Proceedings

NTUA Wind Tunnel Technical Info Day

These are the presentations of the 1st tWEET-IE Technical Info Day

The event was addressed to industry and commercial stakeholders interested in the NTUA WT facilities and serbices

NTUA Wind Tunnel Facility – Capacity and Services

Athens, 26th June, 2024

Venue: National Technical University of Athens, 2nd floor, ANYM Building

https://maps.app.goo.gl/4sMZtr3nVKXts9bq8

www.tweet-ie.eu
www.wt.fluid.mech.ntua.gr

TWEET-IE

Twin Wind tunnels for Energy & the EnvironmenT

INNOVATIONS - EXCELLENCE

Co-funded by the European Union

INVITATION

In the framework of the Horizon-Europe TWEET-IE project,

we are pleased to invite you to attend the NTUA Wind Tunnel Technical Info Day.

We will be presenting our capacity for research and services

through presentations of past and present case studies.

TWEET-IE project: Technical Info Day

NTUA Wind Tunnel Facility – Capacity and Services

Athens, 26th June, 2024

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AGENDA

Wednesday June 26th, 2024

10:00 Welcome and opening

The TWEET-IE project (Prof. Demetri Bouris)

10:15 Aerodynamics and Wind Energy

Wind Tunnel Testing (Asst. Prof. Marinos Manolesos)
Computational Fluid and Structural Dynamics (Assoc. Prof. Vasilis Riziotis)

11:15 Environmental Flows and Buildings

Wind Tunnel Testing and Computational Fluid Dynamics (Prof. Demetri Bouris)

11:45 Coffee Break

Discussion – Round Table

12:30 Tour of Wind Tunnel Facilities

Demonstration of wind tunnel testing facility

13:30 End of Event

National Technical University of Athens

TECHNISCHE UNIVERSITÄT MÜNCHEN

KIT Karlsruhe Institute of Technology

TU Delft Delft University of Technology

POLITECNICO MILANO 1863

TWEET-IE Twin Wind tunnels for Energy & the EnvironmenT INNOVATIONS - EXCELLENCE

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Technical Info Day

NTUA Wind Tunnel Facility – Capacity and Services

Prof. Demetri Bouris

June 25th , NTUA, Athens

TWEET-IE / Twin Wind tunnels for Energy and the EnvironmenT – Innovations and Excellence

HORIZON-WIDERA-2021-ACCESS-03-01 / PR# 101079125

TWEET-IE
Twin Wind tunnels for Energy & the EnvironmenT
INNOVATIONS - EXCELLENCE

CO-FUNDED BY THE EUROPEAN UNION

The TWEET-IE project

- **Twin Wind Tunnels for Energy and the EnvironmenT – Innovations and Excellence**

- **Call Topic :** HORIZON-WIDERA-2021-ACCESS-03-01
- **Type of action:** HORIZON Coordination and Support Actions

  i.e. not a research project … but there is a research component
- **Duration:** 1 November 2022 - 31 October 2025 (36 months)
- **Budget:** 1 498 250.00 €

Participants:

NTUA, National Technical University of Athens

TUM, Technical University of Munich

KIT, Karlsruhe Institute for Technology

POLIMI, Polytechnic Institute of Milano

TU Delft, Technical University of Delft

The TWEET-IE project

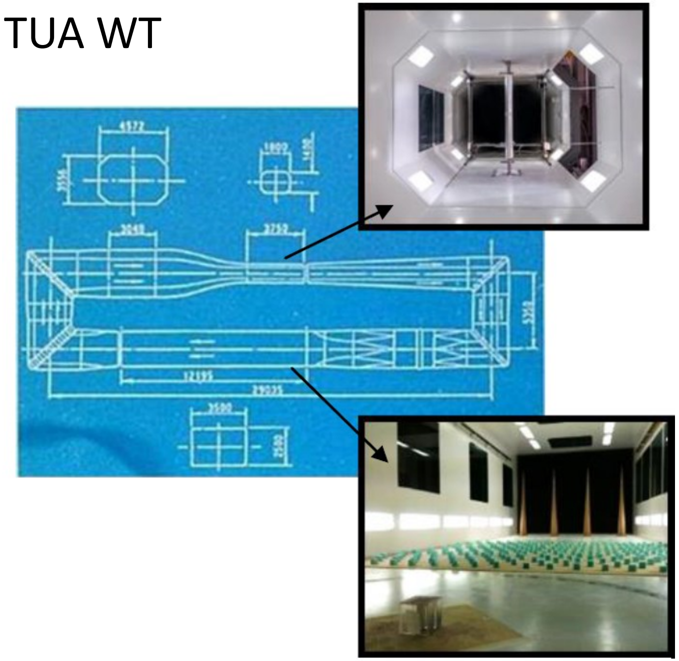
Project goal :

to re-invent, mobilize and promote the NTUA WT

for EU level research

through shared experience

with top-class Leading Partners.



The TWEET-IE project

Pillar I. Widening of management and administration capabilities

- Human and Material Resources
- Certification and Accreditation

Pillar II. Widening of technical capacity and competence

- Physical modeling & measurement of vegetation in urban flows
- Phys. mod. & meas. of wind farms and wake effects.
- Phys. mod. & meas. of airfoil aerodynamic enhancement devices.
- Large scale PIV measurement technology.

Pillar III. Widening of outreach, visibility and profile

- Improving the profile with respect to EU Research needs
- Improving the profile with respect to Services towards Industry

Selected Outputs

- ✓ SWOT analysis and definition of KPIs for NTUA WT facility assessment
- ✓ Facility Assessment Reports
- ✓ Inauguration of NTUA WT administration and management unit
- Sustainability plan of NTUA WT facility
- ✓ Web page and social media presence (LinkedIn, Facebook, Instagram)
- ✓ Summer schools
- ✓ Research activities
    - ✓ Effects of vegetation on flows in the urban environment
    - ✓ Wake interactions of a cluster of turbines and wake steering techniques
    - Micro devices for enhanced performance of airfoil sections
    - Scale effects in Urban Flows

KPIs

Definition of KPIs related to:

- educational/training activities
- research activities
- improving technical capacity
- improving management skills
- publicity and networking activities

Distinguished as:

- Short term – within the duration of the project
- Longer term – horizon of 2-5 years after the conclusion of the project

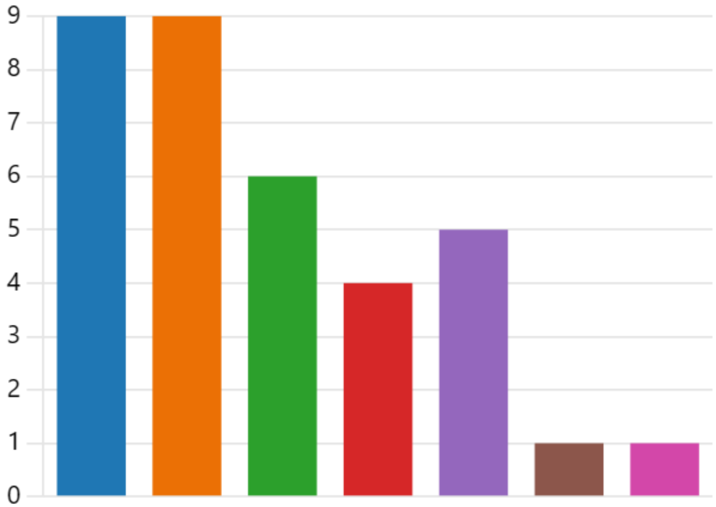
TWEET-IE
Twin Wind tunnels for Energy & the EnvironmenT
INNOVATIONS - EXCELLENCE

Questionnaire for industry needs

What types of wind tunnel testing would be most valuable to your industry?

