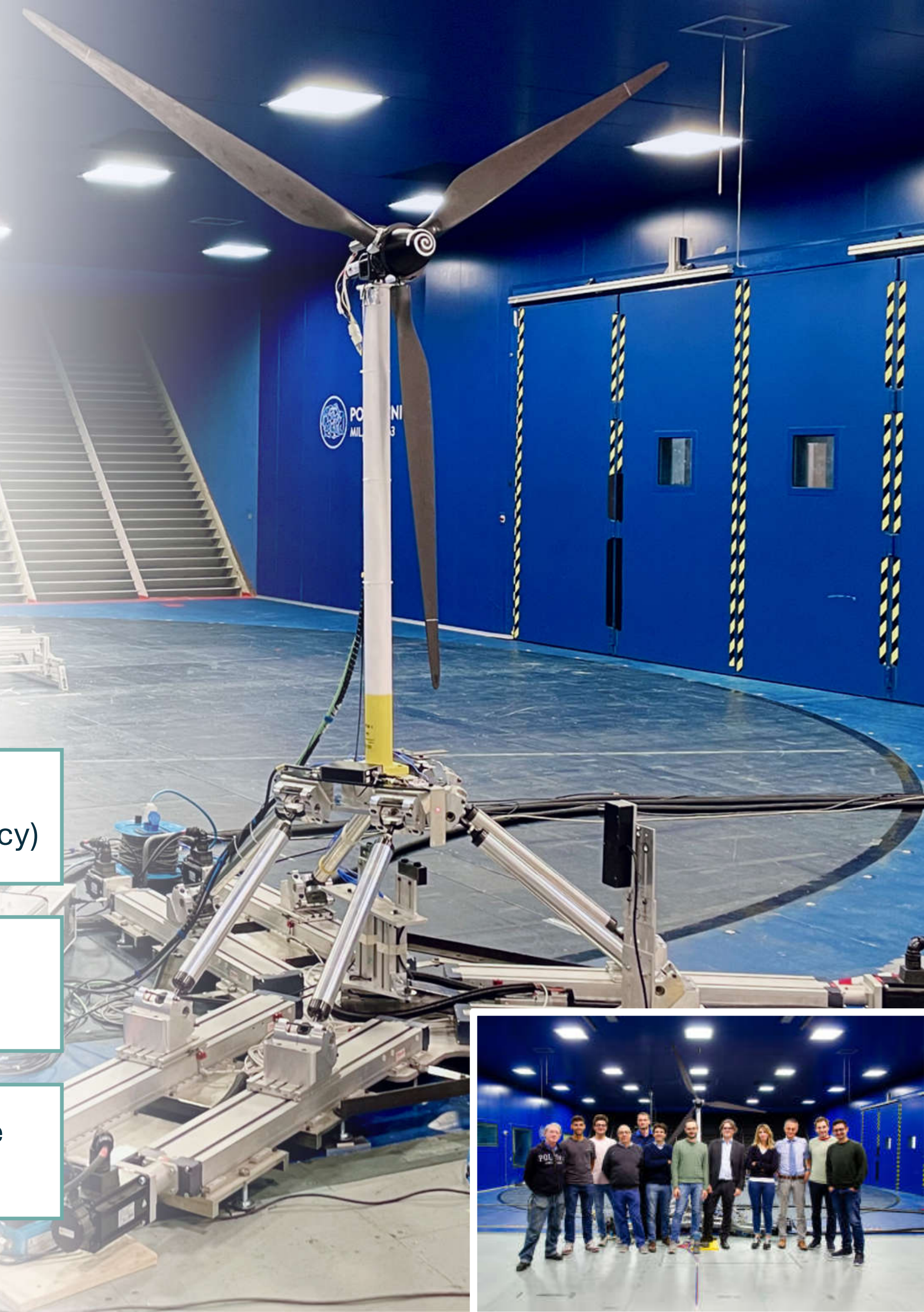


Blade resolved CFD

assess how **platform motion impacts the wake** of a single FOWT (at different distance and reduced frequency)

provide **guidelines for the tuning of lower fidelity models** (especially FVW)

evaluate **ability of simulation tools to capture wake development** floating wind turbine



NETTUNO – Phase II

In January 2025 two identical model wind turbines were tested in the wind tunnel of Politecnico di Milano

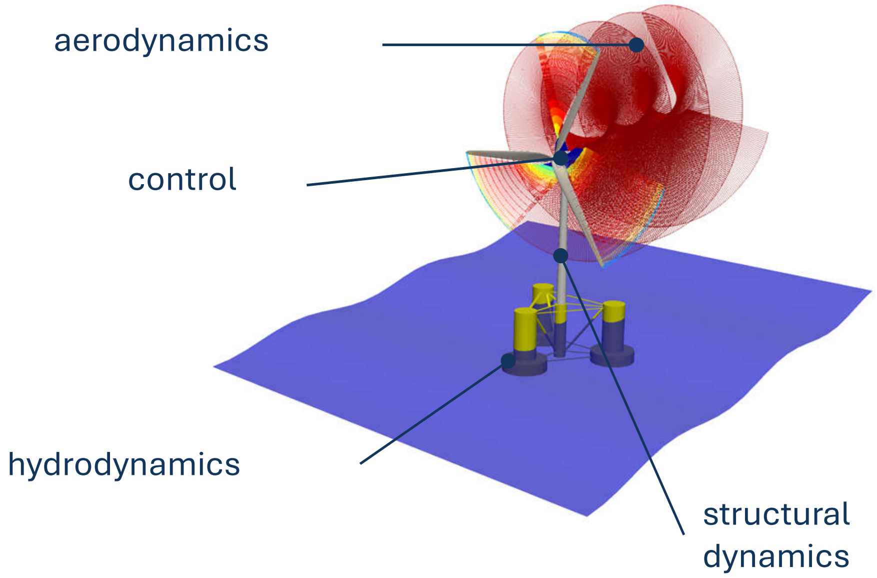
assess how **platform motion impacts the loads of a downstream turbine**

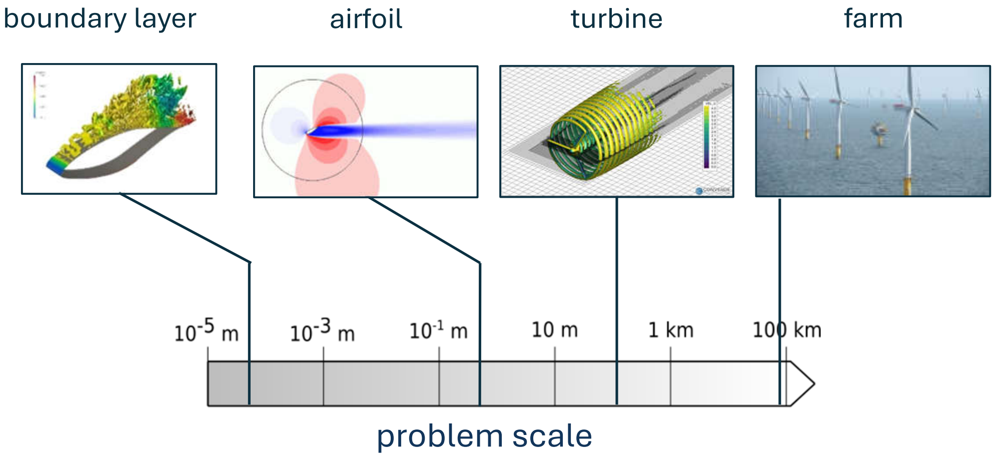
evaluate **ability of simulation tools to capture rotor-wake interactions**

Are our aeroelastic tools up to the task?

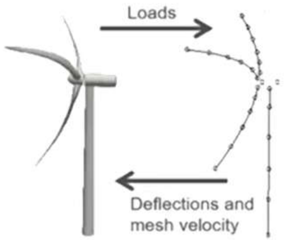
Multi-phyics and multi-scale issues

These effects (and many others in FOWTs) depend on many **coupled physiscs** and many **different scales**!





Aeroelasticity



Oscillating platform

<u>MULTIPHYSICS</u>: FSI & Hydrodynamics

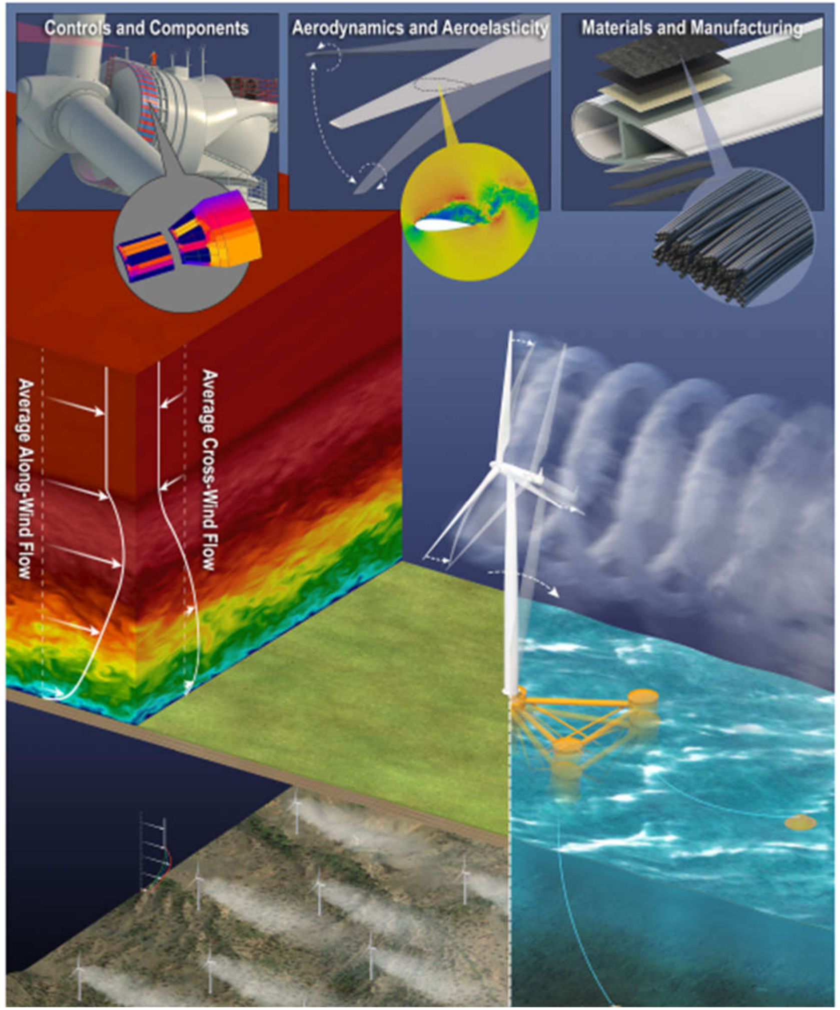
Multi-phyics and multi-scale issues

Several talks would not be sufficient to comprehensively address all the questions

- ✓ improvements needed in all aspects of future turbine desing*, with a holistic perspective

While structural models and hydrodynamics appear as adaptations of consolidated theories or models, discussion is ongoing on whether our **aeroelastic simulation tools** need to evolve

1. Are engineering models used so far in onshore wind able to capture the effects of FOWT dynamics on performance and loads?
2. Which level of fidelity is needed to capture FOWT wake characteristics (so important for park analyses)?
3. Could high-fidelity simulation represent a game-changer for FOWTs?

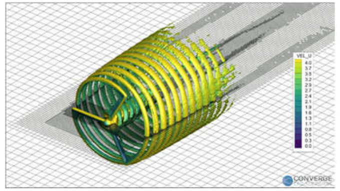


* Veers, P., et al., 2023, "Grand challenges in the design, manufacture, and operation of future wind turbine systems", Wind Energy Science, DOI: 10.5194/wes-8-1071-2023

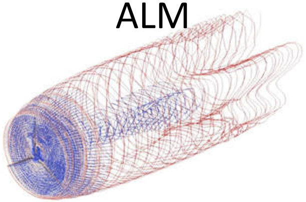
Aerodynamic forces on FOWTs

Experiments (PoliMi) in tests with imposed pitch/surge motion

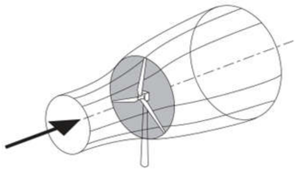
- ✓ part of IEA Task 30 (OC6 Phase III)



ALM



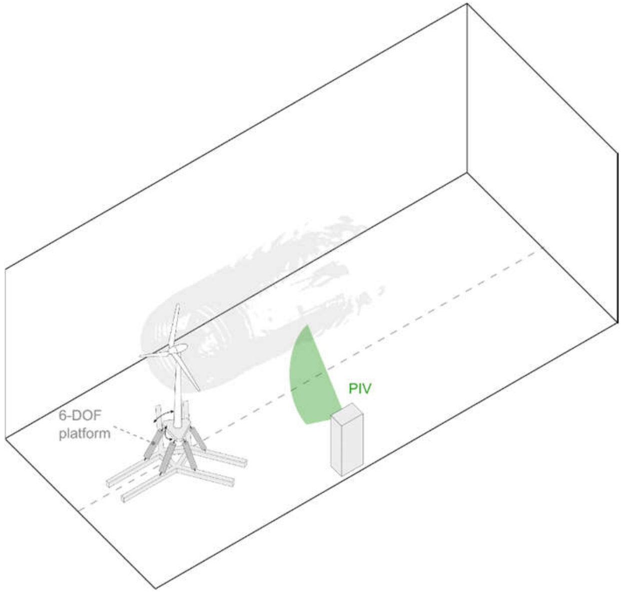
LLFVW



BEM

LC	3.1	3.5	3.7	3.20	3.21
f (Hz)	0.125	1	2	3	4
A (deg)	3	1.4	0.3	0.3	0.3
U_∞ (m/s)	4.19	4.19	4.19	4.19	4.19
f_r (-)	0.0710	0.5683	1.1367	1.7050	2.2733
f^{fs} (Hz)	0.005	0.04	0.08	0.12	0.16
A^{fs} (m)	9.375	2.625	0.6	0.6	0.6

comparison to experiments (shaded columns: 3.1, 3.5, 3.7)
code-to-code comparisons



Blade Element Momentum Theory is the workhorse of the industry

Local BEM formulation, structural velocity treated as apparent wind: $Ur = (U_\infty - U_{struct}) * (1 - a)$

Can it simulate moving rotors?

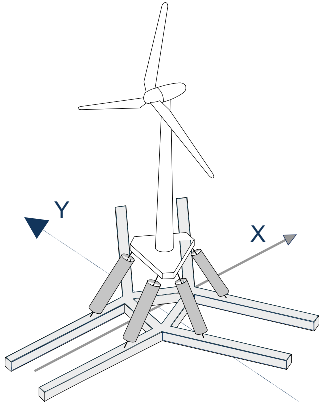
- ✓ three-way code comparison: BEM (OpenFAST), LLFVW (OpenFAST) and ALM (in-house)

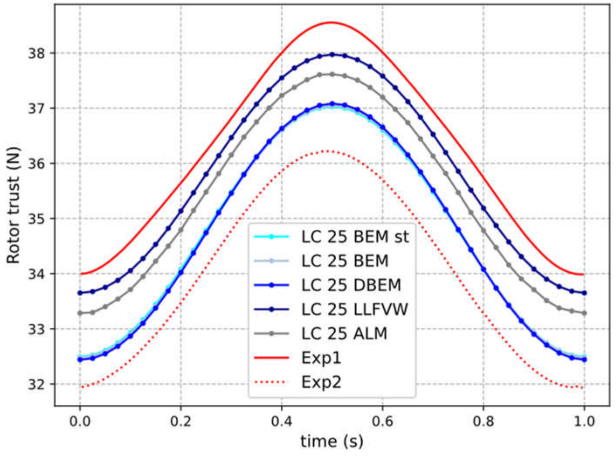
Papi, F., Jonkman, J., Robertson, A., and Bianchini, A.: Going beyond BEM with BEM: an insight into dynamic inflow effects on floating wind turbines, Wind Energ. Sci., 9, 1069–1088, https://doi.org/10.5194/wes-9-1069-2024, 2024.

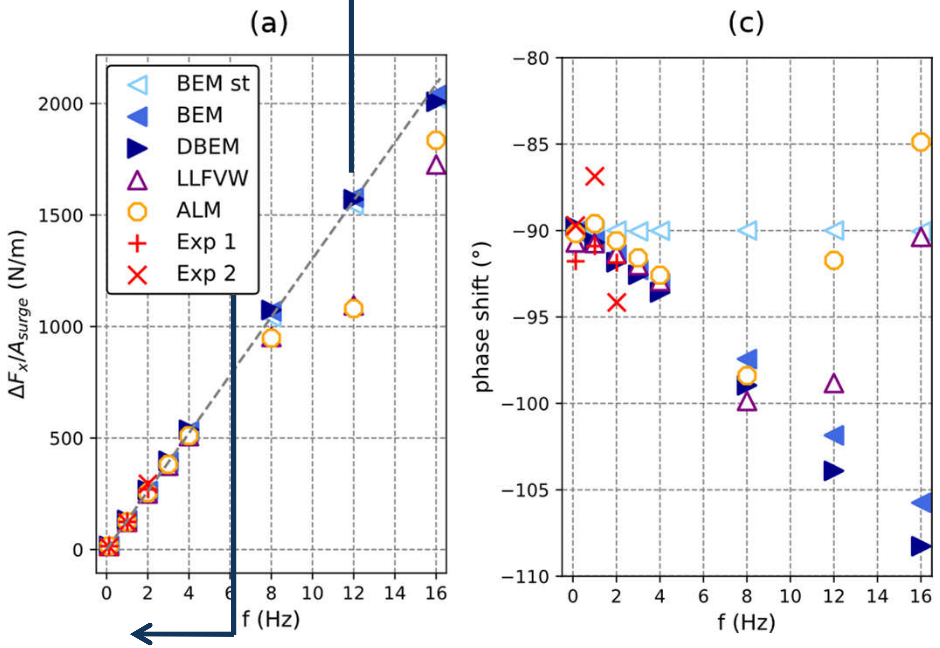
Aerodynamic forces on FOWTs

BEM is in agreement with higher-order codes at most significant oscillation frequencies..but there are exceptions!

$f = 3\Omega$ vorticity shed from blades synchronizes







good agreement between codes at significant FOWT frequencies

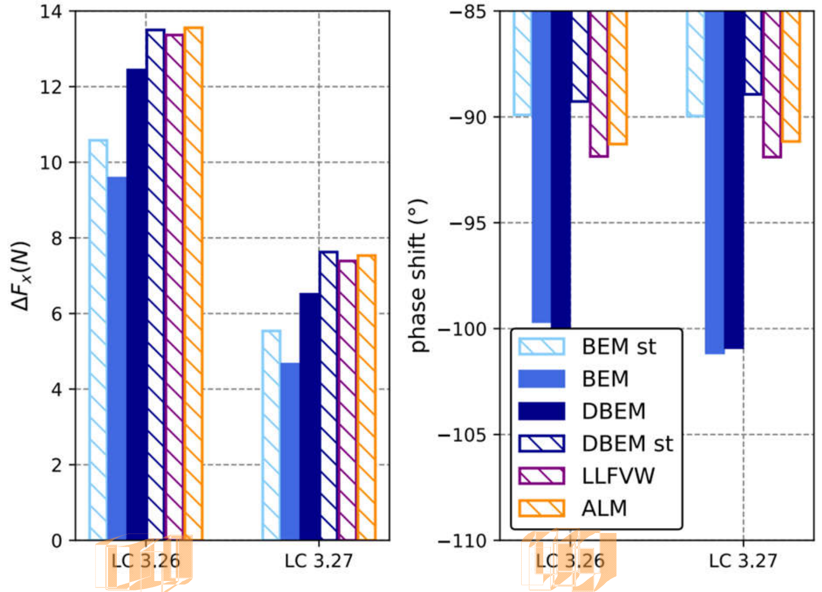
Papi, F., Jonkman, J., Robertson, A., and Bianchini, A.: Going beyond BEM with BEM: an insight into dynamic inflow effects on floating wind turbines, Wind Energ. Sci., 9, 1069–1088, https://doi.org/10.5194/wes-9-1069-2024, 2024.

