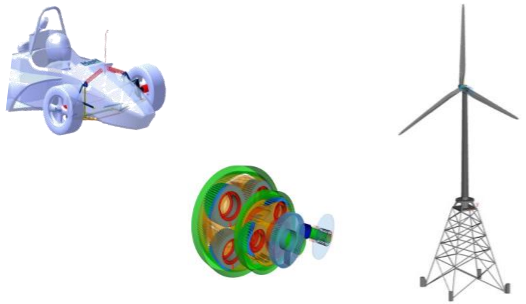
Gefördert durch:

Bundesministerium
für Wirtschaft
und Klimaschutz

aufgrund eines Beschlusses
des Deutschen Bundestages



Assessment of structural loads in wind farms under consideration of wake redirection control

RAVE Workshop - 11 May 2023

Matthias Kretschmer[1,2], Po Wen Cheng[2]

[1] MesH Engineering GmbH, [2] Stuttgart Wind Energy at the University of Stuttgart

RAVE
RESEARCH AT ALPHA VENTUS

University of Stuttgart
Stuttgart Wind Energy (SWE)
@ Institute of Aircraft Design

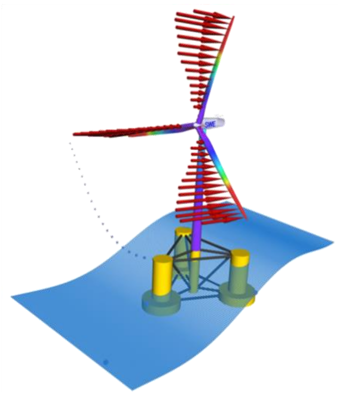
SWE

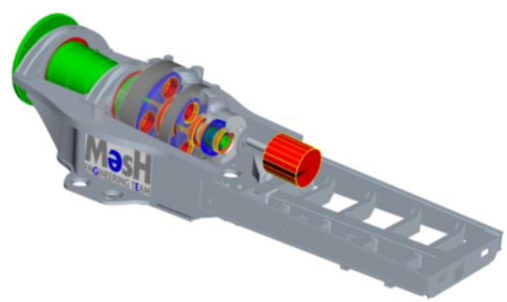
WINDFORS
Windenergie
Forschungscluster

MesH
ENGINEERING TEAM

MesH Engineering GmbH

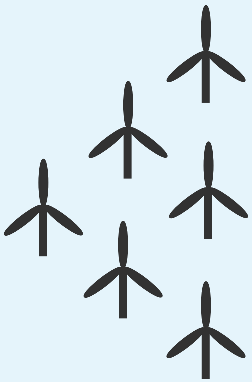
- Medium-sized engineering partner located in Stuttgart
- Founded in 2002
- Approx. 40 employees (Automotive & Wind)
- Expertise in:
  - Dynamic Simulations: MBS, FEM, CFD, etc.
  - Digitalization, Data Analysis, Machine Learning and IoT
  - Software Development





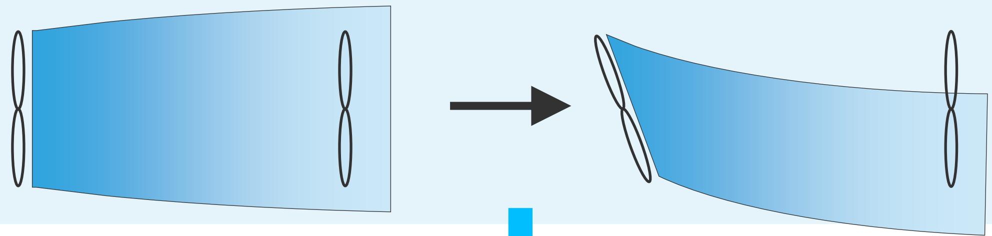
Motivation / Research gap

Wind turbine array



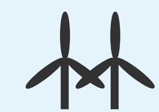
Wake losses

Mitigation of wake losses with wake redirection control

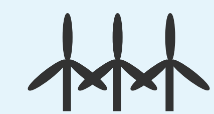


Previous research:

- 2 turbine setup: up to 35 % power increase
  (full-scale experiment, Doekemeijer et al. [1])



- 3 turbine setup: up to 15 % power increase
  (full-scale experiment, Doekemeijer et al. [1],
  wind tunnel tests, Campagnolo et al. [2],
  high-fidelity simulations, Gebraad et al. [3])



Research objectives / content

→**This thesis [4]: Investigating the consequences of wake redirection control on the structural loads**

Validating the aeroelastic simulation environment against measurement data.

→

Analysing the effects from yawed operation on the structural loads of free stream and waked turbines.

→

Developing optimised wind farm operation strategies using wake redirection control

MesH ENGINEERING TEAM

Validating the aeroelastic simulation environment

Validating the aeroelastic simulation environment against measurement data.

Analysing the effects from yawed operation on the structural loads of free stream and waked turbines.