- *Aerodynamic performance (lift, drag, downforce, stability)*
- *Structural loads and stresses*
- *Flow visualization and characterization*
- *Noise and vibration analysis*
- *Environmental testing (e.g., icing, rain)*
- *I'm not aware of any use for wind tunnel testing in my industrial activities.*
- *Other (please specify)*

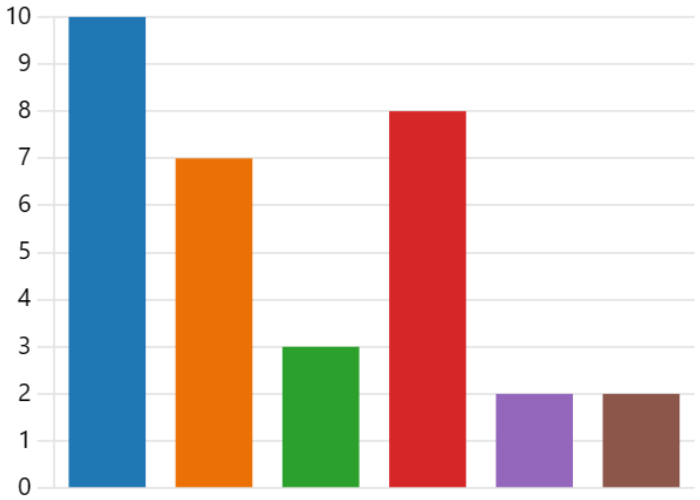
Aerodynamic performance (lift, ...	9
Structural loads and stresses	9
Flow visualization and characteri...	6
Noise and vibration analysis	4
Environmental testing (e.g., icin...	5
I'm not aware of any use for win...	1
Other	1



Widening of visibility and profile

What do you consider to be the main challenges with wind tunnel testing?

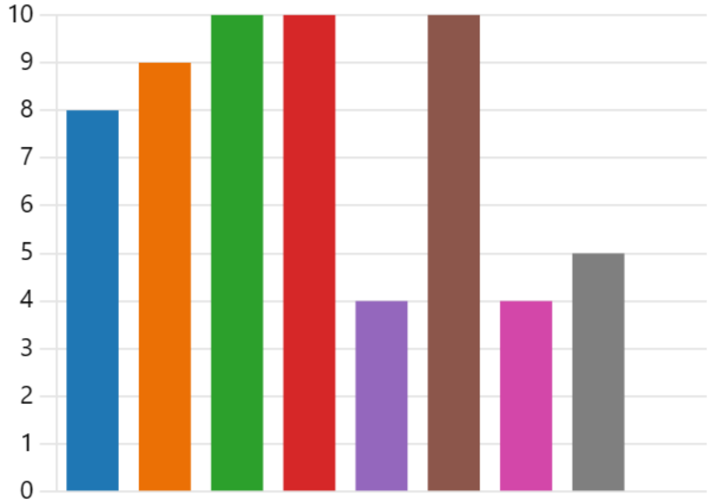
Cost	10
Availability	7
Expertise	3
Testing capabilities (e.g., speed, ...	8
Data analysis and interpretation	2
Other	2



Widening of visibility and profile

What are the most important features you (would) look for in a wind tunnel testing facility?

Specific capabilities (e.g., Reynol...	8
Range of test models/objects ac...	9
Measurement equipment, data ...	10
Expertise of staff	10
Customer service and support	4
Price and availability	10
Confidentiality	4
Communication and Responsive...	5
Other	0