Aerodynamic forces in low wind speeds

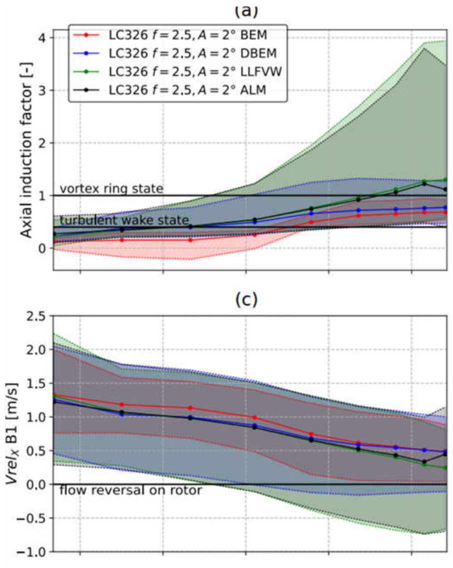
Extreme ideal case at low wind speed, **pitch oscillation A=1,2°, f= 2.5 Hz**

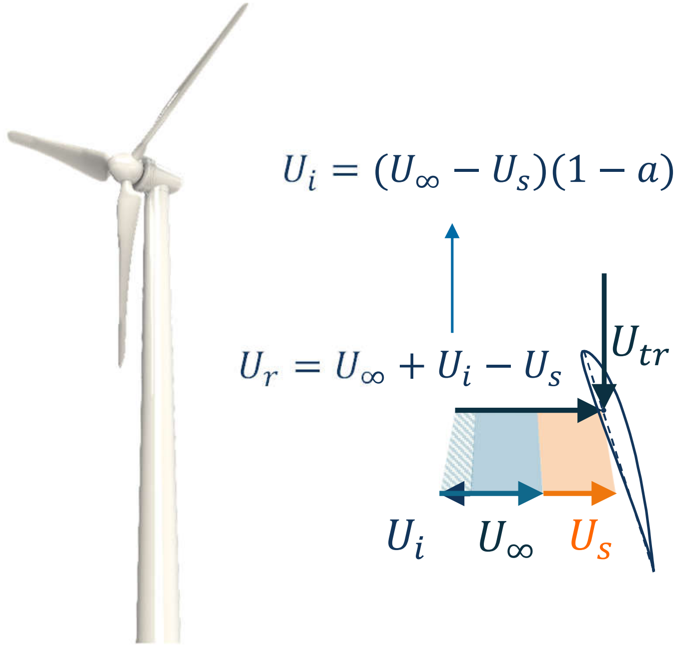
- ✓ fore-aft blade tip velocity is comparable to wind speed
- ✓ BEM reliably predicts global rotor force oscillation magnitude
- ✓ differences in spanwise blade loads

rotor thrust



LC 3.26 spanwise loads





Papi, F., Jonkman, J., Robertson, A., and Bianchini, A.: Going beyond BEM with BEM: an insight into dynamic inflow effects on floating wind turbines, Wind Energ. Sci., 9, 1069–1088, https://doi.org/10.5194/wes-9-1069-2024, 2024.

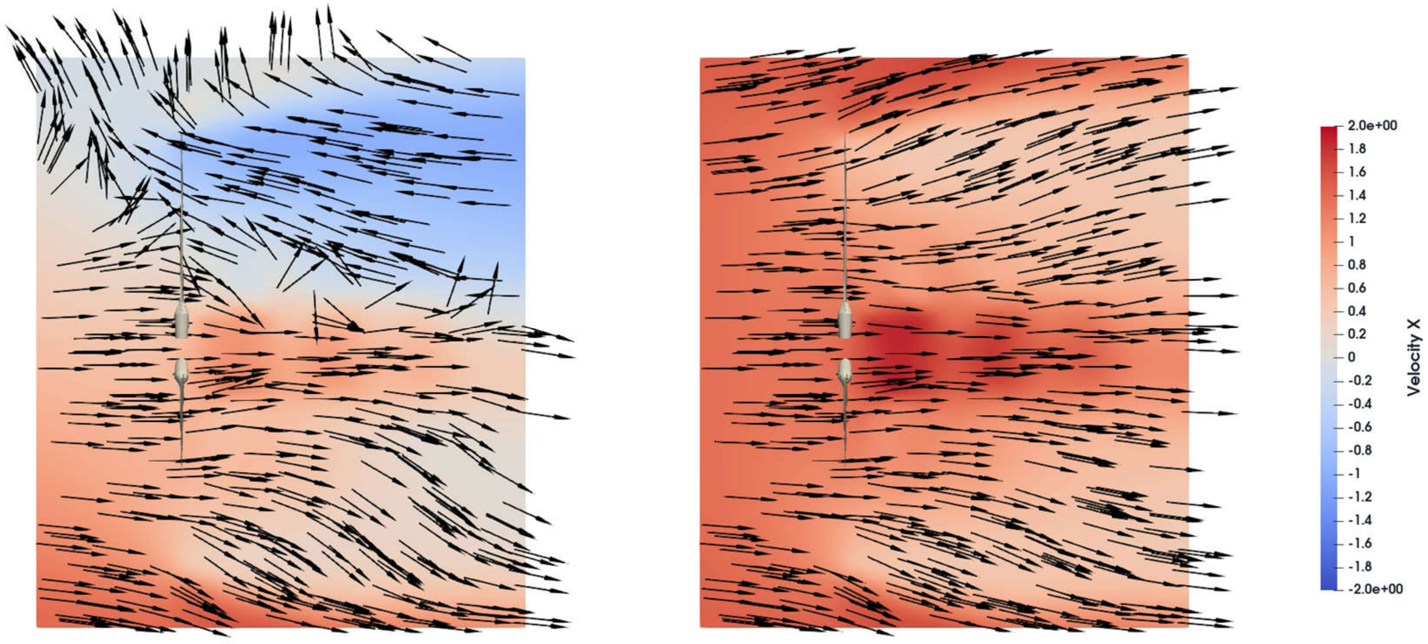
Aerodynamic forces in low wind speeds

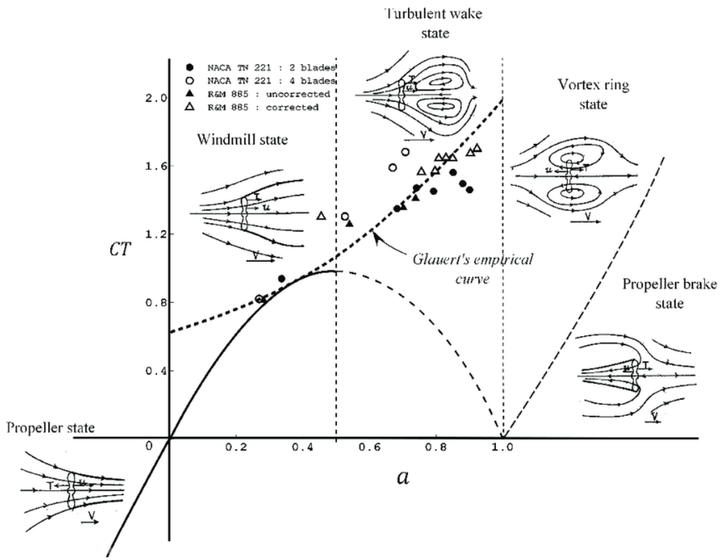
In **stationary** reference frame (right) there is **no flow reversal**

In **rotor** reference frame (left) extensive **flow reversal**

$A = 2°$ $\quad f = 2.5\ Hz$ $\quad f_{fs} = 0.1\ Hz$

BEM cannot distinguish between flow reversal and an incorrect wake state

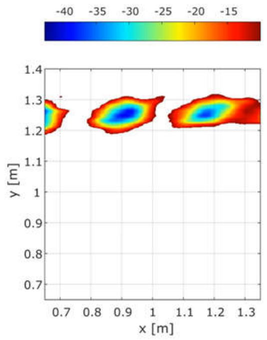




Papi, F., Jonkman, J., Robertson, A., and Bianchini, A.: Going beyond BEM with BEM: an insight into dynamic inflow effects on floating wind turbines, Wind Energ. Sci., 9, 1069–1088, https://doi.org/10.5194/wes-9-1069-2024, 2024.

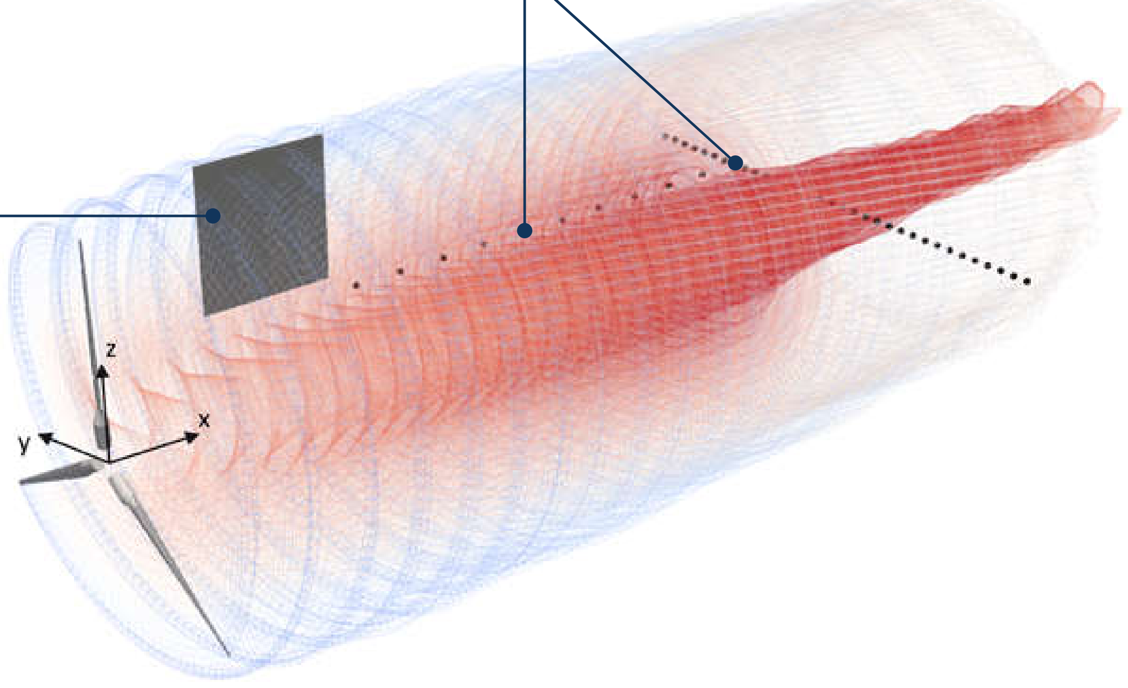
FOWT wake characteristics

During the OC6 phase III project a first analysis on wake characteristics was performed



PIV plane

HWA velocity measurements
up to 2.4D downstream

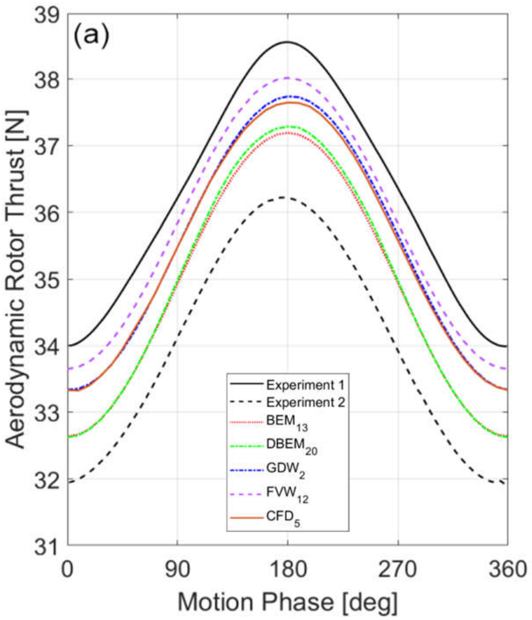


Cioni, S., et al.: On the characteristics of the wake of a wind turbine undergoing large motions caused by a floating structure: an insight based on experiments and multi-fidelity simulations from the OC6 project Phase III, Wind Energ. Sci., 8, 1659–1691, https://doi.org/10.5194/wes-8-1659-2023, 2023.

FOWT wake characteristics

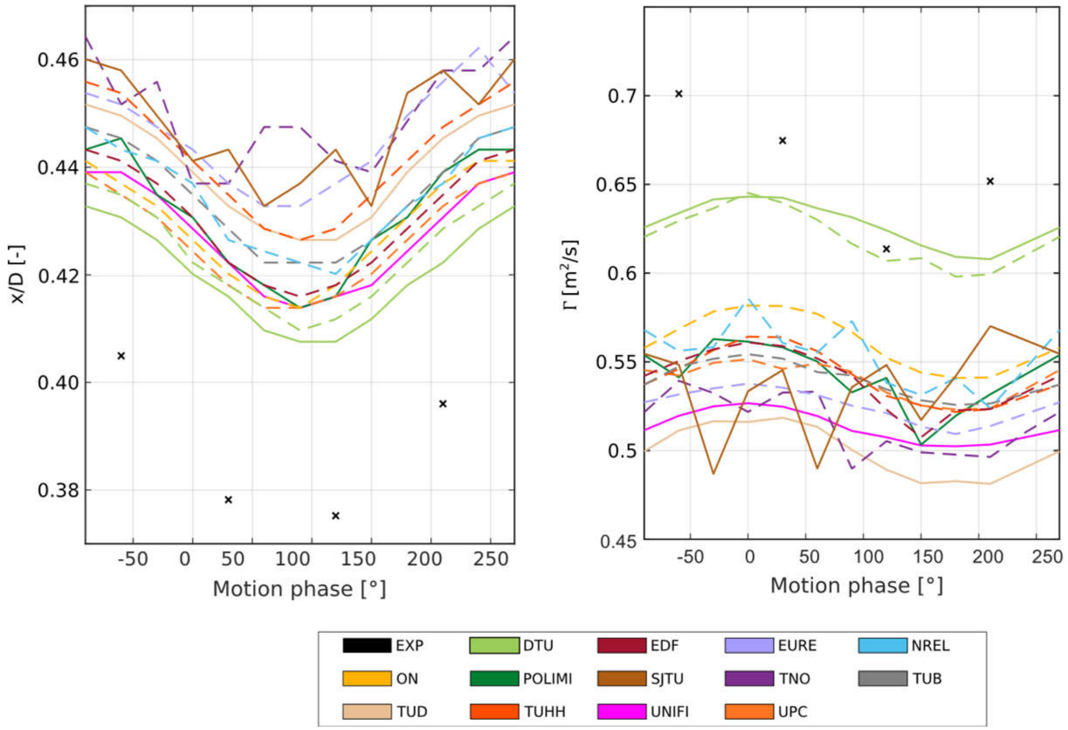
The motion of the platform induces periodic changes in the relative wind speed

- ✓ periodic oscillations in rotor loading
- ✓ periodic oscillations in wake characteristics



Vortex streamwise position

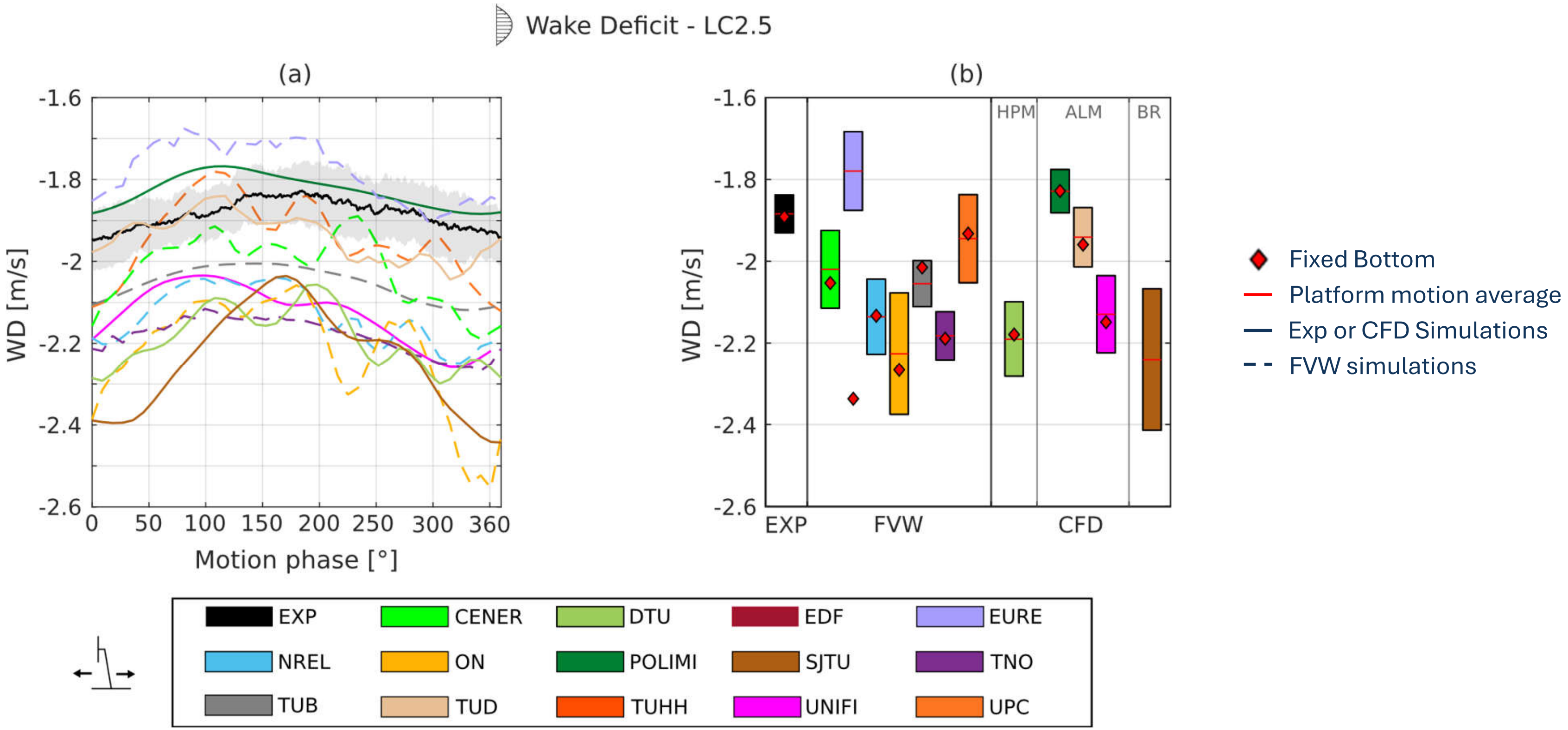
Vortex strength



Wake deficit

Modification to the tip vortex helix affects the mean wake deficit in the wake?