Developing optimised wind farm operation strategies using wake redirection control

MesH ENGINEERING TEAM

Validating the aeroelastic simulation environment

Selection of the aeroelastic simulation environment

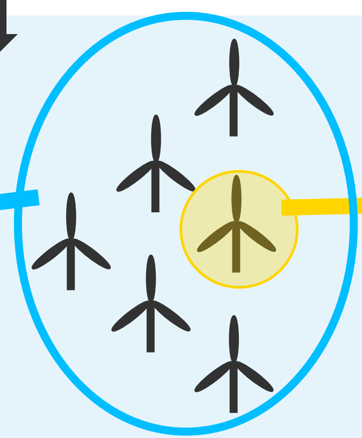
Key Criteria

- Predicting the power performance and structural loads of wind farms
- Balance: accurate modeling of the relevant physics while maintaining low computational cost

→ Choice: simulation tool FAST.Farm

Wind farm dynamics

- Wake calculation: Dynamic wake meandering model
- This thesis: contribution of a module to model the wake-added turbulence



Wind turbine dynamics

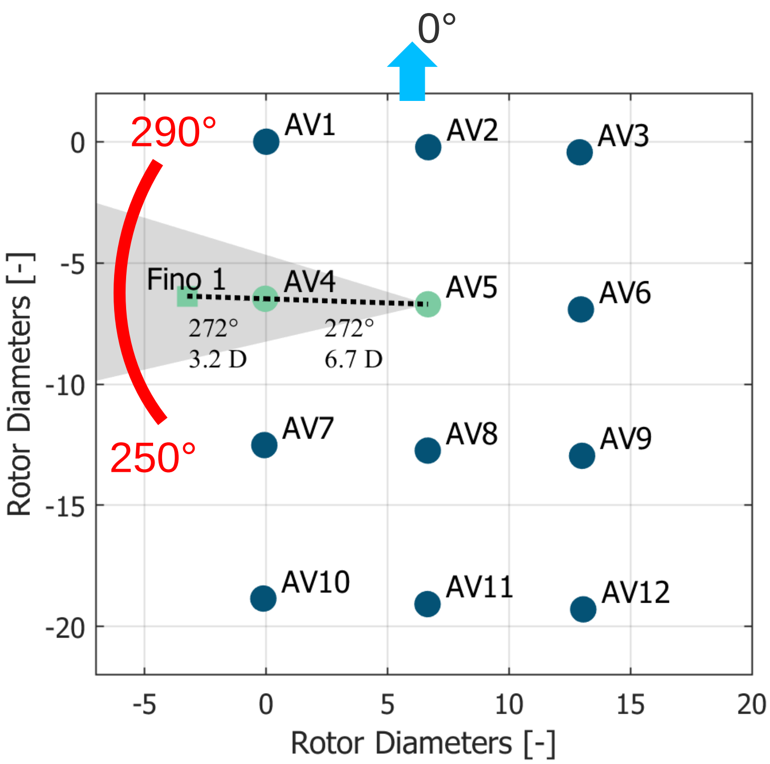
- OpenFAST simulation

→ Aeroelastic turbine response

→ Validation required, especially for the calculation of structural loads.

Validating the aeroelastic simulation environment

Measurement data: alpha ventus wind farm



- Meteorological measurements at the FINO 1 met mast
- Turbine load measurements at AV4 and AV5
  - Senvion 5M turbines
  - 5 MW rated power
  - Rotor diameter $D = 126\,m$

Supported by:
Federal Ministry for Economic Affairs and Climate Action
on the basis of a decision by the German Bundestag
Projektträger Jülich Forschungszentrum Jülich
BUNDESAMT FÜR SEESCHIFFFAHRT UND HYDROGRAPHIE
Fraunhofer IWES
MesH ENGINEERING TEAM

Validating the aeroelastic simulation environment

Procedure

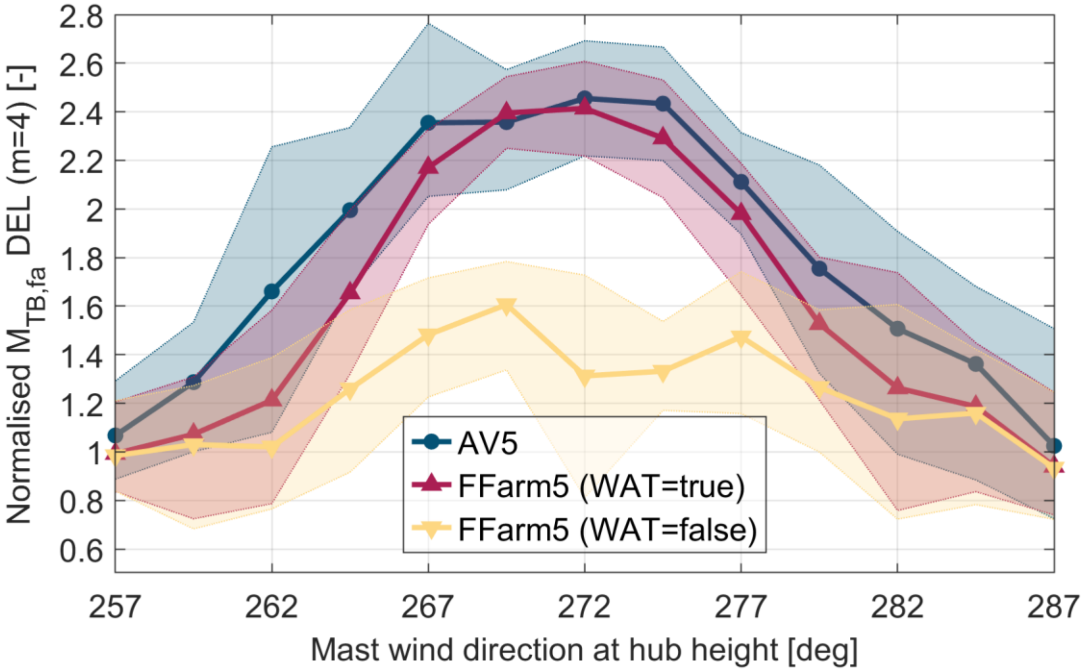
Aeroelastic simulation model ⟷ Operational wind farm