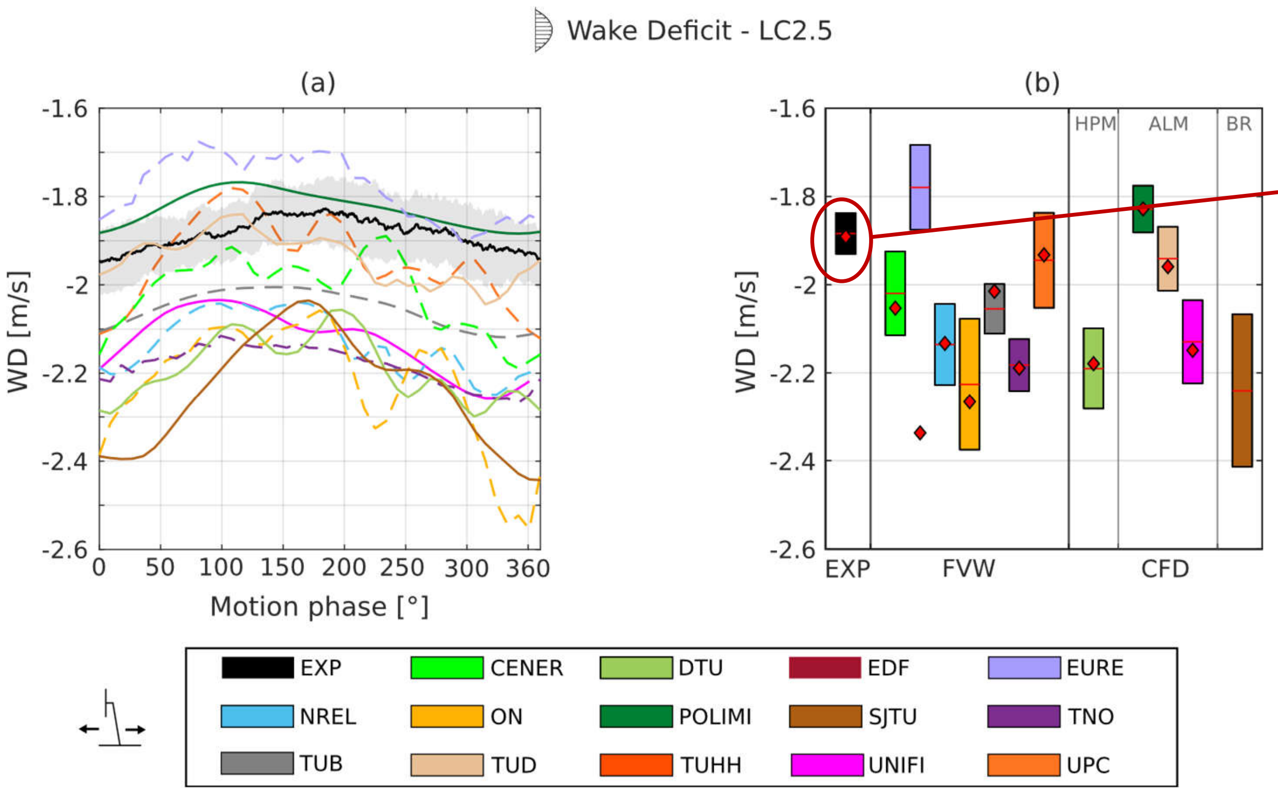
Minor differences with respect to equivalent fixed-bottom cases at 2.4D



Wake deficit

Modification to the tip vortex helix affects the mean wake deficit in the wake?

Minor differences with respect to equivalent fixed-bottom cases at 2.4D

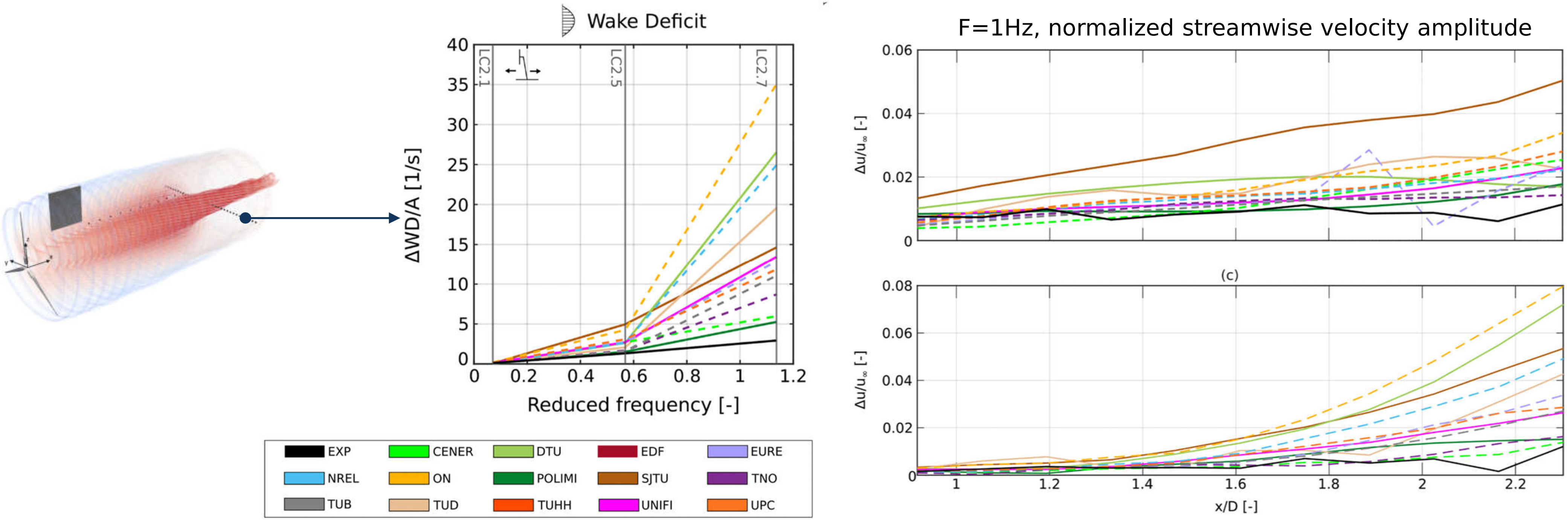


thrust oscillations induce velocity oscillations in the wake!

FOWT wake characteristics – mid wake

As we move downstream and as oscillation frequency increases

- ✓ velocity oscillations in wake increase
- ✓ spread between codes predictions increases



Cioni, S., et al.: On the characteristics of the wake of a wind turbine undergoing large motions caused by a floating structure: an insight based on experiments and multi-fidelity simulations from the OC6 project Phase III, Wind Energ. Sci., 8, 1659–1691, https://doi.org/10.5194/wes-8-1659-2023, 2023.

Recent insights from experiments and numerical simulations

Why wind farms?

Floating wind turbines will allow the exploitation of wind energy resource in deep waters

New floating wind turbines will be installed in **clusters**:

- ✓ reduction of installation costs
- ✓ reduction of O&M costs

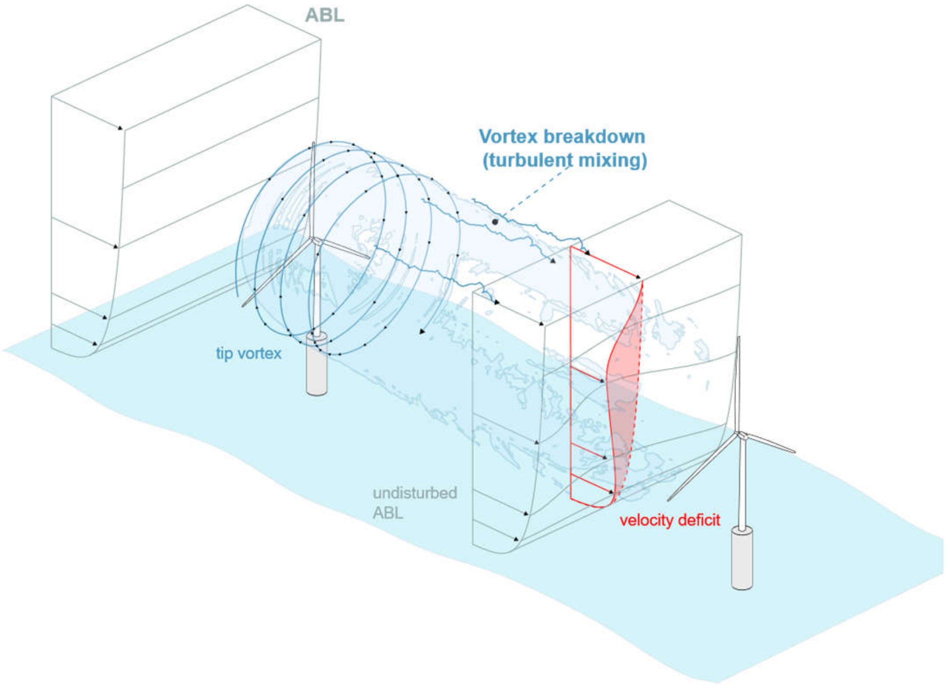
Rotor-wake interactions become significant:

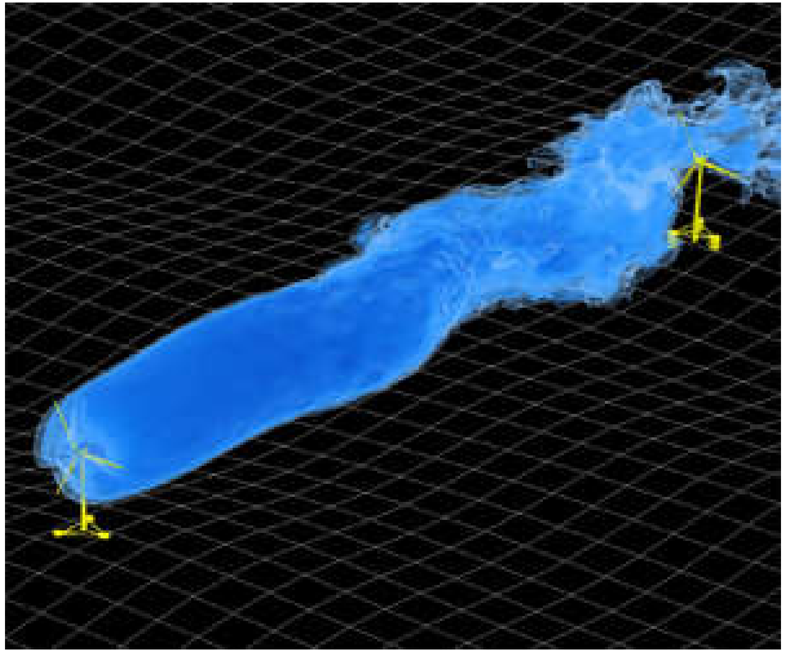
- ✓ reduced power output
- ✓ increased fatigue loading

Preliminary hypothesis

In the initial phases of development of FOWTs wind energy experts hypothesized that:

- ✓ the motion of FOWTs might improve mixing in the wake increasing wind farm power
- ✓ wake dynamics induced by the motion may increase fatigue loading





https://doi.org/10.1017/jfm.2023.1097

Open questions

Research is, however, needed in this field

1. Is the enchanced mixing taking place in every conditions?
2. If not, which are the conditions that trigger it?
3. Which is the role of turbulence?
4. To what extent loads in downwind turbines are affected?

Experimental results

Motion conditions

Sinusoidal motion

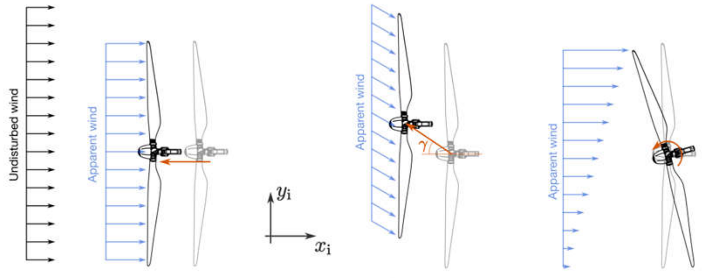
Direction of platform motion	Amplitude (a) [m] or [°]	Frequency (f) [Hz]	Reduced frequency (f_r) [–]	Δu [$\mathrm{m\,s^{-1}}$]
Fixed	–	–	–	–
Surge	0.032 m	0.5	0.3	0.1
	0.064 m	0.5	0.3	0.2
	0.016 m	1.0	0.6	0.1
	0.032 m	1.0	0.6	0.2
	0.048 m	1.0	0.6	0.3
	0.016 m	2.0	1.2	0.2
	0.032 m	2.0	1.2	0.4
	0.048 m	2.0	1.2	0.6
Pitch	1.3°	0.5	0.3	0.1
	2.5°	0.5	0.3	0.2
	3.0°	0.5	0.3	0.25
	0.6°	1.0	0.6	0.1
	1.3°	1.0	0.6	0.2
	1.9°	1.0	0.6	0.3
	0.3°	2.0	1.2	0.1
	0.6°	2.0	1.2	0.2
	1.3°	2.0	1.2	0.4
	1.9°	2.0	1.2	0.6
Surge–sway 30°	0.032 m	0.5	0.3	0.1
Surge–sway 15°	0.032 m	1.0	0.6	0.19
Surge–sway 30°	0.032 m	1.0	0.6	0.17
Surge–sway 45°	0.032 m	1.0	0.6	0.14
Surge–sway 30°	0.032 m	2.0	1.2	0.35
Roll–pitch 15°	1.3°	1.0	0.6	0.20
Roll–pitch 30°	1.3°	1.0	0.6	0.18
Roll–pitch 45°	1.3°	1.0	0.6	0.15
Yaw	2°	0.5	0.3	–
	2°	1.0	0.6	–
	3°	1.0	0.6	–
	2°	2.0	1.2	–

Reduced frequency:

$$f_r = \frac{fD}{U_\infty}$$

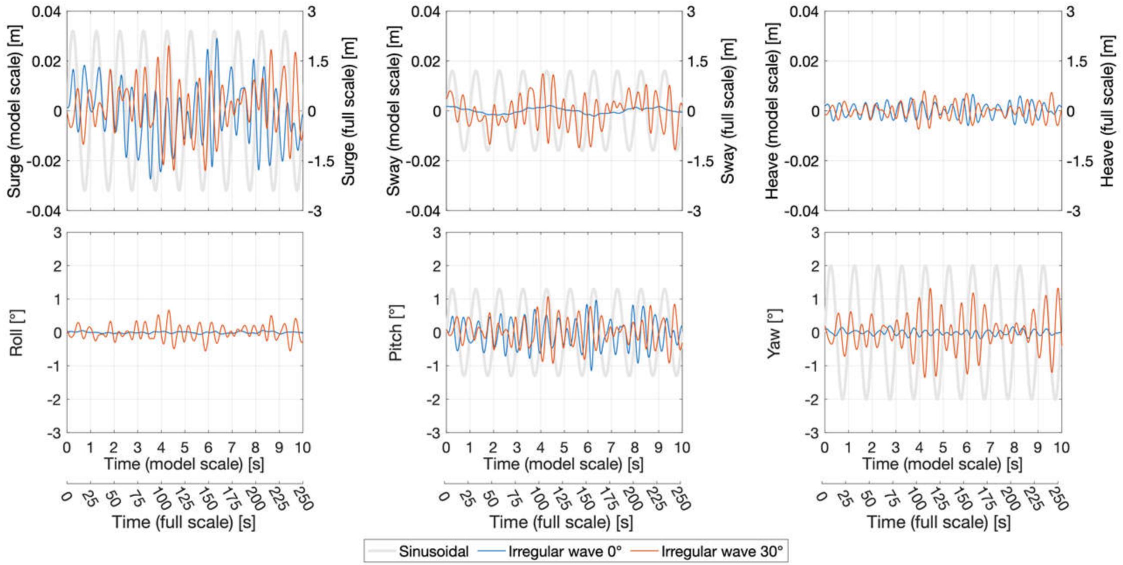
Amplitude of apparent wind speed:

$$\Delta u = 2\pi f \cdot A_\mathrm{m}$$



(a) Surge Pitch (b) Surge+sway Pitch+roll (c) Yaw

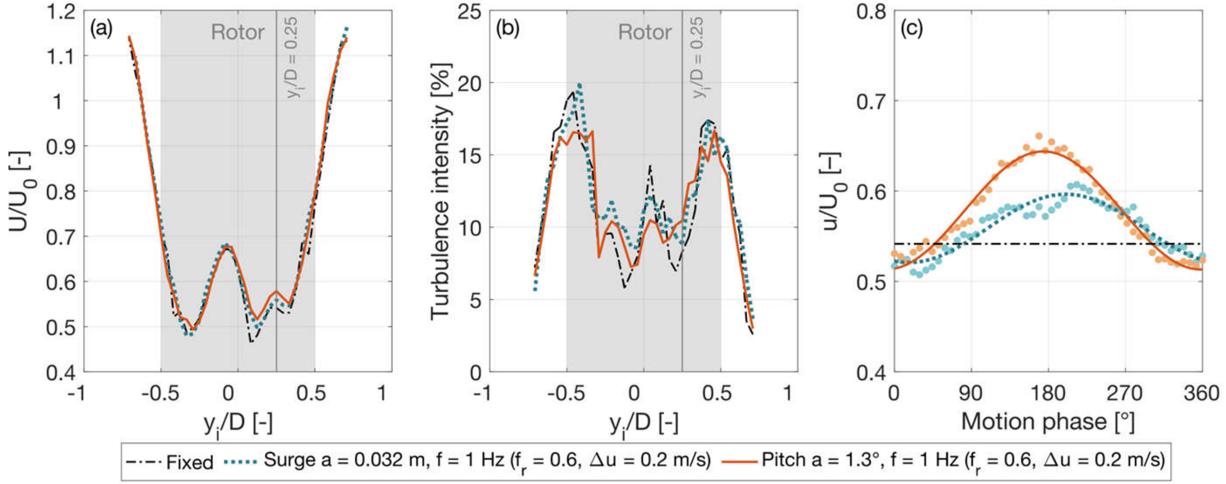
Irregular-wave motion

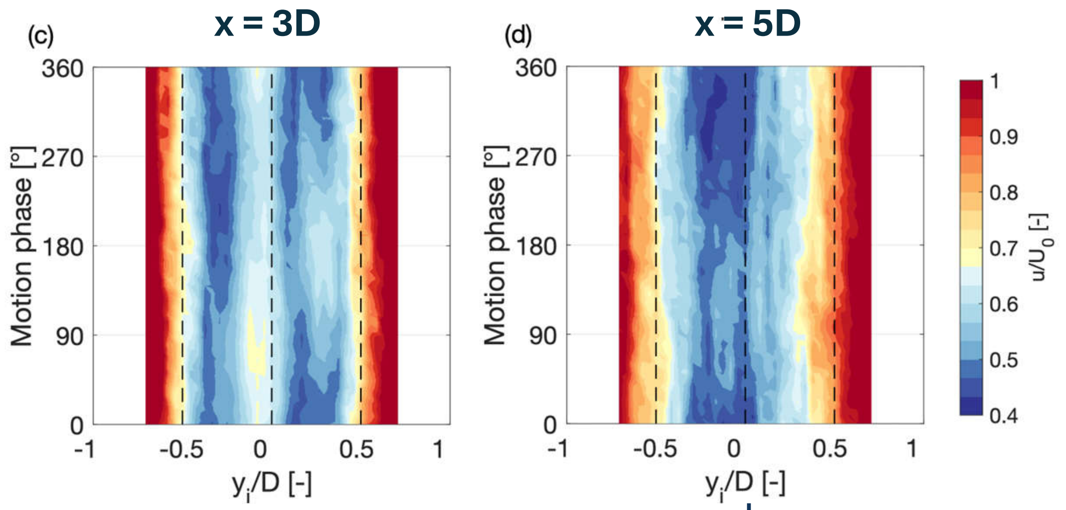


- Softwind + DTU 10MW
- Pre-computed motions with OpenFAST
- Inflow and turbine settings matching the experiment (rated wind speed, fixed rotor speed and blade pitch)
- Waves: significant height of 5 m and a peak period of 12 s, at 0° and 30° with respect to wind direction

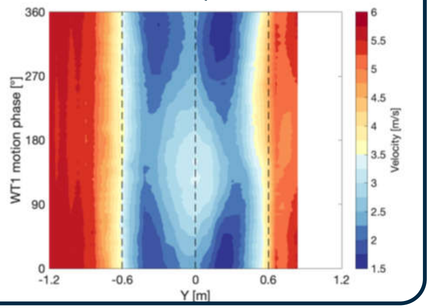
Sinusoidal surge/pitch – Wake

Wake at x = 3D



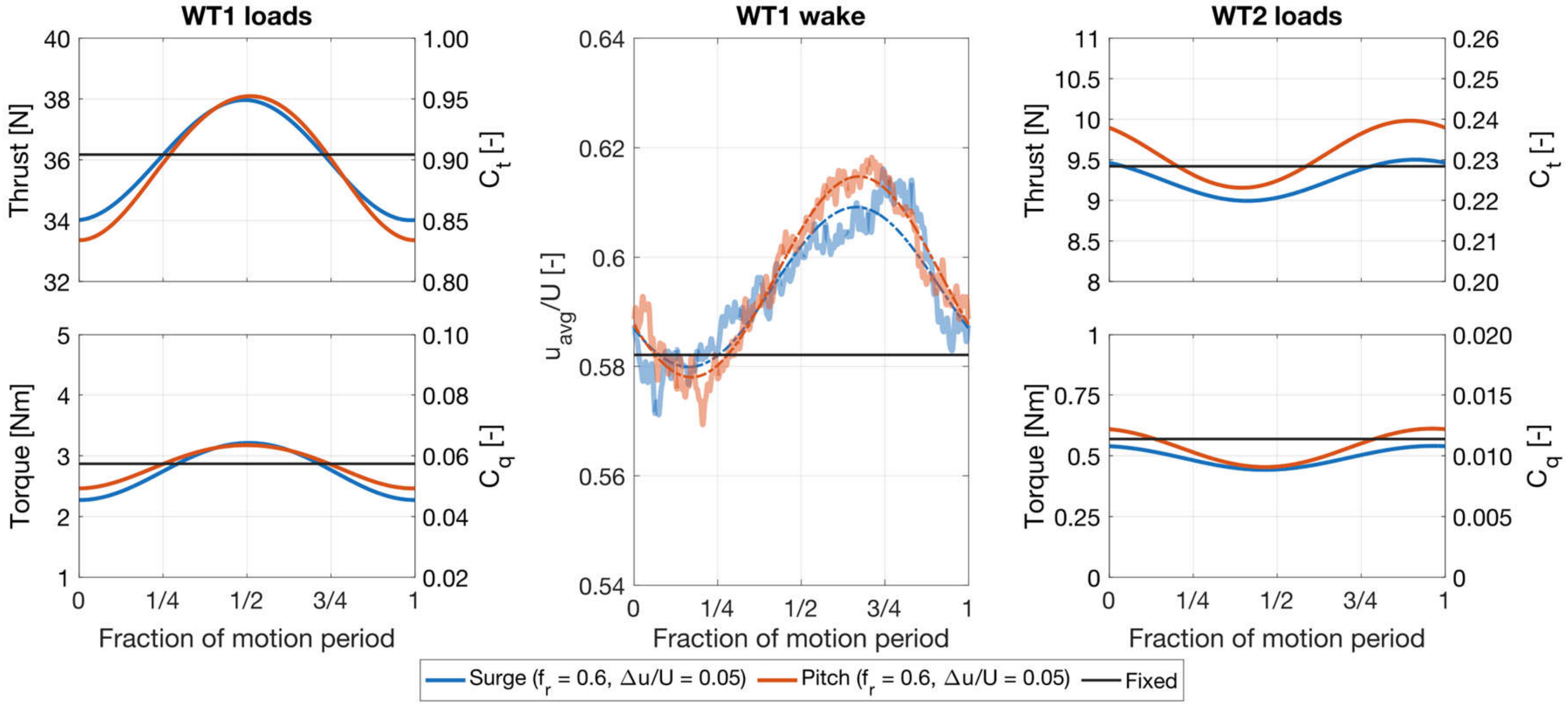


Rotor diameter = 1.2 m, same inflow, same red. freq. , wake at 5.5D



- Mean velocity and turbulence profiles similar to the bottom-fixed case
- Wake velocity oscillates at the platform motion frequency
- Oscillations not fully coherent across the wake width

Sinusoidal surge/pitch – Downstream loads

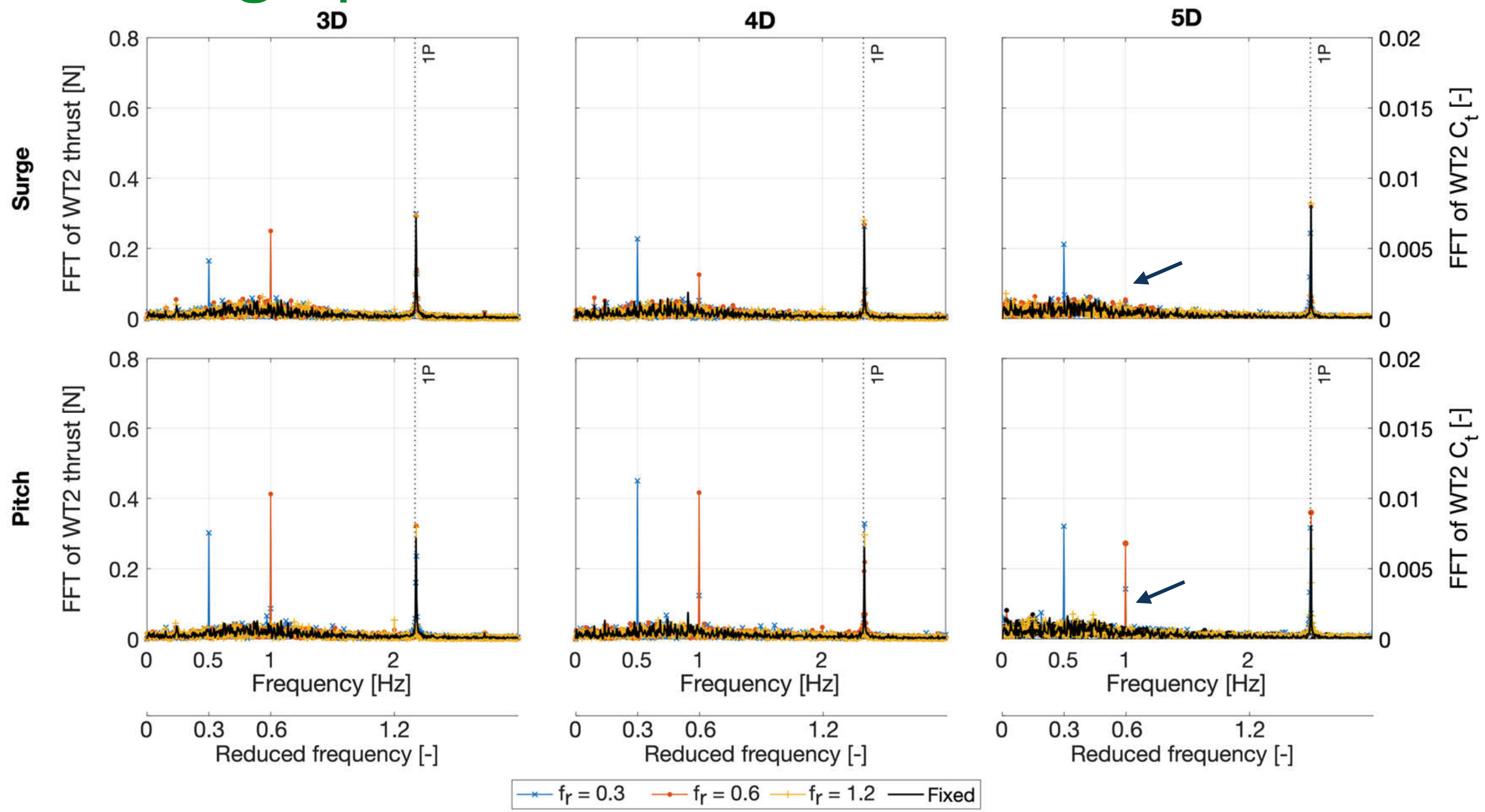


Upstream turbine
Sinusoidal oscillations in thrust and torque at the motion frequency
Oscillations driven by apparent wind variations

Wake
Pulsating wake (periodic acceleration/deceleration)
Spatially averaged wake velocity fluctuates by ~1.5% of U

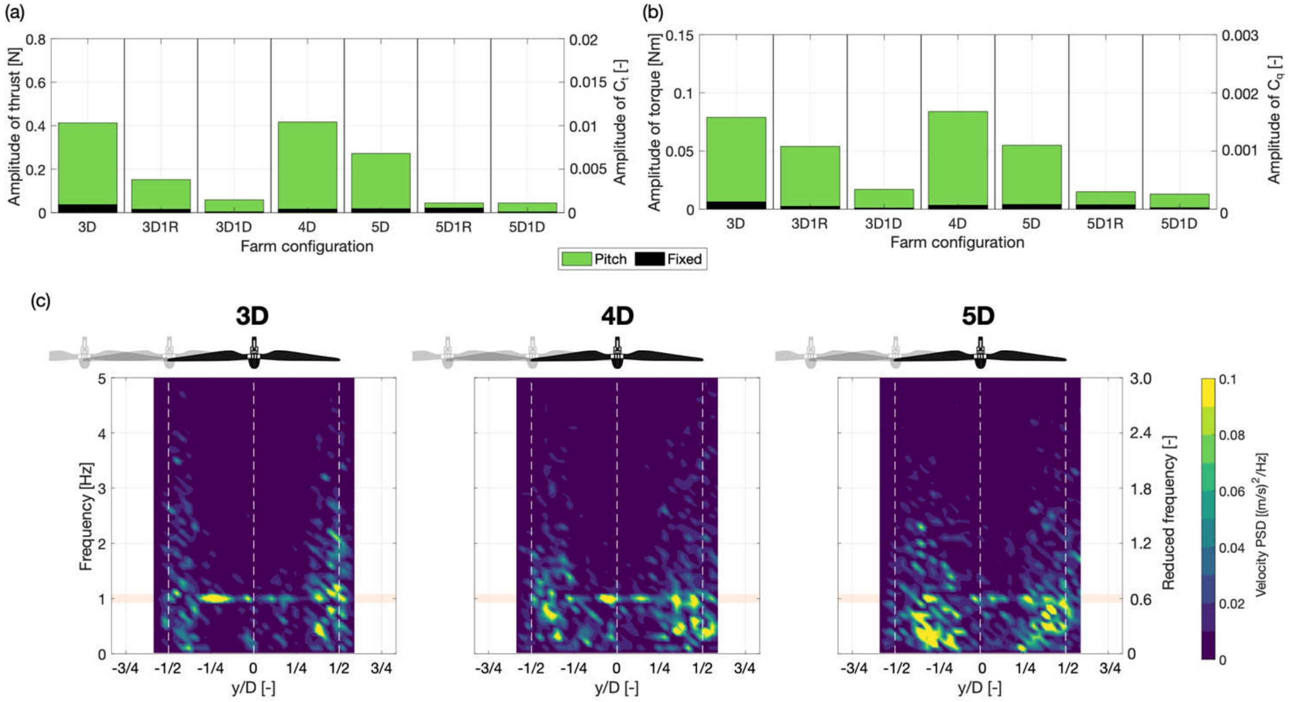
Downstream turbine
WT2 load oscillations, same frequency as WT1 motion
Amplitude much smaller than WT1
Phase lag due to wake advection

Sinusoidal surge/pitch – Downstream loads



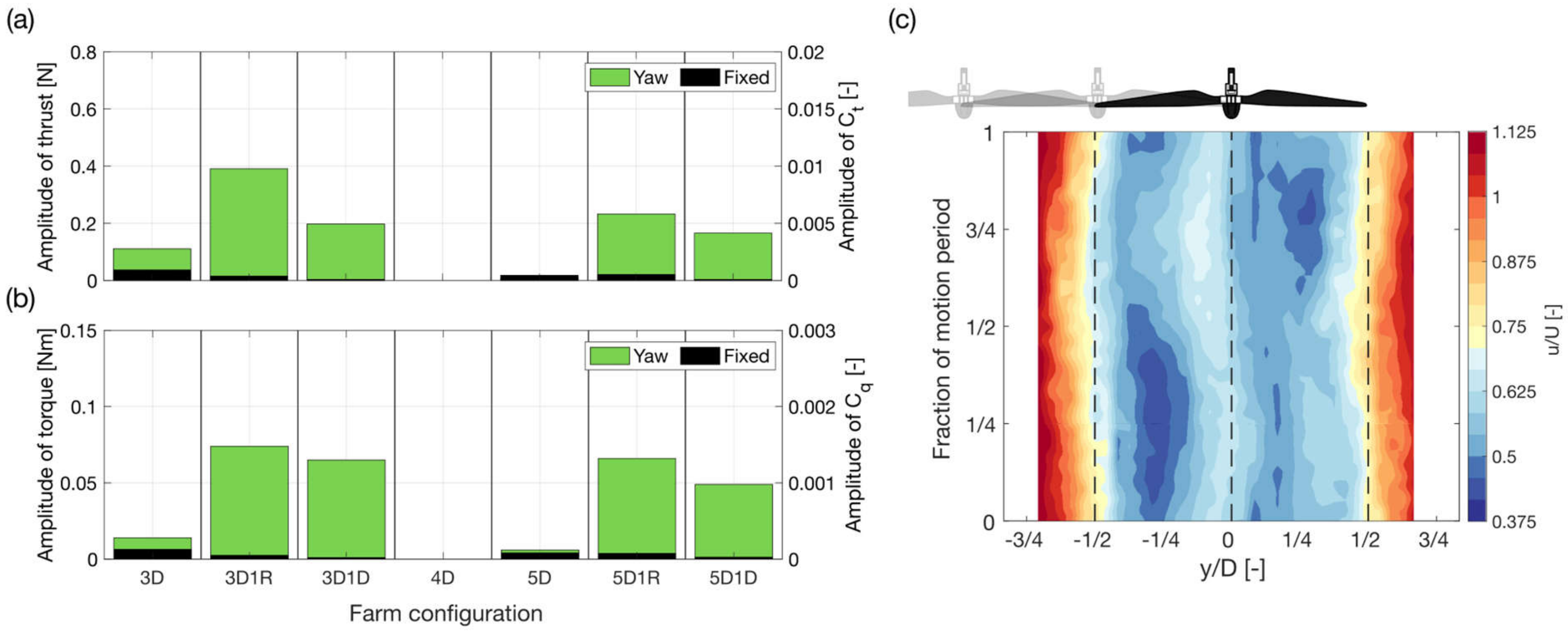
- Downstream loads mirror upstream motion frequency when wake structures remain coherent:
  - ➢ effects weaken with distance and at higher reduced frequencies.
- Pitch can introduce additional harmonics due to wake deflection.

Sinusoidal pitch – Downstream loads



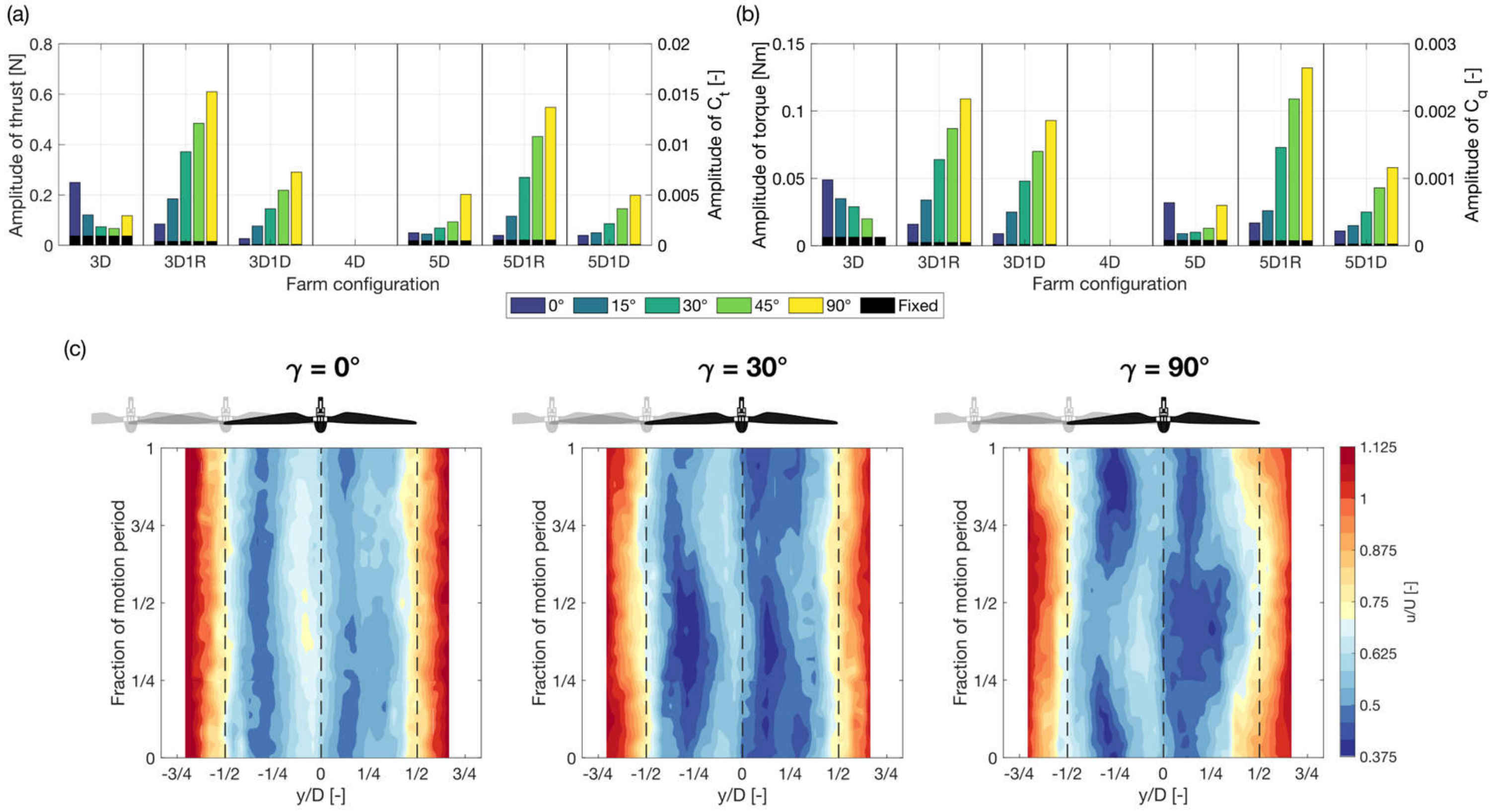
- Periodic inflow oscillations weaken from 3D to 5D
  - Motion-induced wake structures are progressively masked by turbulence downstream.
- Maximum thrust and torque oscillations occur in aligned configurations
  - WT2 is fully immersed in the pulsating wake
  - Velocity fluctuations affect the entire rotor-swept area, maximizing rotor-averaged load oscillations

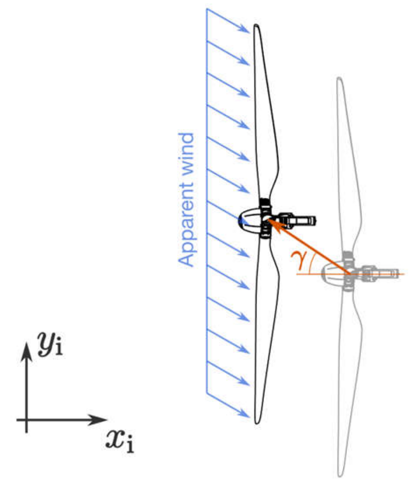
Sinusoidal yaw



- Surge/pitch → wake pulsation (streamwise velocity modulation)
- Yaw → lateral meandering + antisymmetric velocity field
- In aligned layouts, rotor-averaged thrust/torque oscillations remain small due to cancellation.
- With lateral offset (especially 1R), cancellation is broken → dynamic loads comparable to pitch-induced wake pulsation.