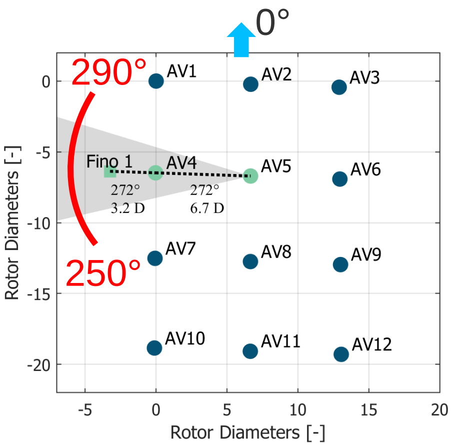
One-to-one simulation approach

- Replication of the measured metocean conditions (10-min statistics)
  - Wind speed, wind direction, atmospheric stability, vertical wind profile, turbulence intensity, turbulent length scale, wave height
- Replication of the real turbines
  - Aeroelastic model, introducing mass and aerodynamic imbalances

Validating the aeroelastic simulation environment

Fatigue loads at the tower-base





Metocean conditions	
Wind speed	6.5 – 7.5 m/s
Turbulence intensity	3 – 15 % (mean: 6%)
Power law shear exponent	0 – 0.2 (mean: 0.03)
Atmospheric stability	unstable (52 %) neutral (29 %) stable (19 %)
Significant wave height	1.1 – 3.2 m

- Trends are captured by FAST.Farm in good agreement
- Wake-added turbulence (WAT) important for the loads at the tower-base

Validating the aeroelastic simulation environment

Validating the aeroelastic simulation environment against measurement data.

Analysing the effects from yawed operation on the structural loads of free stream and waked turbines.

Developing optimised wind farm operation strategies using wake redirection control

Analysing the effects from yawed operation

Validating the aeroelastic simulation environment against measurement data.

→

Analysing the effects from yawed operation on the structural loads of free stream and waked turbines.

→

Developing optimised wind farm operation strategies using wake redirection control

Analysing the effects from yawed operation

Objectives

- Gaining understanding in the structural loading of wind turbines during skewed and waked inflow conditions
- Generating loads data base for the use in the optimisation

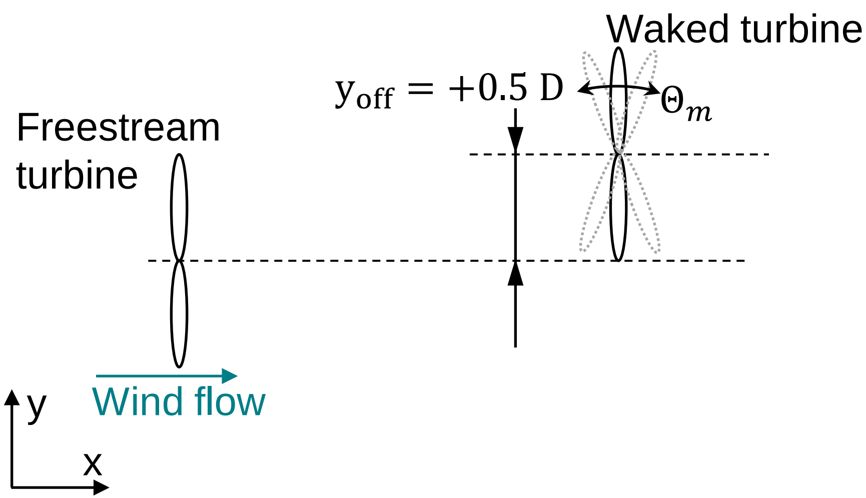
Ingredients

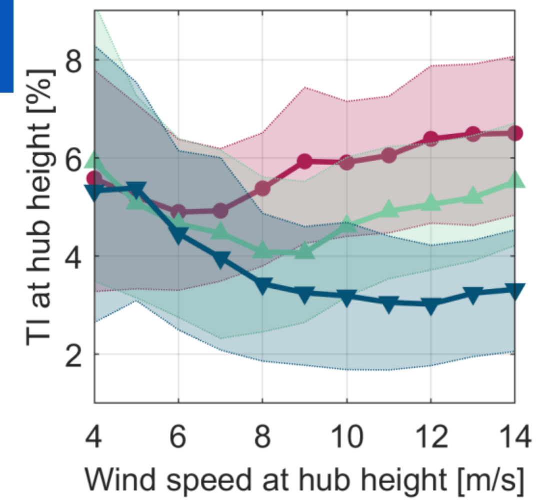
- Validated aeroelastic simulation tool for calculating the loads
- Realistic offshore conditions derived from FINO 1
- Turbine model NREL 5MW (similar to the Senvion 5M model from the validation study)
- Systematic variation of relevant parameters (sensitivity study)

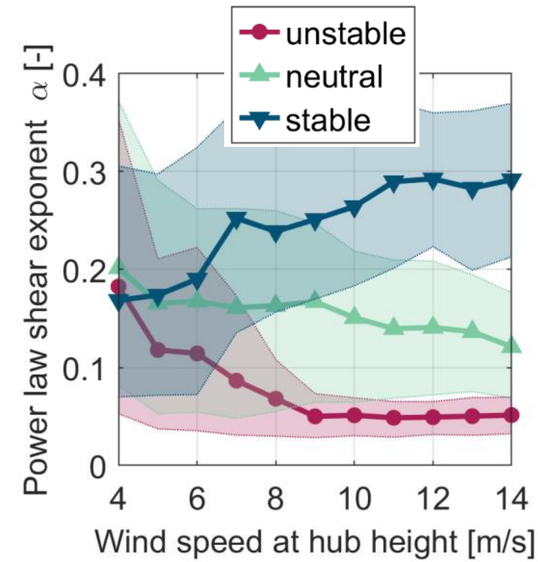
MesH ENGINEERING TEAM

Analysing the effects from yawed operation

Relevant parameters



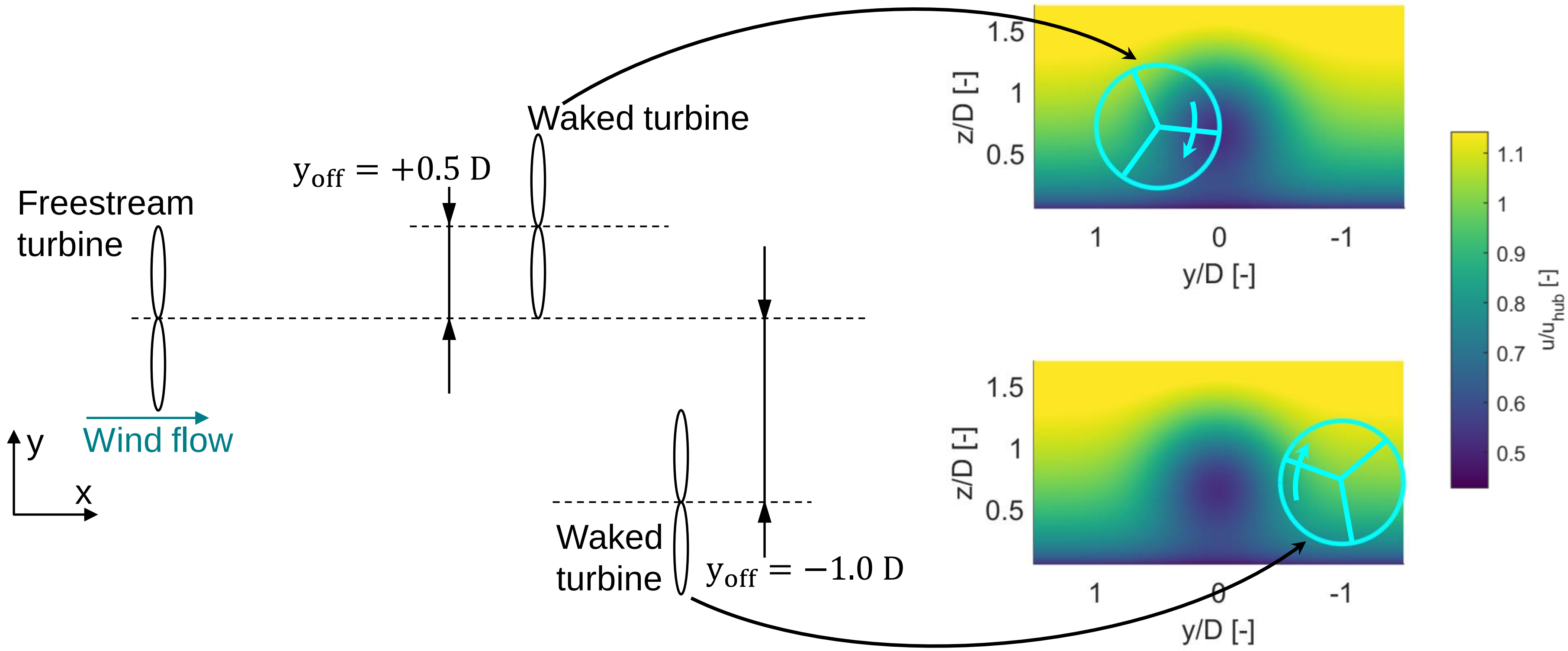




Parameter	Value
Wind speed at hub height [m/s]	[5 : 1 : 11]
Yaw misalignment of waked turbine $\Theta_{m,T2}$ [°]	[-30 : 5: 30]
Lateral turbine spacing [D]	[-1.25 : 0.25 : 1.25]
Longitudinal turbine spacing [D]	[5, 7, 9]
Meteorological conditions	Mean conditions at FINO 1

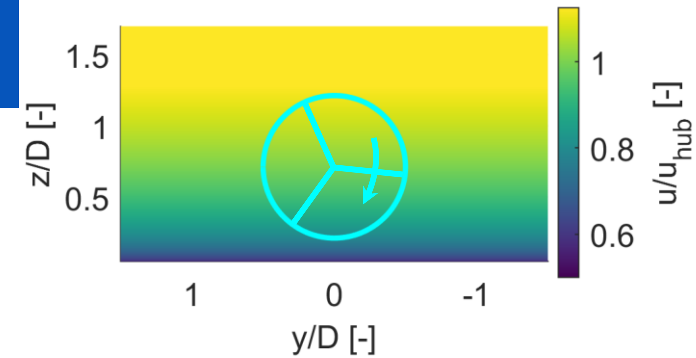
Analysing the effects from yawed operation