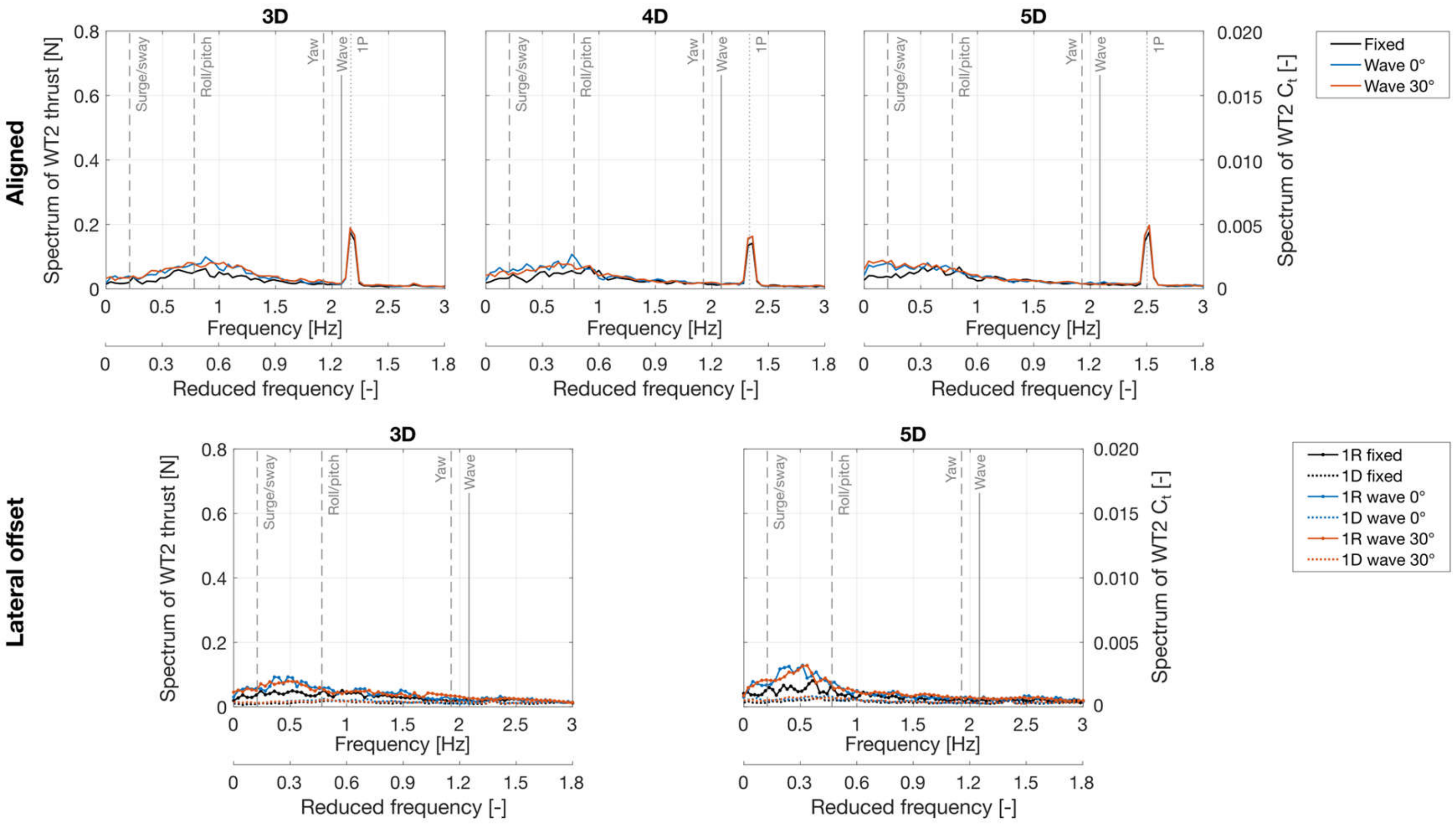
Sinusoidal surge+sway





- Increasing γ shifts wake behavior from pulsation → meandering.
- Aligned turbines: load oscillations decrease with γ due to cancellation.
- Offset turbines: load oscillations increase with γ due to broken symmetry (largest in pure sway)
- Crosswind motion can generate equal or larger cyclic loads than surge or pitch.

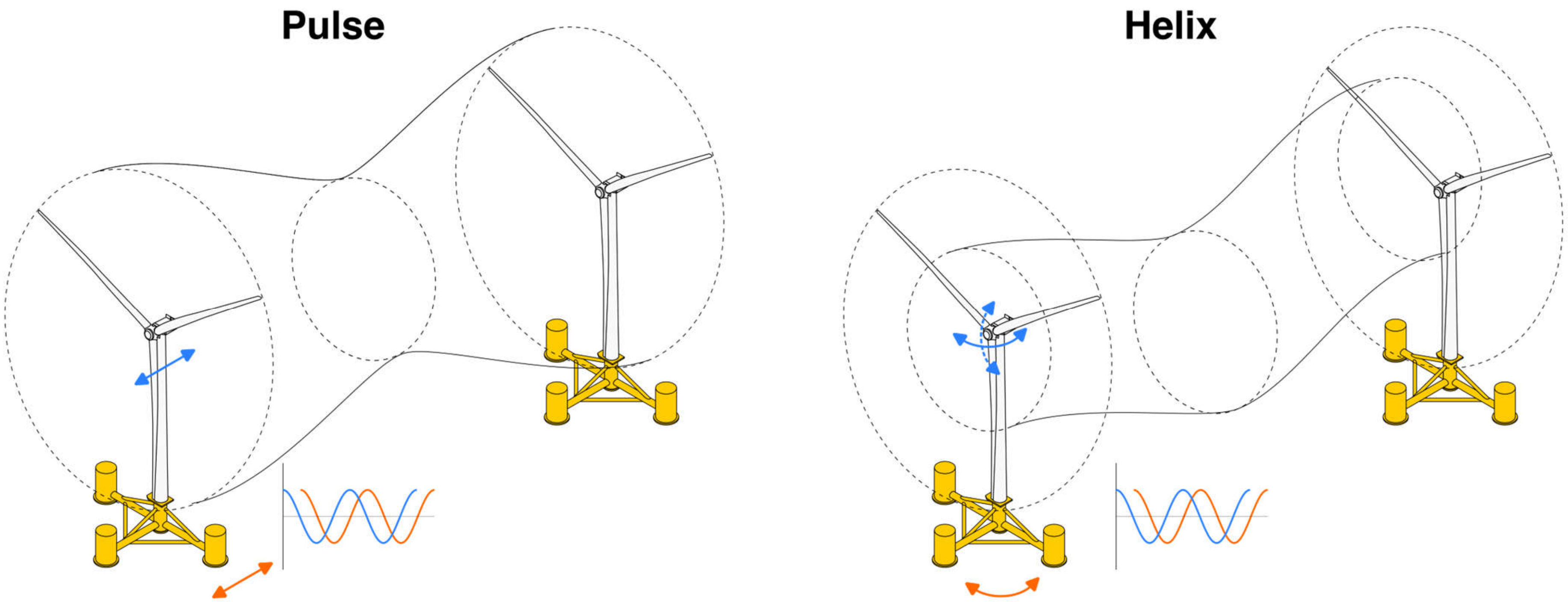
Irregular-wave motion – Downstream loads



- Wave-driven motion increases downstream turbine loads at **low reduced frequencies (<0.6)**.
- No amplification near wave spectral peak (fr≈1.25).
- Load increases are **smaller than with sinusoidal motion**, due to reduced coherence.

- Strongest effects occur in aligned and 1R configurations; negligible at 1D offset.

Active wake control

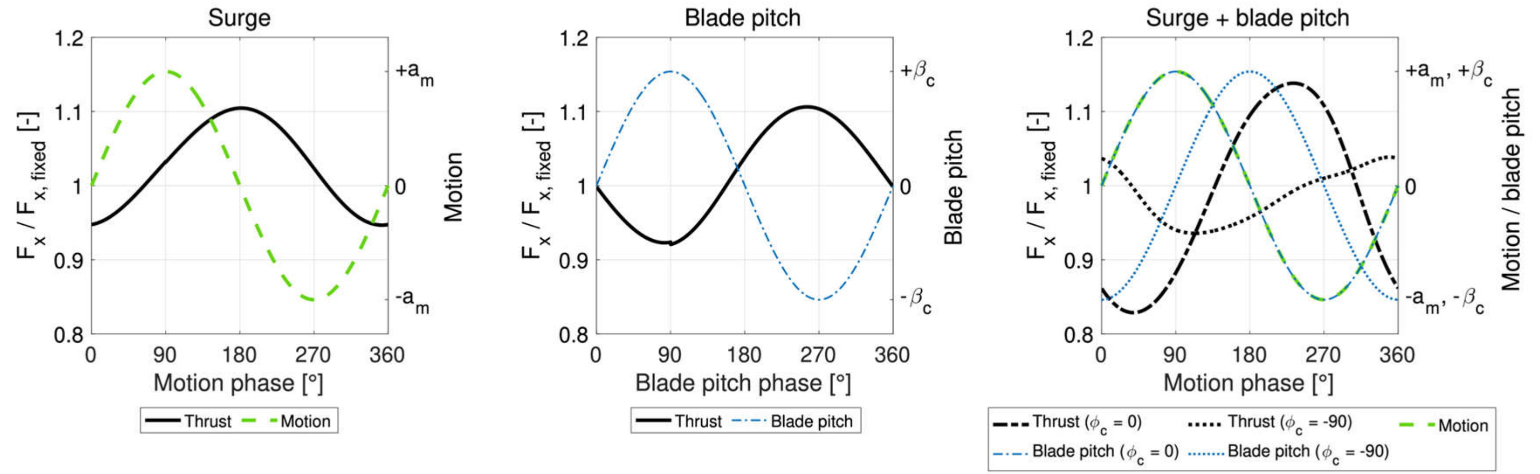


Pulse = dynamic induction control with sinusoidal collective blade pitch

Helix = cyclic individual blade pitch

- Active wake control strategies combined with the platform movements they generate.
- Uncoupled platform motions.
- Parametric study of the phase shift between wake excitation and platform response.

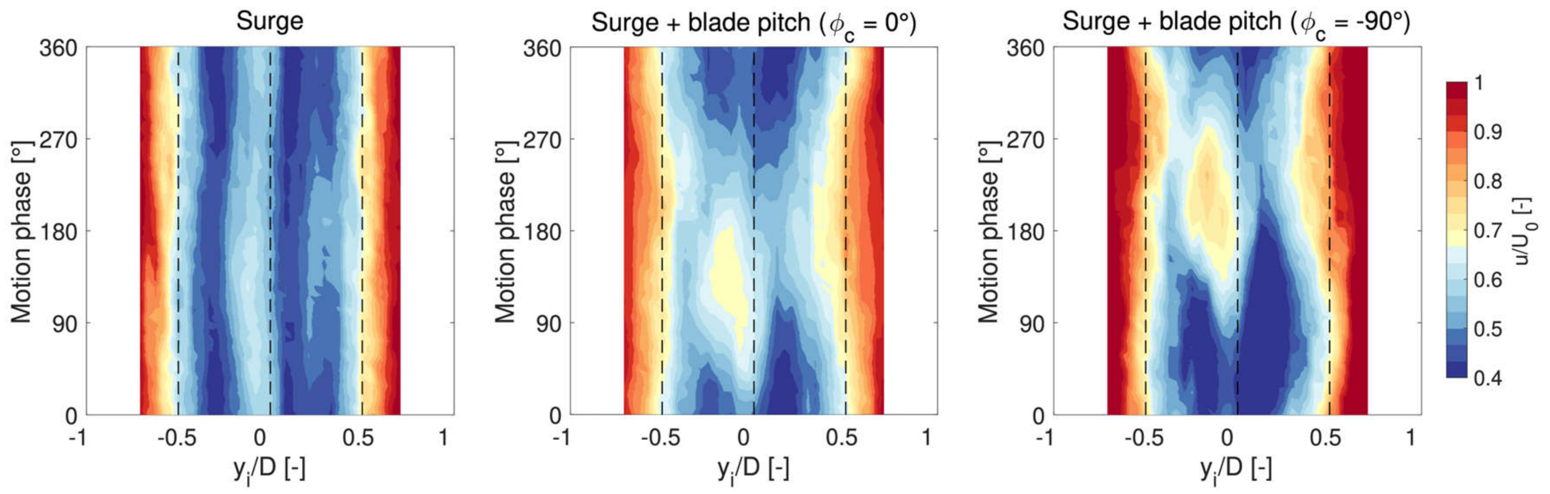
Pulse + surge motion – Upstream turbine loads and wake



Thrust Response

Thrust response strongly depends on phase offset between blade pitch and surge (ϕc):

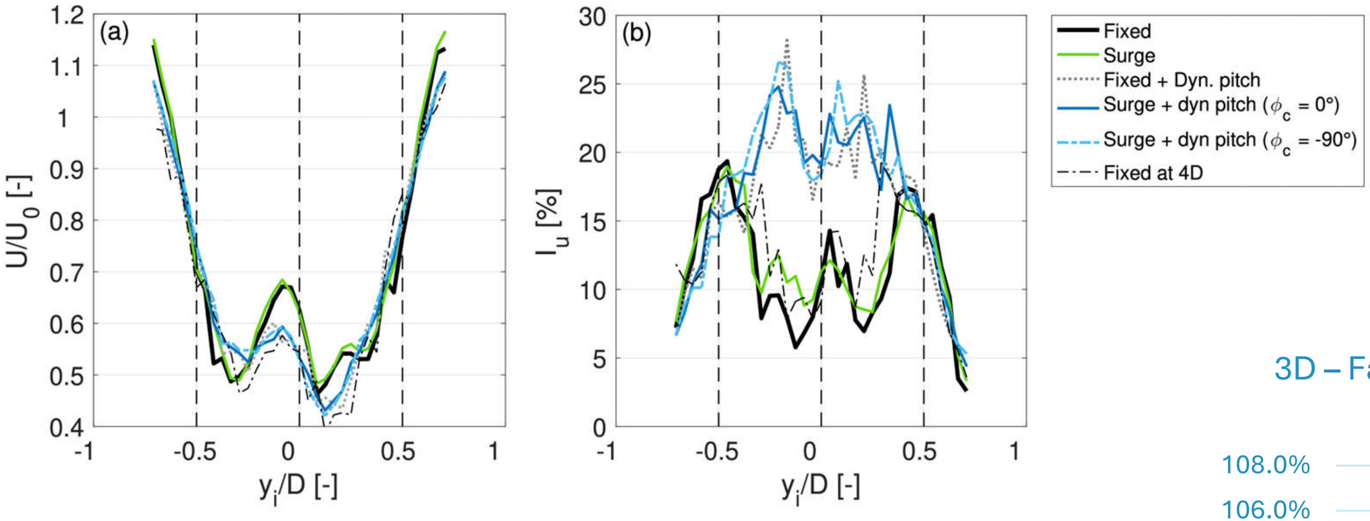
- ϕc = −90° blade pitching mitigates surge-induced thrust oscillations
- ϕc = 0° blade pitching amplifies surge-induced thrust oscillations



Wake response

- Coherent oscillations across entire wake width (pulsing)
- Changing phase offset (ϕc) does not significantly change fluctuation amplitude.

Pulse + surge motion – Wake and downstream turbine power



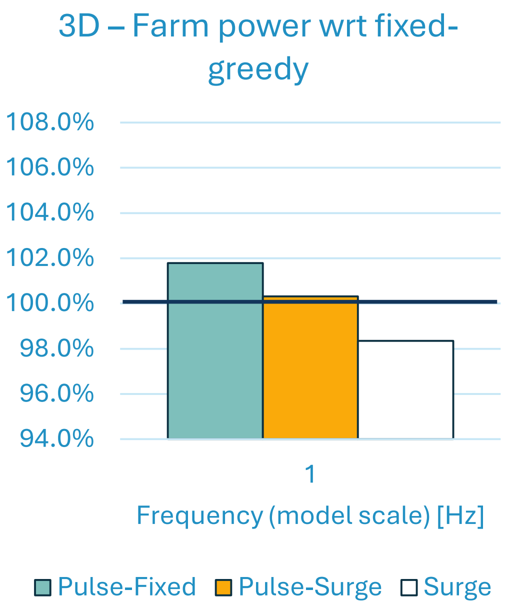
Mean Wake and Turbulence

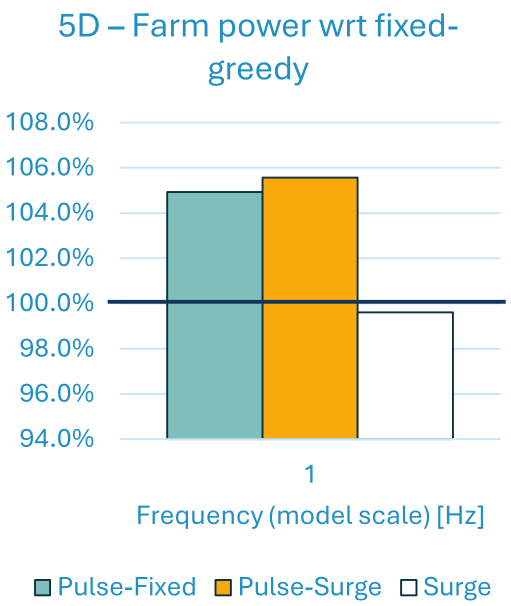
Significantly increases turbulence intensity at wake center.

- Increased turbulence enhances wake–free-stream mixing → faster wake recovery
- At x = 3D wake deficit with dynamic pitching ≈ wake deficit at 4D without pitching → accelerated recovery

Farm power

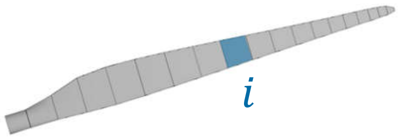
- Surge only: no significant increment
- 3D: tiny increase with dynamic blade pitch
- 5D: 5% increase with dynamic blade pitch





Numerical results

Numerical Models



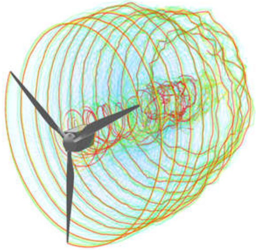
$$F_l = \sum_i \frac{1}{2} C_l(\alpha) c\rho W^2 l_i$$

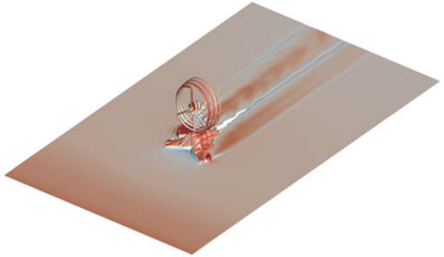
$$F_d = \sum_i \frac{1}{2} C_d(\alpha) c\rho W^2 l_i$$

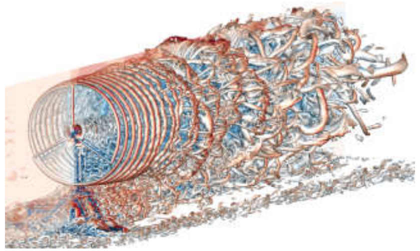
LLFVW

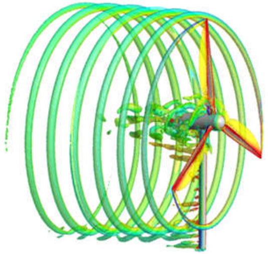
ALM

Blade Resolved









convecting vortex filaments

- ✓ accurate load prediction
- ✓ signficantly faster than CFD

URANS

- ✓ ≈15M cartesian cells

LES

- ✓ ≈120M cartesian cells

URANS

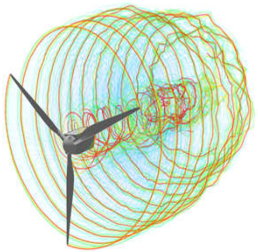
- ✓ ≈ 80M cartesian cells

Numerical Models

1 ENGINEERING MODEL

can this engineering model
give meaningful information?

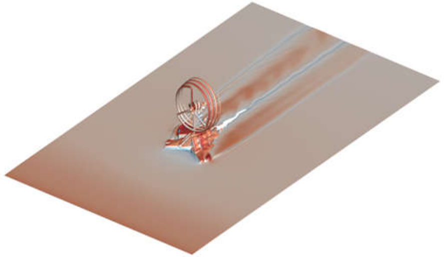
how does it need to be calibrated?

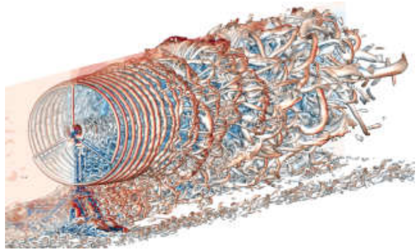


2 SOLUTION OF WAKE

Is ALM the cost-to-preformance
sweetspot?

Is URANS sufficent?

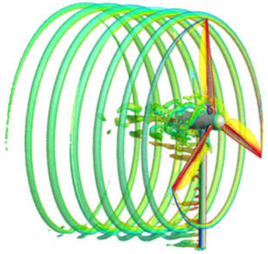




3 BLADE & WAKE SOLUTION

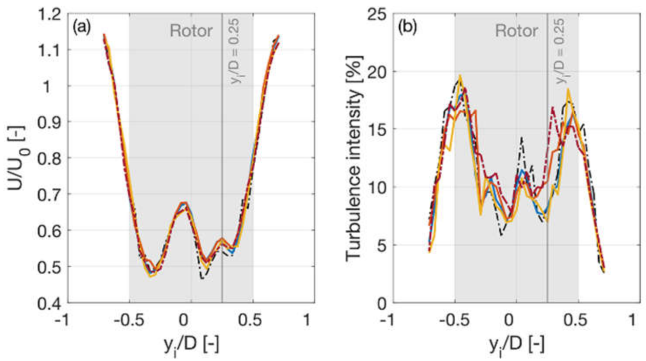
Digital-twin of experiments

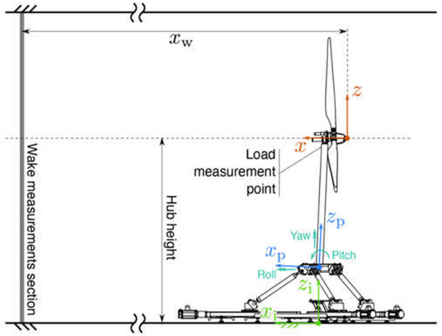
spanwise load distribution
validation



Validation with respect to experiments

validation on a single turbine

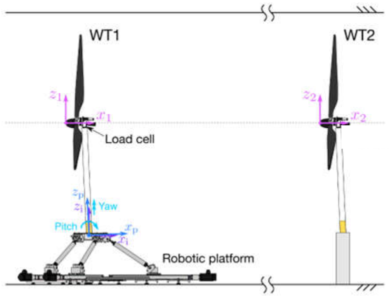


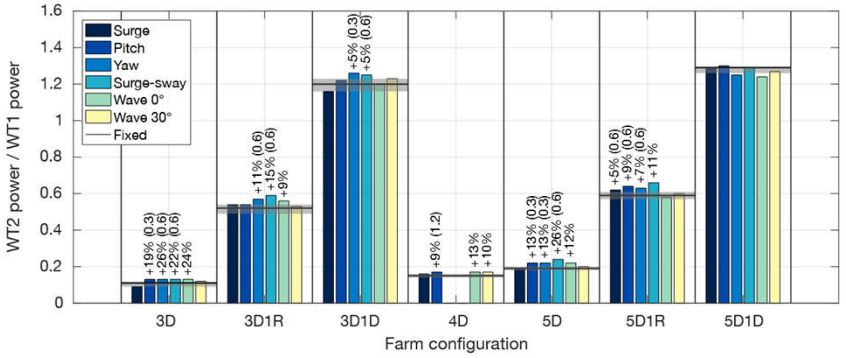


wake-rake measurements
3 D & 5 D downstream
pitch, surge, yaw motion

validation on two turbines

load measurements
on downstream rotor
pitch, surge, yaw motion





TETHYS

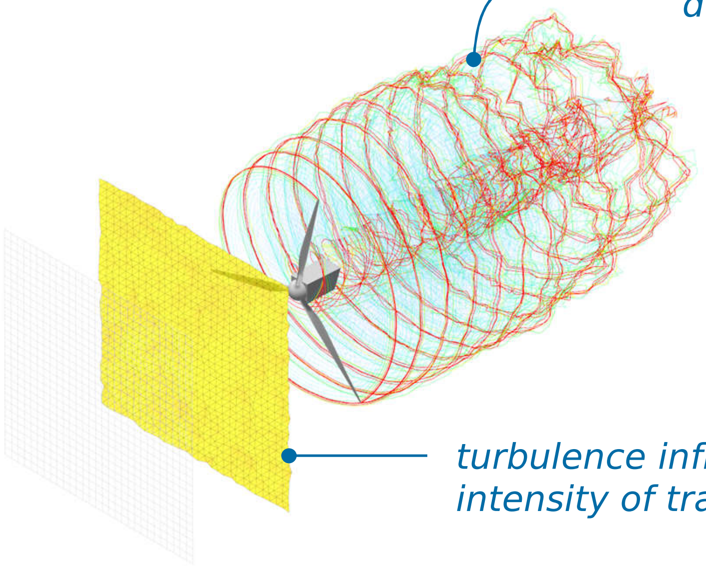
Inflow turbulence

1 ENGINEERING MODEL

LLFVW

Inflow turbulence is included in the simulation using a **frozen turbulence approach**

Turbsim was used to **match the inflow turbulent spectra** from the wind tunnel



vortex filaments convected downstream with velocity:

$$u = u_{wind} + u_{ind}$$

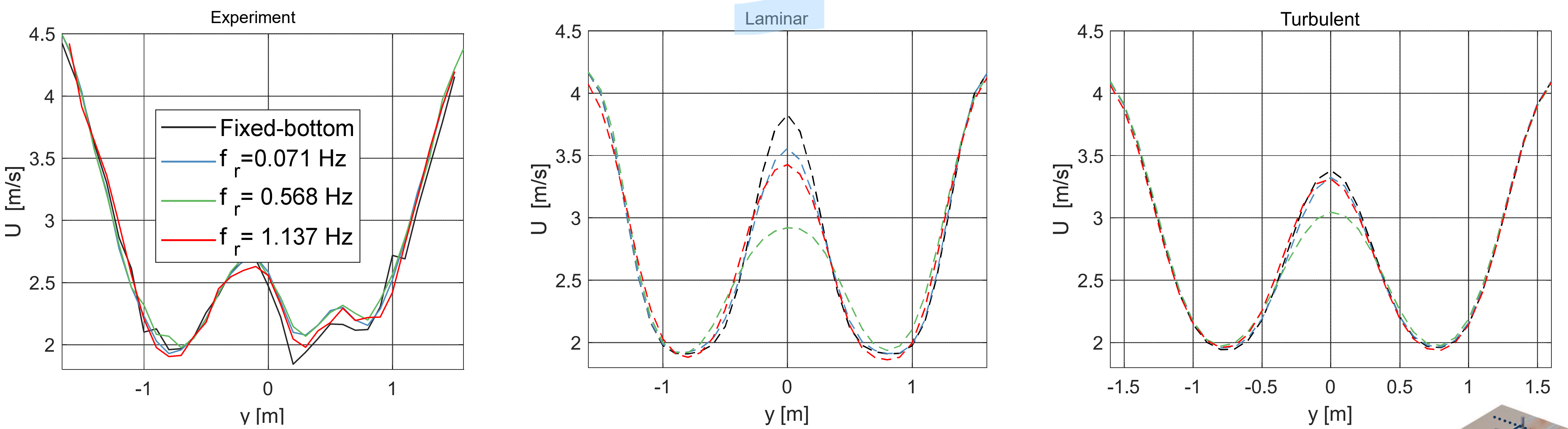
- ✓ **local**
- ✓ hub-height
- ✓ shear w/o turbulence

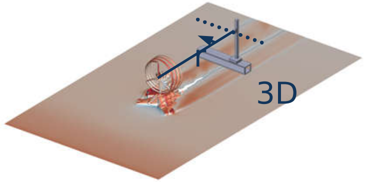
turbulence influences blade forces and intensity of trailing vortices

Inflow turbulence

1 ENGINEERING MODEL

For laminar inflow conditions the wake breakdown is anticipated by platform motion



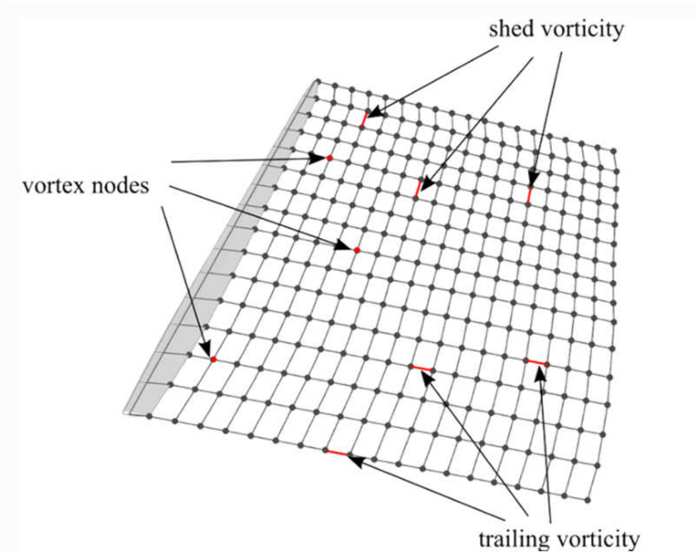


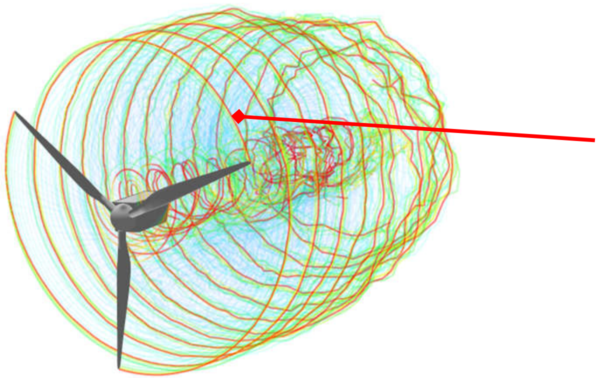
Can the FVW method capture the wake?

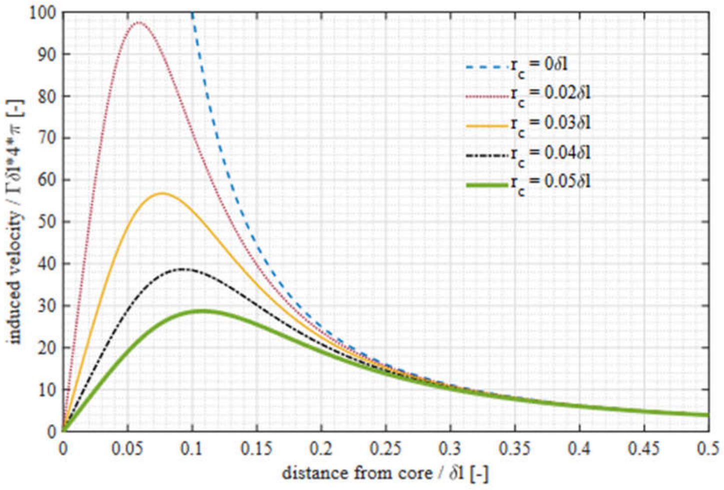
1 ENGINEERING MODEL

The wake is solved as the juxtaposition of vortex filaments shed at the lifting line. **Significant user input** required:

- ✓ **initial size** of the vortex filaments
- ✓ **turbulent viscosity** – used to reproduce dissipation effects in non-viscous FVW model







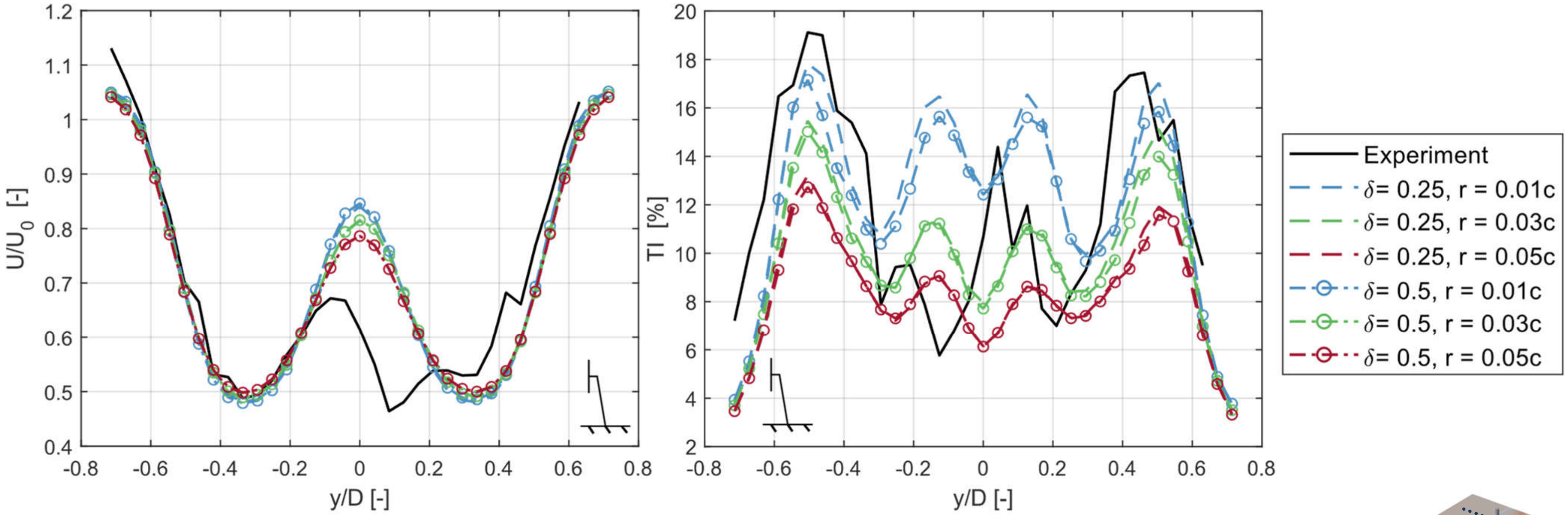
FVW simulation parameters

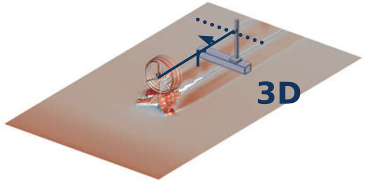
1 ENGINEERING MODEL

The definition of the inputs has a **significant impact on the reliability of the simulation**

$$r_c = r_0 + \sqrt{\frac{4a\delta_v \nu \Delta t}{1+\epsilon}}$$

r_0: initial core radius
δ_v: turbulent viscosity
ϵ: vortex strain
ν: kinematic viscosity
Δt: time step

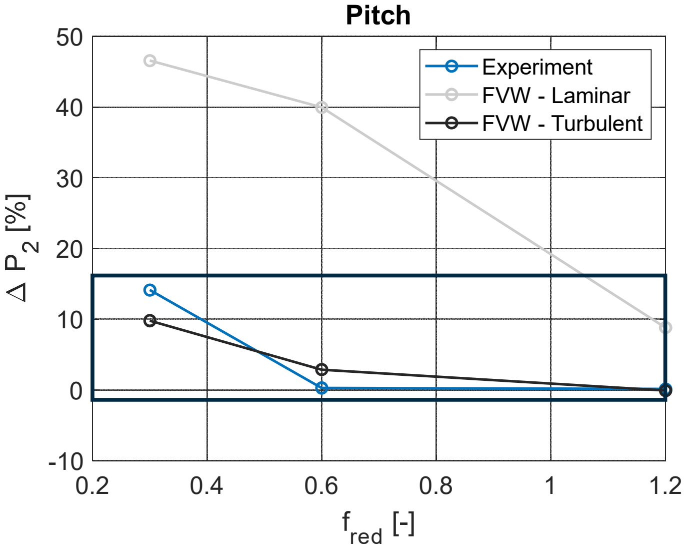


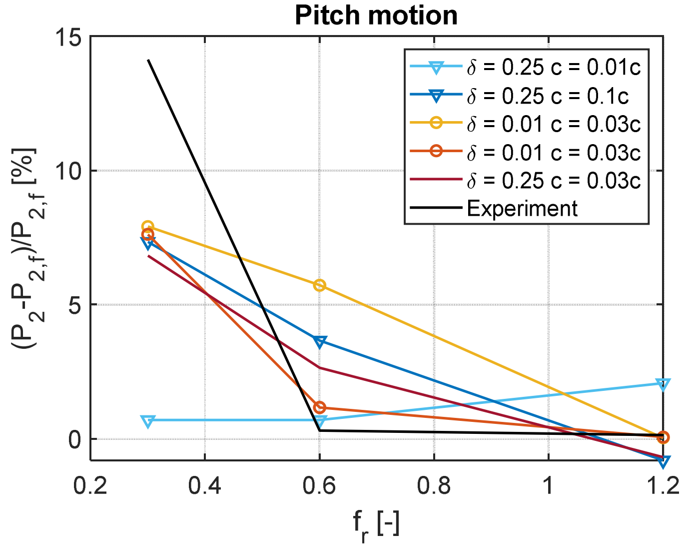


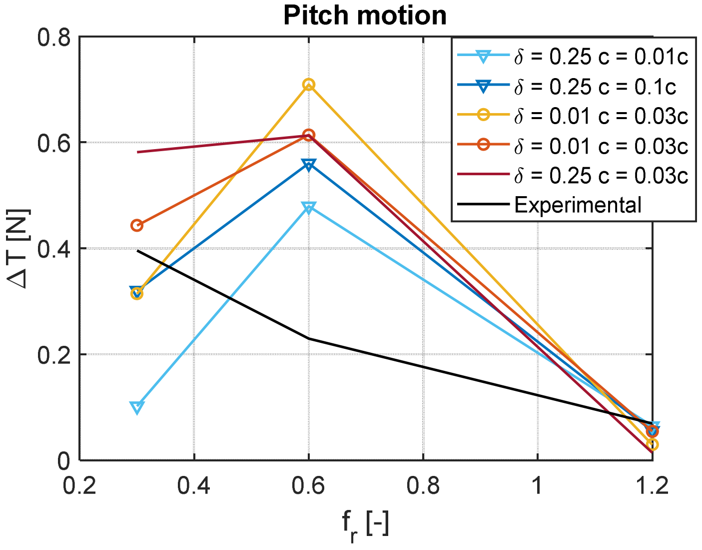
FVW simulation parameters

1 ENGINEERING MODEL

Turbulence, initial vortex core radius and turbulent viscosity also affect the predicted load oscillations on a downstream turbine @5D