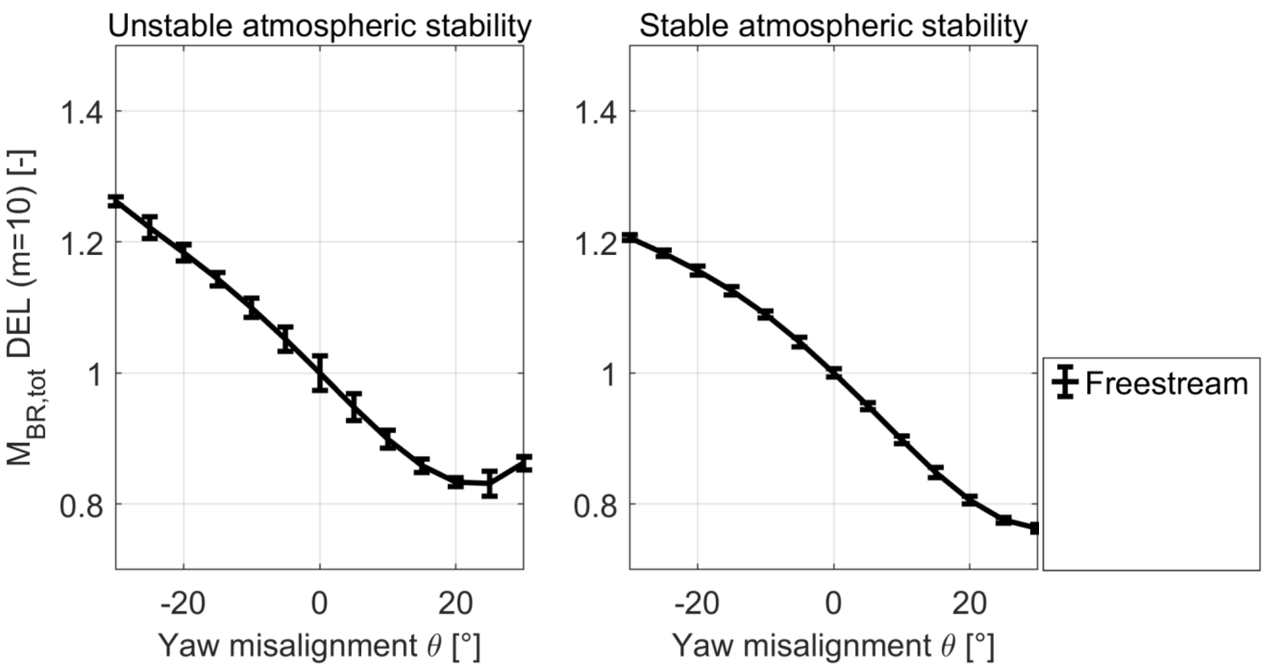
Inflow conditions at waked turbine



Analysing the effects from yawed operation

Example: Fatigue loads at the blade-root





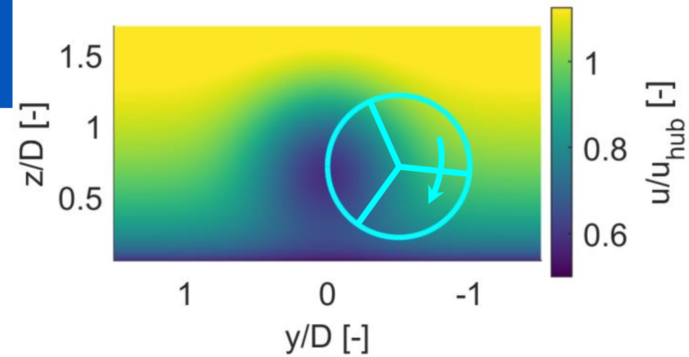
Unstable AS	Stable AS
$u_{hub} = 8\ m/s$	
$x_{off} = 7\ D$	
$\alpha_{shear} = 0.08$	$\alpha_{shear} = 0.24$
$TI = 5.5\ \%$	$TI = 3.8\ \%$

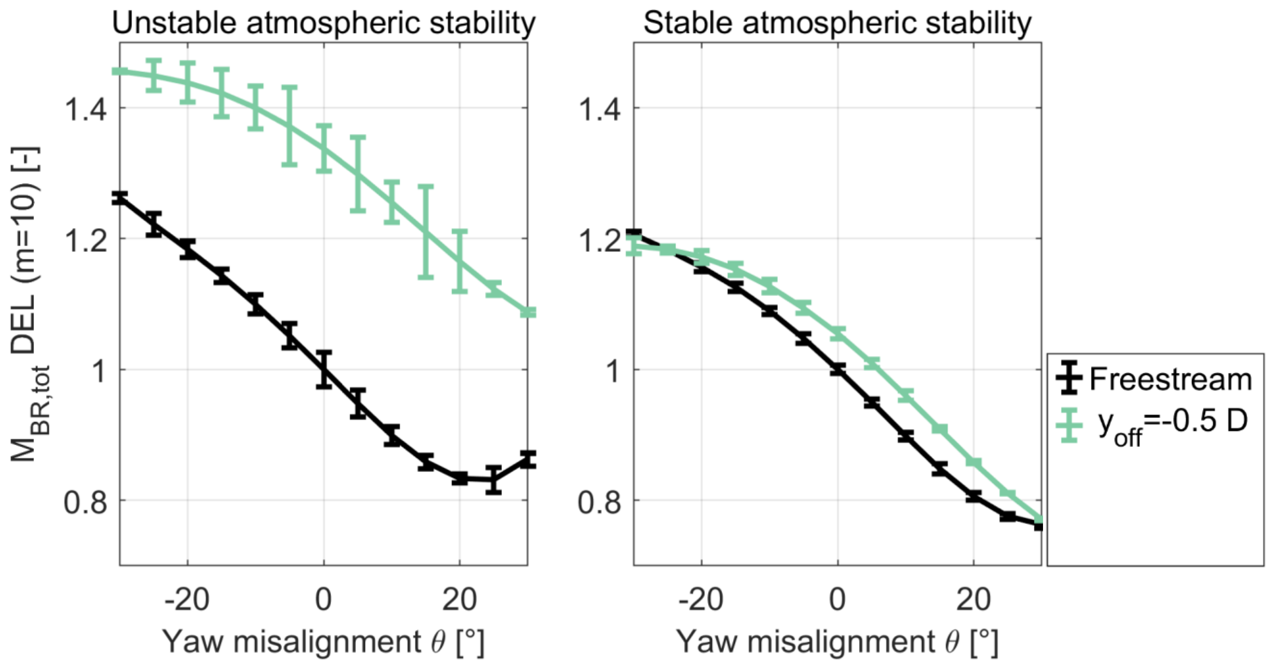
- Resultant bending moment at the blade-root, normalised by the results at $\theta = 0°$ from freestream conditions

MesH ENGINEERING TEAM

Analysing the effects from yawed operation

Example: Fatigue loads at the blade-root

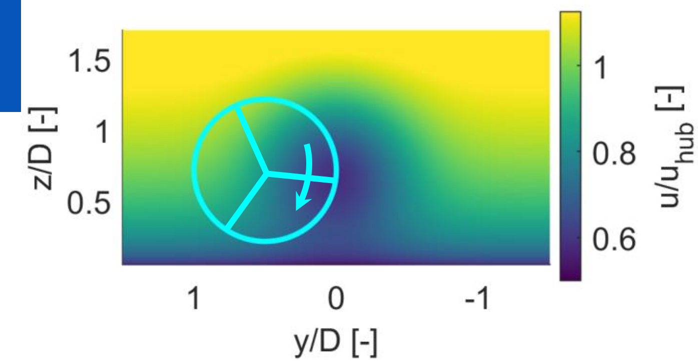




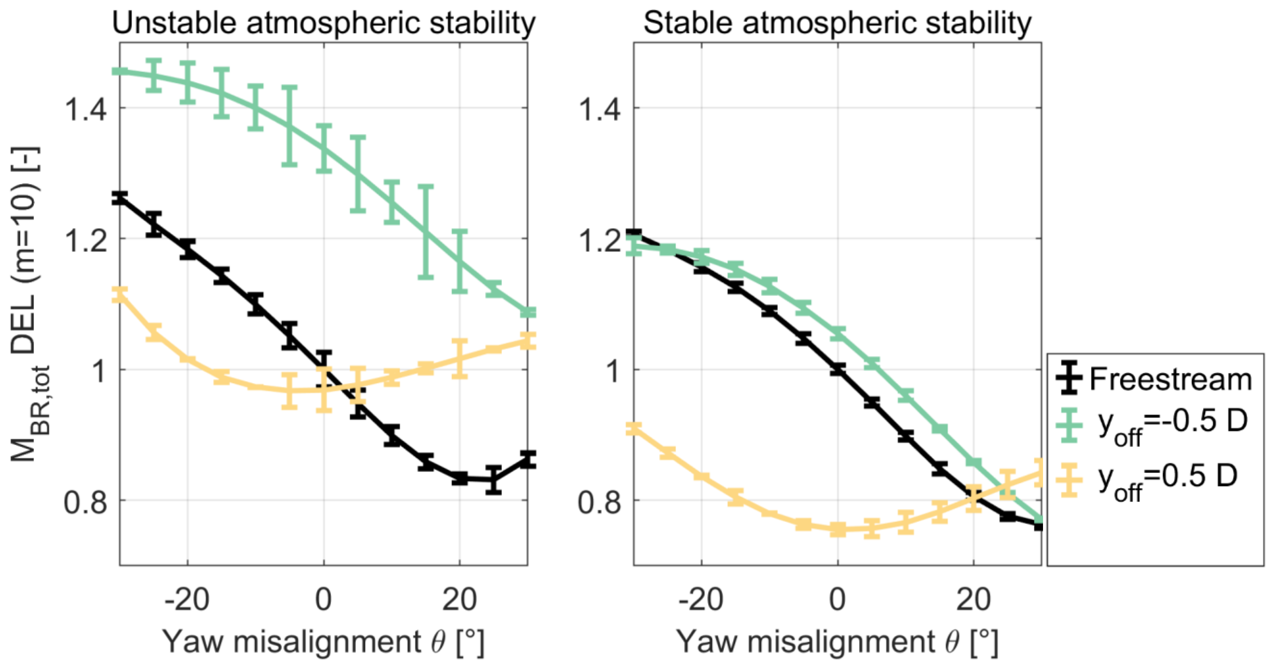
Unstable AS	Stable AS
$u_{hub} = 8\ m/s$	
$x_{off} = 7\ D$	
$\alpha_{shear} = 0.08$	$\alpha_{shear} = 0.24$
$TI = 5.5\ \%$	$TI = 3.8\ \%$