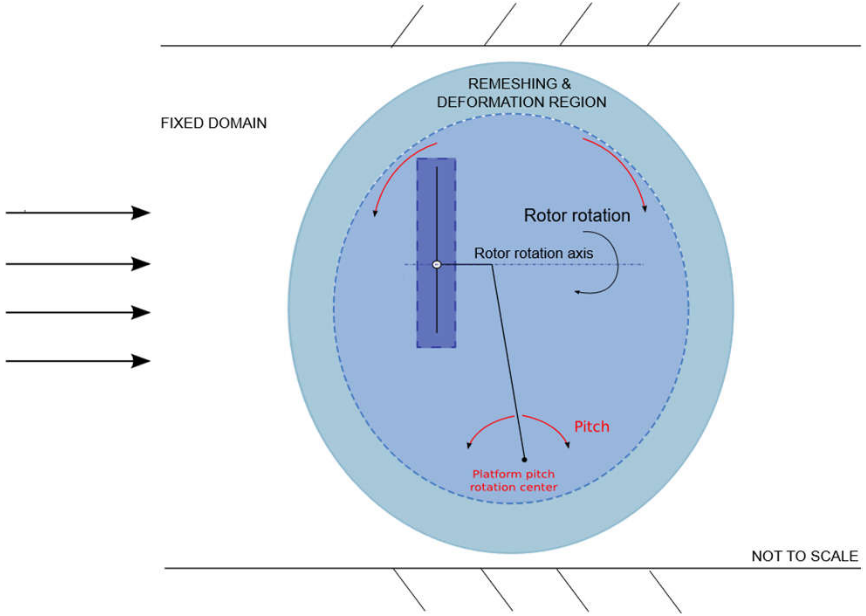




Overall FVW is reasonably predictive if fine-tuned

Blade Resolved reference

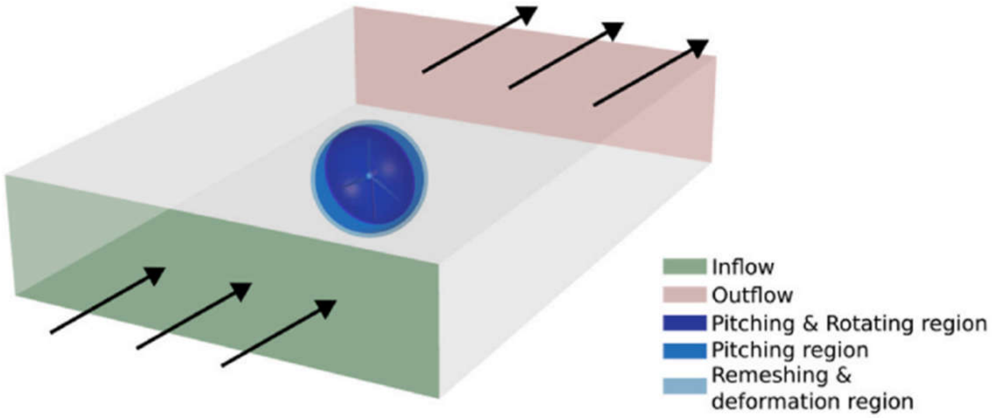
3 BLADE & WAKE SOLUTION



URANS with k-ω SST turbulence model in Ansys Fluent©:

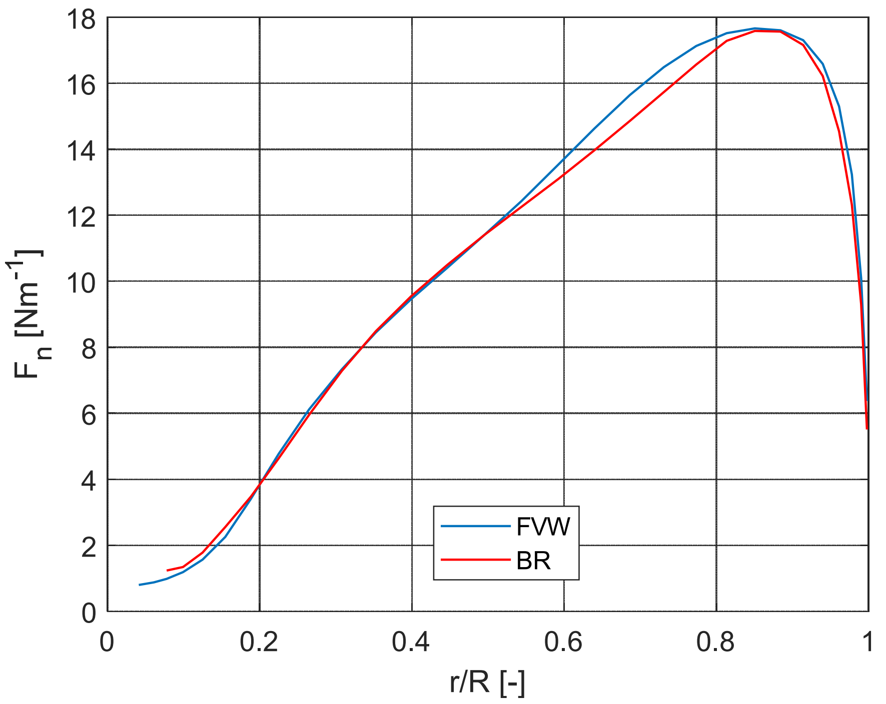
- tower and nacelle are included
- pitching motion is introduced with a deforming and remeshing strategy
- ≈60M polyhedral and tetrahedral cells

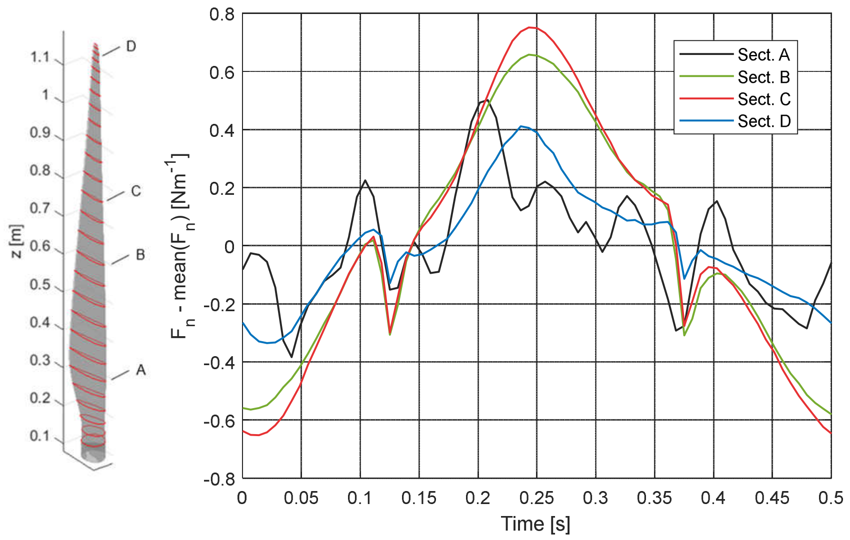
Blade-resolved results are leveraged to obtain additional information on the spanwise rotor response, **not available from the experiments**



Blade-resolved simulation of FOWTs

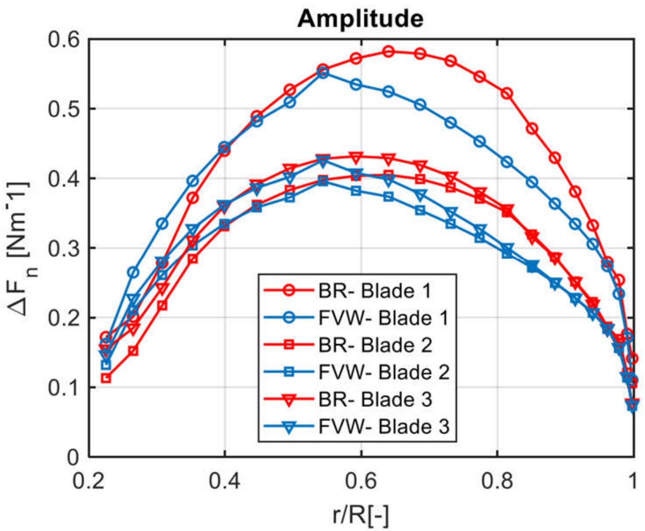
3 BLADE & WAKE SOLUTION

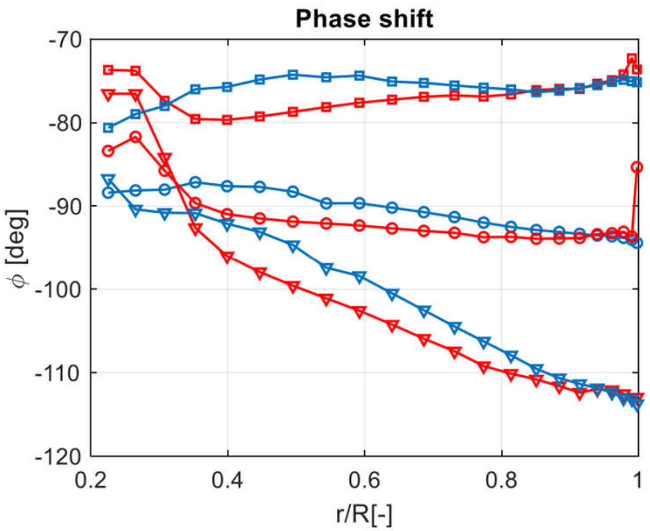


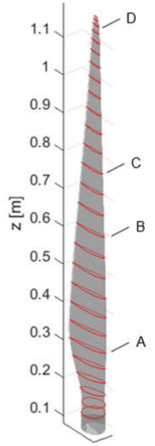


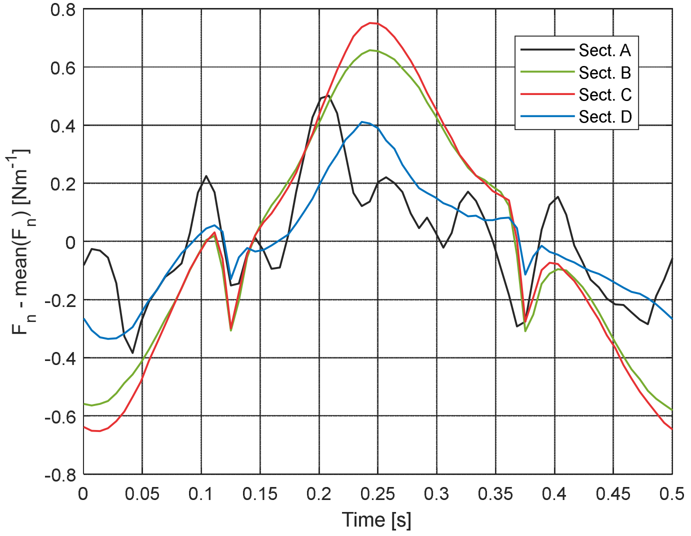
Blade-resolved simulation of FOWTs

3 BLADE & WAKE SOLUTION





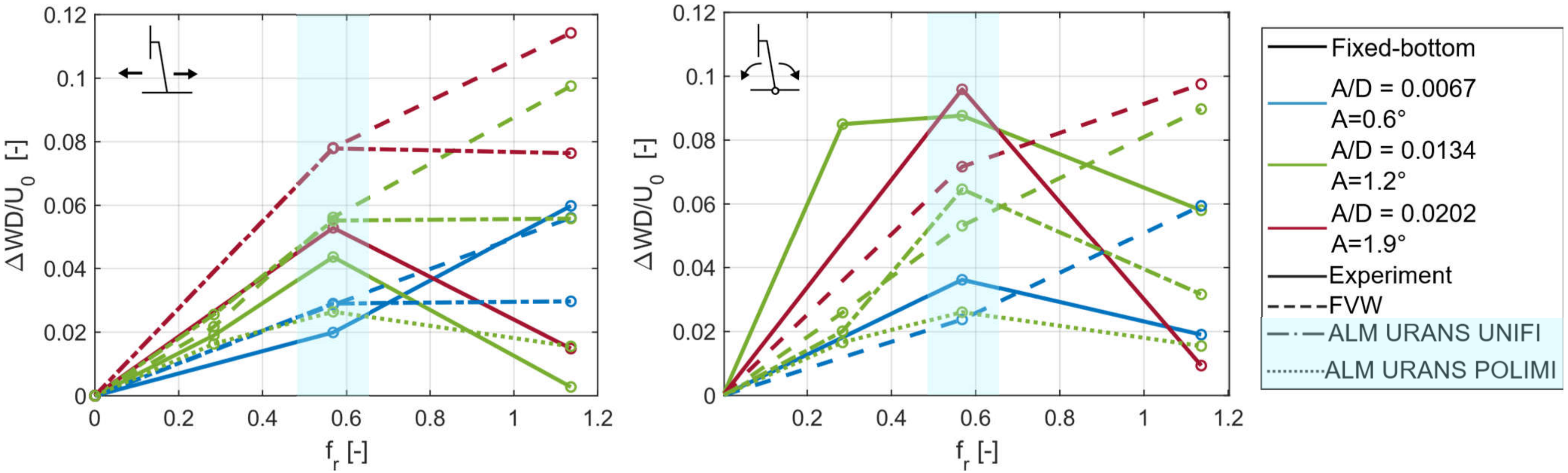




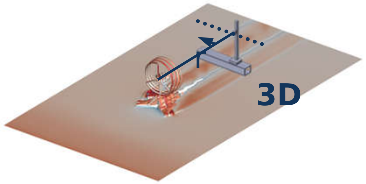
Multi-Fidelity comparison @ 3D – Velocity Oscillations

2 SOLUTION OF WAKE

Mid-fidelity ALM is able to better follow experimental trend



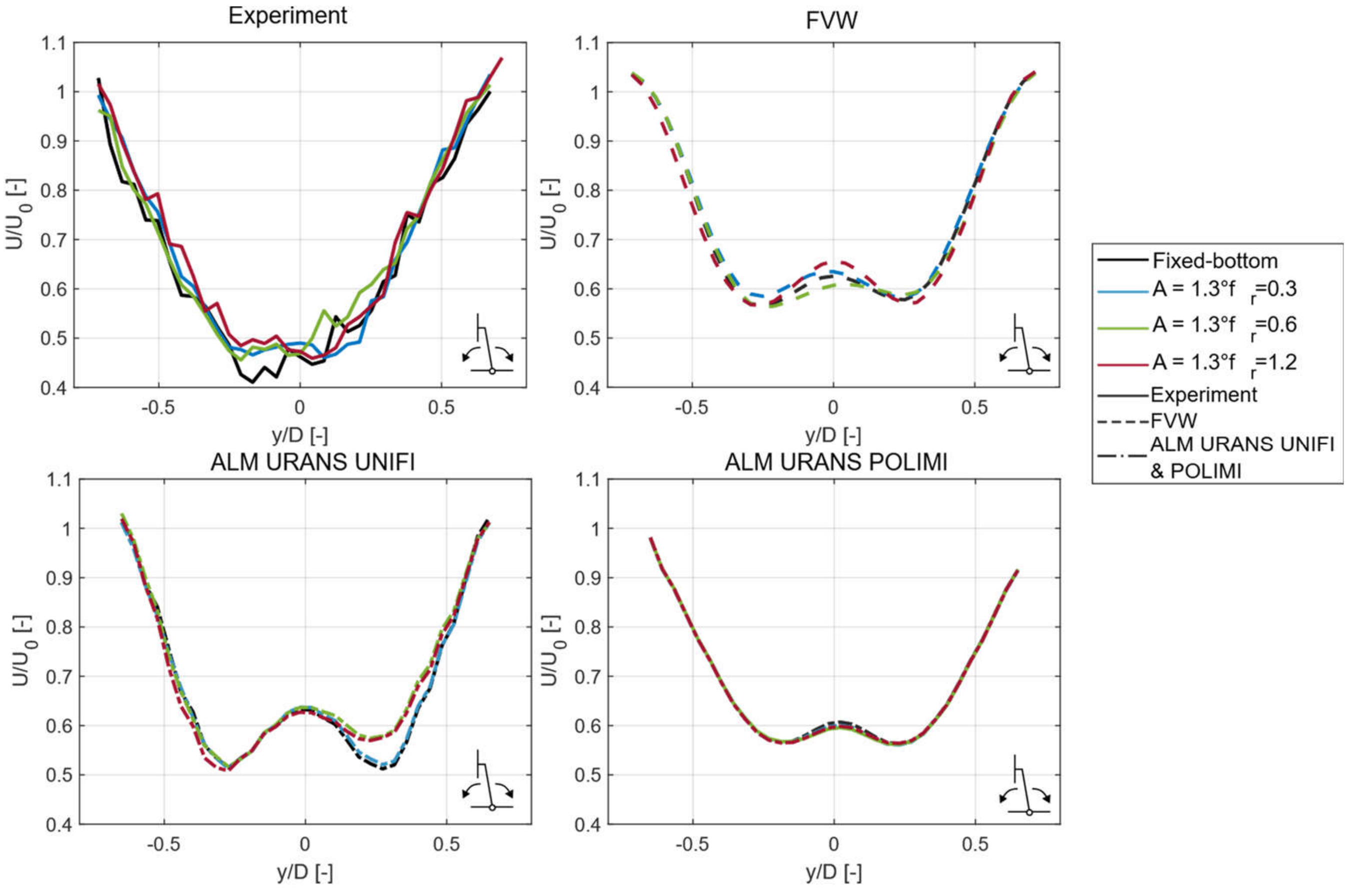
$$\frac{WD}{U_0} = \frac{\int (U - U_0)\,dA}{AU_0}$$