- Change in load distribution compared to freestream conditions caused by waked inflow

Analysing the effects from yawed operation



Example: Fatigue loads at the blade-root



Unstable AS	Stable AS
$u_{hub} = 8\ m/s$	
$x_{off} = 7\ D$	
$\alpha_{shear} = 0.08$	$\alpha_{shear} = 0.24$
$TI = 5.5\ \%$	$TI = 3.8\ \%$

➡ Complex load distributions depending on the environmental conditions, yaw misalignment angle and wake condition

MesH ENGINEERING TEAM

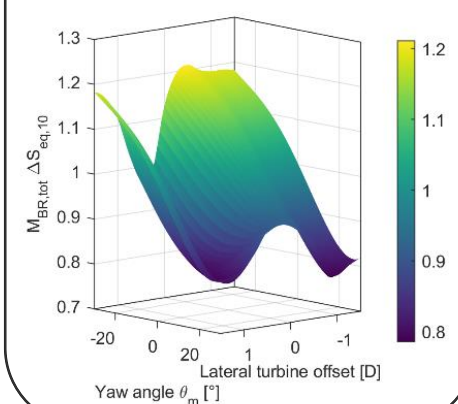
Analysing the effects from yawed operation

Aggregation of results in surrogate model

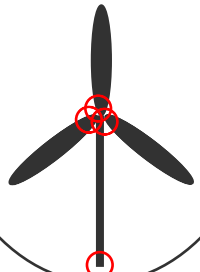
Structural loads from aeroelastic simulations with FAST.Farm

- Wind speed
- Atmospheric stability
- Yaw misalignment θ_m
- Wake-center position

Load surrogate model



DEL @ desired sensor loaction



MesH ENGINEERING TEAM

Analysing the effects from yawed operation

Validating the aeroelastic simulation environment against measurement data.

Analysing the effects from yawed operation on the structural loads of free stream and waked turbines.

Developing optimised wind farm operation strategies using wake redirection control

Developing optimised wind farm operation strategies

Validating the aeroelastic simulation environment against measurement data.

Analysing the effects from yawed operation on the structural loads of free stream and waked turbines.

Developing optimised wind farm operation strategies using wake redirection control

Developing optimised wind farm operation strategies

Procedure

Definition of optimisation objectives / operation strategies

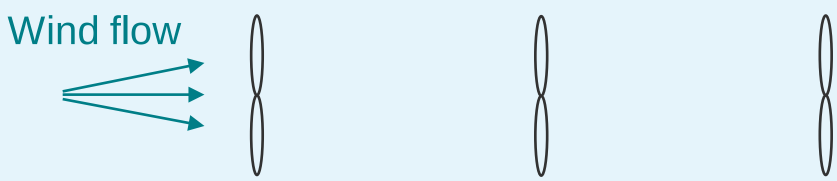
(0: Baseline)
A: Power maximisation
C: Minimisation of structural loads

Optimisation with reduced order models

Evaluation of optimised strategies using FAST.Farm

Variation

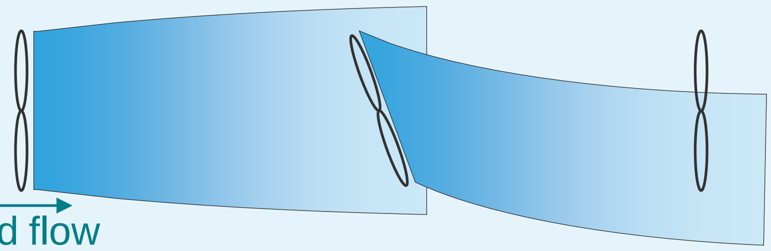
- Wind speed ($5 - 10\ m/s$)
- Wind direction (no wake – full wake)
- Atmospheric stability (unstable, neutral, stable)



Developing optimised wind farm operation strategies

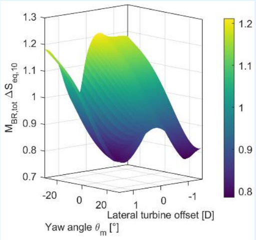
Optimisation Loop

1. Flow field calculation with reduced order model (FLORIS)



- Atmospheric conditions
- Yaw misalignment θ_m
- Wake-center position

2. DEL calculation with surrogate model



3. Evaluation of objective function

e.g.