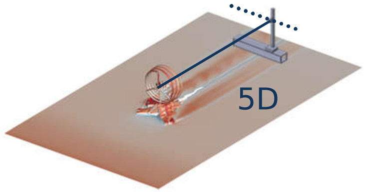


full breakdown: **DOI: 10.5194/wes-2025-149**

Multi-Fidelity comparison @ 5D – Mean Velocity

2 SOLUTION OF WAKE

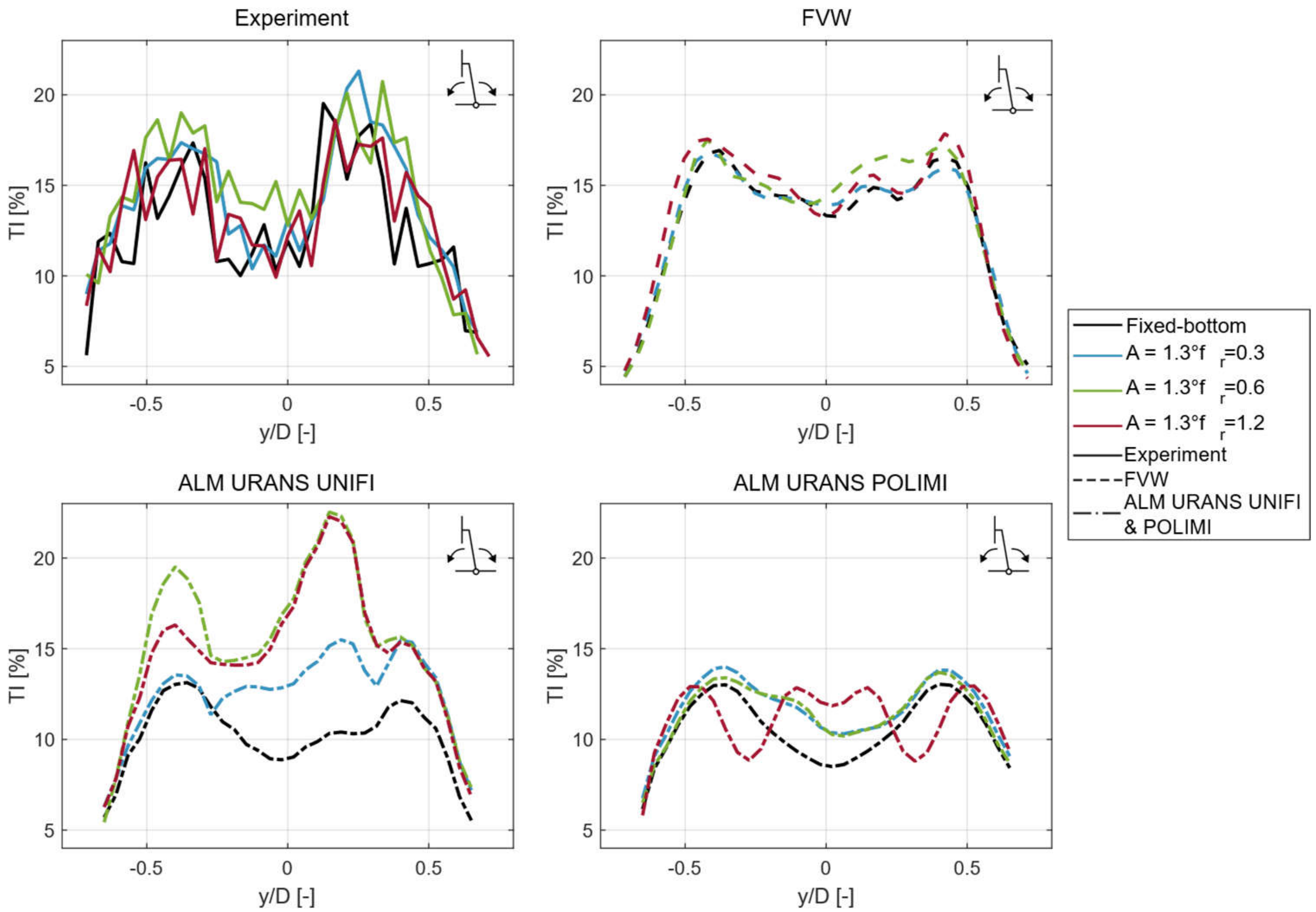


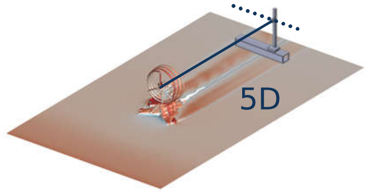


full breakdown: **DOI: 10.5194/wes-2025-149**

Multi-Fidelity comparison @ 5D – Turbulence Intensity

② SOLUTION OF WAKE



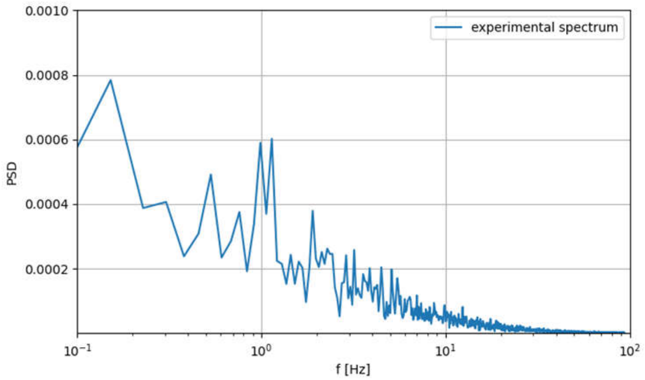


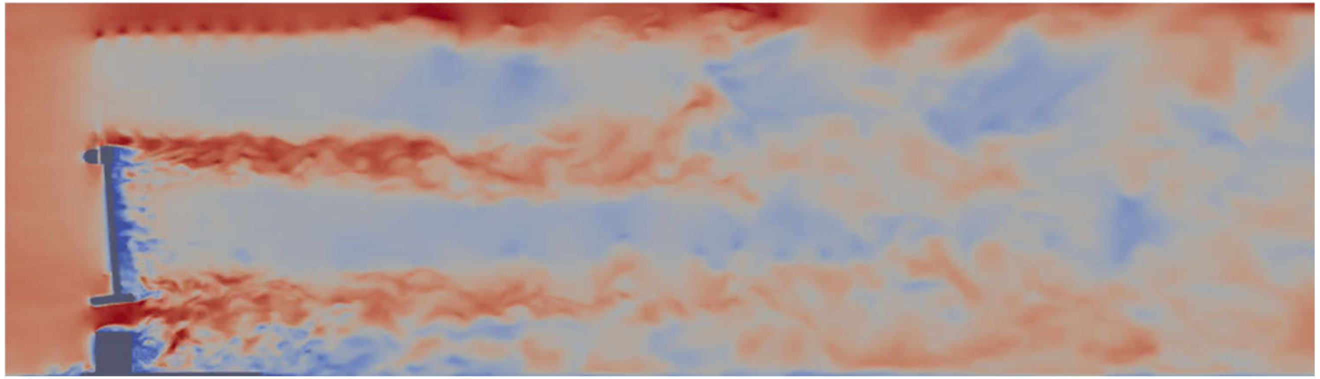
full breakdown: **DOI: 10.5194/wes-2025-149**

LES simulations

2 SOLUTION OF WAKE

For more insight on wake, ALM is coupled with LES



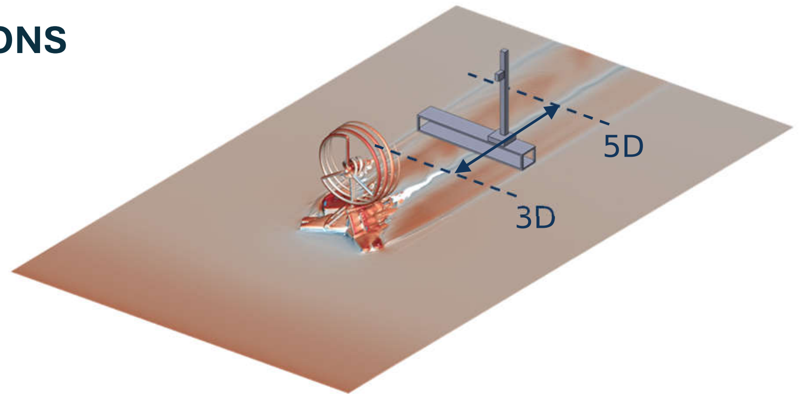


GVPM TURBULENT SPECTRUM

The baseline turbulence in the PoliMi wind tunnel was evaluated

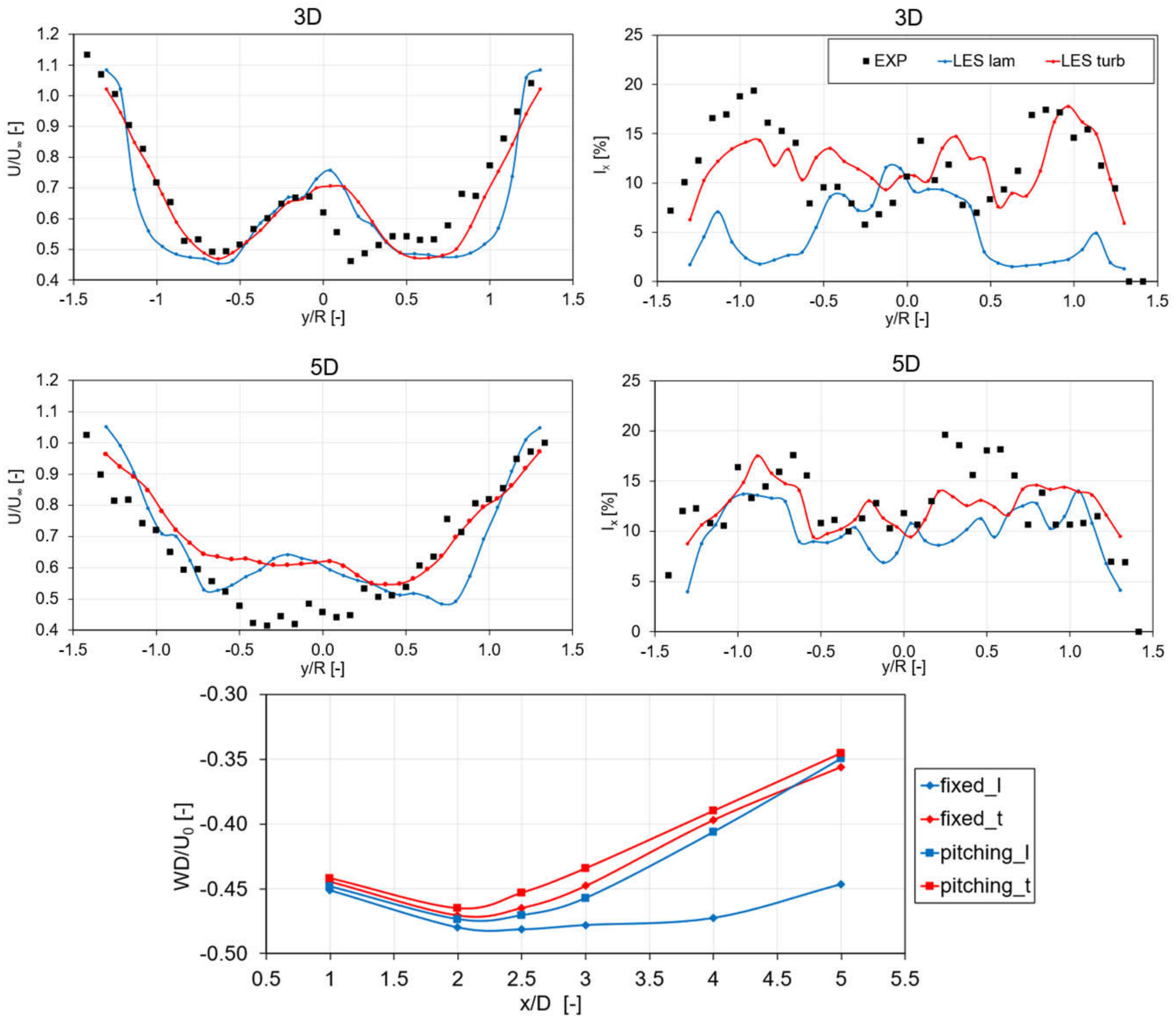
HIGH-FI LES ALM SIMULATIONS

domain discretization needs to be significantly improved



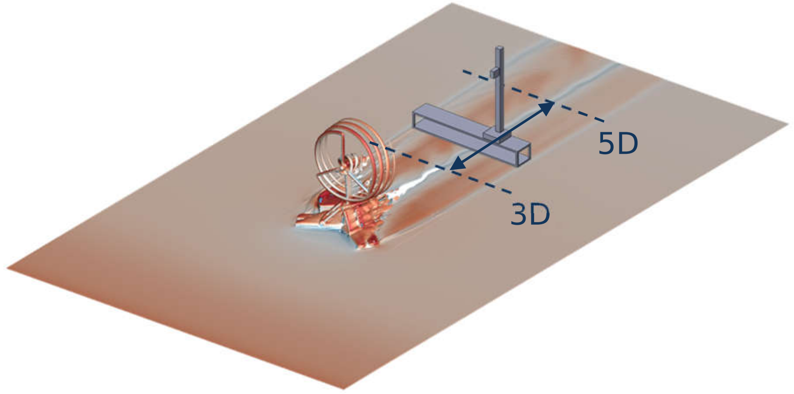
Effect of free-stream turbulence – LES ALM simulations

2 SOLUTION OF WAKE



1.5% TI SIGNIFICANTLY AFFECTS RESULTS

All computations include inflow turbulence



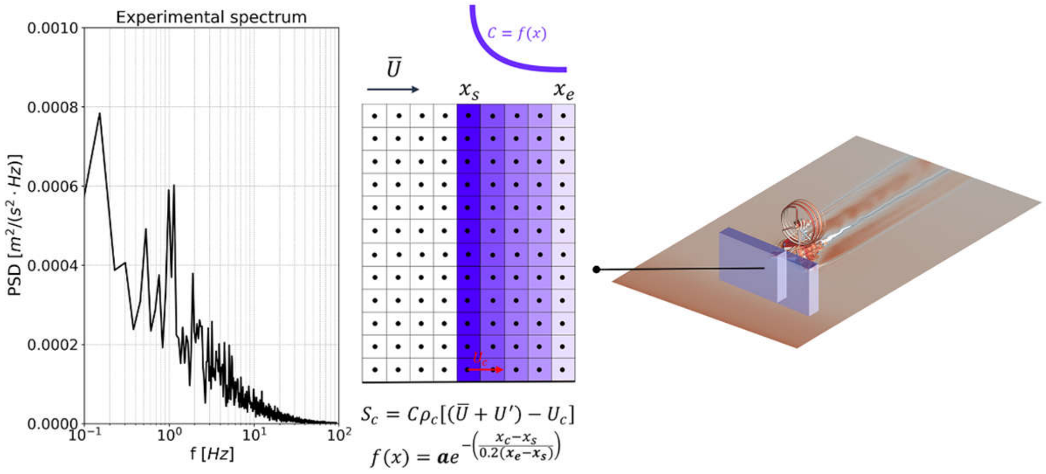
Motion effects on wake recovery are greatly reduced

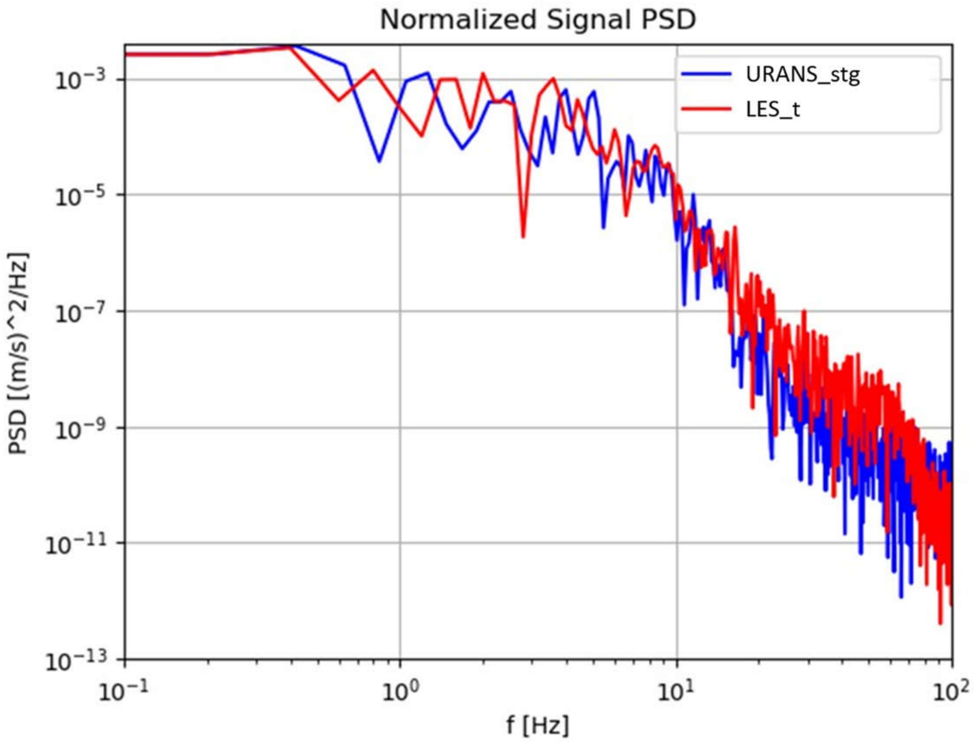
URANS with Synthetic Turbulence Generation

2 SOLUTION OF WAKE

Low-frequency velocity oscillations are also inserted into URANS simulations

- ✓ Insertion through volume forces
- ✓ Low frequency – high length scale
- ✓ ¼ mesh count wrt LES (~ 30M elements)





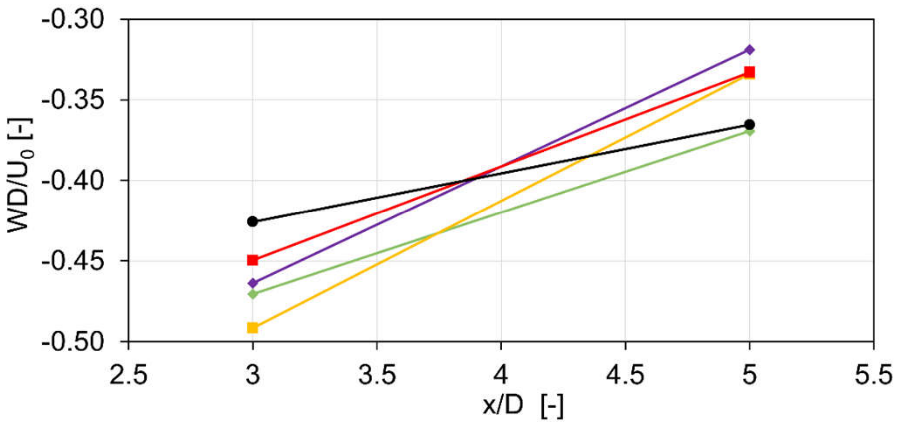
LES simulations – trends in wake evolution

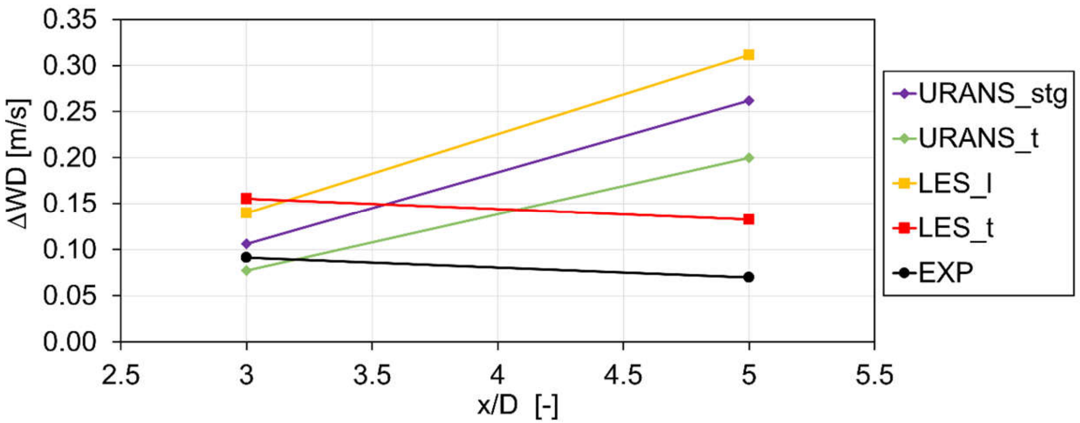
2 SOLUTION OF WAKE

Wake Deficit

- ✓ All URANS approaches are unable to capture the experimental trend in Wake Deficit
- ✓ LES approach with turbulent inflow is the only approach that – despite some minor differences – best captures the evolution of the wake recovery

$$\frac{WD}{U_0} = \frac{\int (U - U_0)\,dA}{AU_0}$$





Conclusions

Inflow conditions impact wake evolution significantly

- ✓ Inclusion of correct level of **inflow turbulence** significantly affects all the tested models

LLFVW is reasonably predictive if tuned

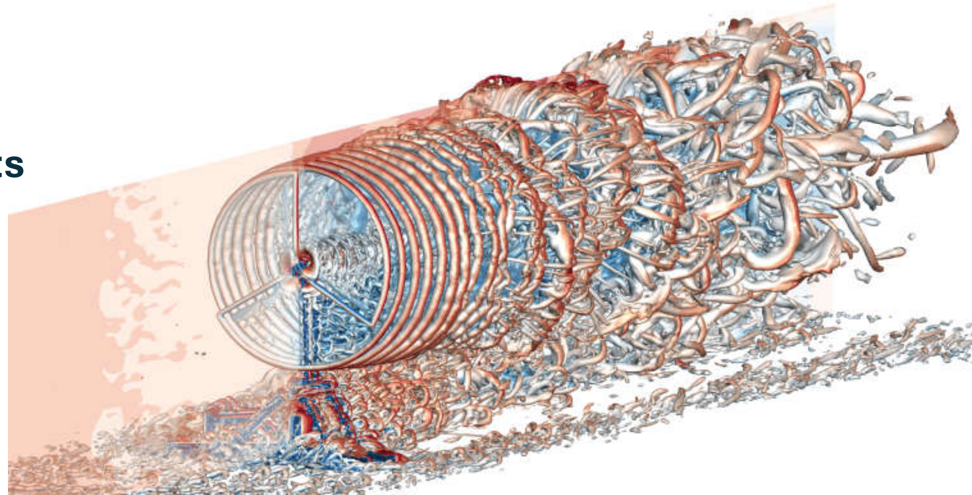
- ✓ fine tuning **initial core radius** and **turbulent viscosity** can improve agreement significantly

Lifting-line codes performed well with respect to blade-resolved reference

- ✓ cross-verification of blade models ensures differences in the wake are not imputable to differeces in rotor loads

URANS ALM outperformed LLFVW @3D

- ✓ More downstream **LES** results are much **more in line with experiments**



THANK YOU

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