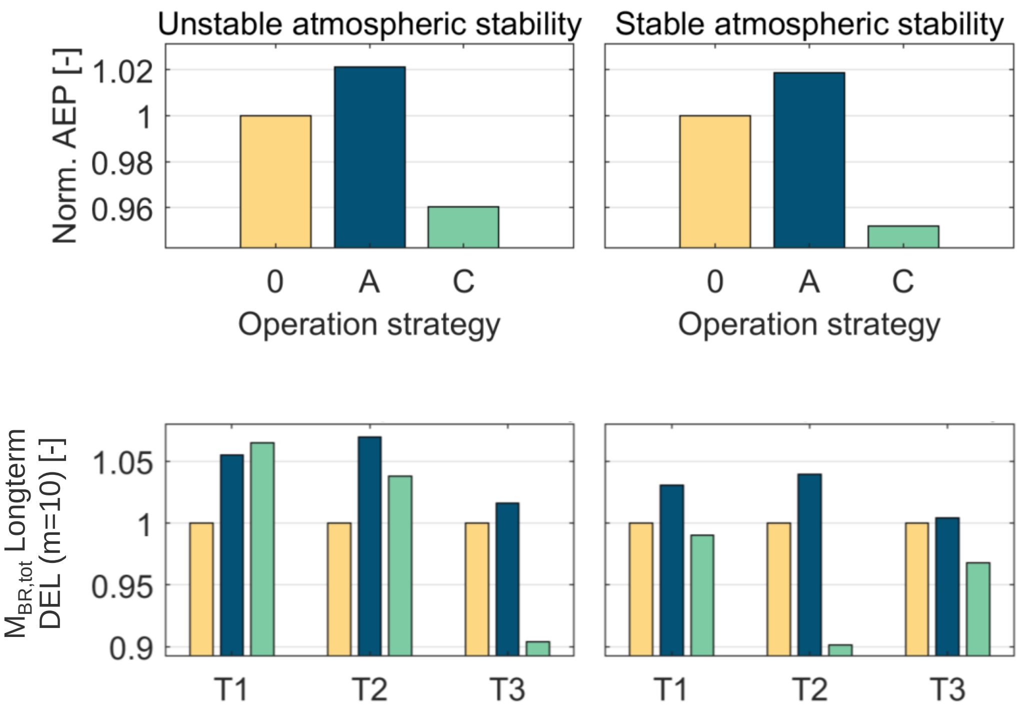
A: Power maximisation

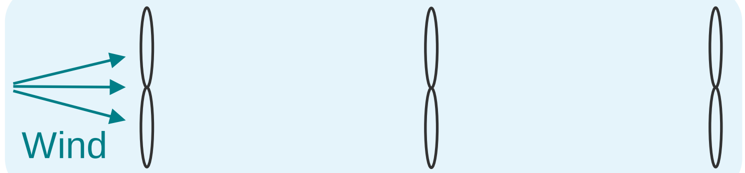
C: Minimisation of structural loads

Updated Yaw set-points

Developing optimised wind farm operation strategies

Longterm results: 3 turbine scenario





Operation strategies

0: Baseline
A: Power maximisation
C: Minimisation of structural loads

- Minimisation of structural loads leads to decrease in AEP
- Higher load reduction potential in stable atmospheric conditions
- Consistent load reductions across turbines and components not possible

Conclusions

- **FAST.Farm improved and validated for the use in offshore conditions**
  - Wake-added turbulence crucial: loads at the tower-base in low ambient turbulence conditions

- **Structural load analyses considering wake redirection control**
  - Complex load distributions: dependent on environmental conditions, yaw misalignment angle and wake condition
  - Identification of favorable conditions for the structural loading: direction of wake-offset, yaw misalignment

Conclusions / Outlook

- **Optimised operation strategies using wake redirection control**
  - Reasonable optimisation results with reduced order flow model and loads surrogate model
  - Besides power maximisation: wake-redirection control can be applied for load balancing

- **From RAVE to WAVE?**
  - Why not Wake redirection control at Alpha VEntus (WAVE)?
  - We have available:
    - Ideal offshore setup: Fino 1 + 3 turbines in a row + 3 reference turbines
    - Validated simulation model
    - Knowledge and tools to evaluate the consequences on structural loads

Thank you!

References

[1] B. M. Doekemeijer, S. Kern, S. Maturu, S. Kanev, B. Salbert, J. Schreiber, F. Campagnolo, C. L. Bottasso, S. Schuler, F. Wilts, T. Neumann, G. Potenza, F. Calabretta, F. Fioretti, and J.-W. van Wingerden, "Field experiment for open-loop yaw-based wake steering at a commercial onshore wind farm in Italy," Wind Energy Science, vol. 6, no. 1, pp. 159–176, 2021, doi: 10.5194/wes-6-159-2021.

[2] F. Campagnolo, V. Petrović, J. Schreiber, E. M. Nanos, A. Croce, and C. L. Bottasso, "Wind tunnel testing of a closed-loop wake deflection controller for wind farm power maximization," Journal of Physics: Conference Series, vol. 753, p. 032006, 2016, doi: 10.1088/1742-6596/753/3/032006.

[3] P. M. O. Gebraad, F. W. Teeuwisse, J. W. van Wingerden, P. A. Fleming, S. D. Ruben, J. R. Marden, and L. Y. Pao, "Wind plant power optimization through yaw control using a parametric model for wake effects - a CFD simulation study: Wind plant optimization by yaw control using a parametric wake model," Wind Energy, vol. 19, no. 1, pp. 95–114, 2016, doi: 10.1002/we.1822.

[4] M.Kretschmer, "Assessment of structural loads in wind farms under consideration of wake redirection control," Ph.D. dissertation, University of Stuttgart, 2023 (under review).

Matthias Kretschmer
E: matthias.kretschmer@mesh-engineering.de
T: 0711 6868818 39

MesH Engineering GmbH | Wankelstraße 3 | D-70563 Stuttgart