Widening of visibility and profile

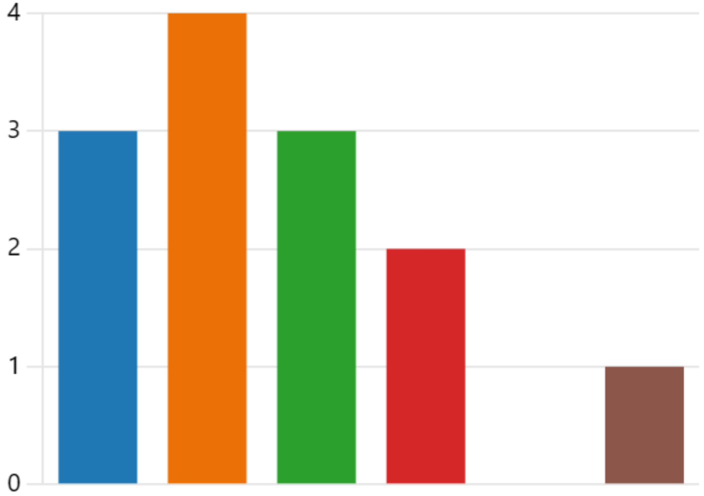
What do you consider to be a typical project timeline for wind tunnel testing?

Less than 1 month	4
1-3 months	7
3-6 months	3
More than 6 months	0

Widening of visibility and profile

What do you consider to be a typical budget for a wind tunnel test campaign?

Less than €5,000	3
€5,000-€10,000	4
€10,000-€20,000	3
€20,000-€50,000	2
€50,000-€100,000	0
More than €100,000	1



TWEET-IE
Twin Wind tunnels for Energy & the EnvironmenT
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Summer School 2024

Session	Mon 15/07/2024	Tue 16/07/2024	Wed 17/07/2024	Thu 18/07/2024	Fri 19/07/2024
09:00 - 11:00	Introduction + Lab Tour	Atmosphering Boundary Layer modelling	Wind Turbine Model Design	Airfoil Testing	Hands-on data analysis
11:00 - 13:00	Wind Tunnel Measurement Techniques	Urban Flows	Wind Farm Testing	Wind Tunnel Session	Visit To Wind Farm
14:30 - 18:30	Wind Tunnel Measurement Techniques	Wind Tunnel Session	Wind Tunnel Session	Hands-on data analysis	Visit To Wind Farm

National Technical University of Athens

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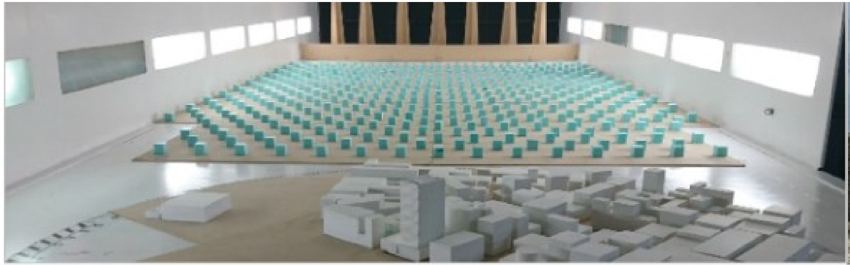

Research Results … so far

Effects of vegetation on flows in the urban environment

Wake interactions of a cluster of turbines and wake steering techniques

Follow us on the web and social media !

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Technical Info Day

NTUA Wind Tunnel Facility – Capacity and Services

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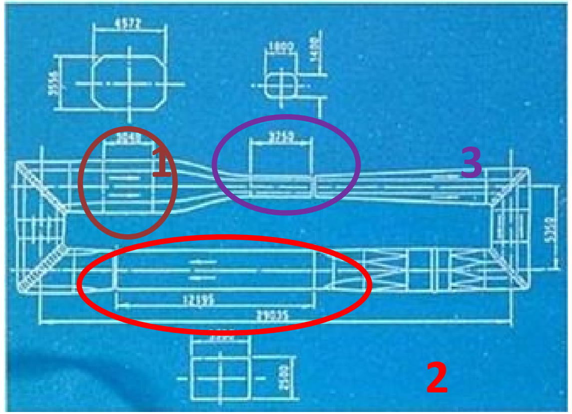
CO-FUNDED BY THE EUROPEAN UNION

The NTUA Wind Tunnel

- Closed circuit
- 7 blade axial fan of 350 hp.
- Subsonic,

  max. speed is 60m/s and

  turbulence level is 0.2%



Total Wind Tunnel Length is 32 m
3 test sections

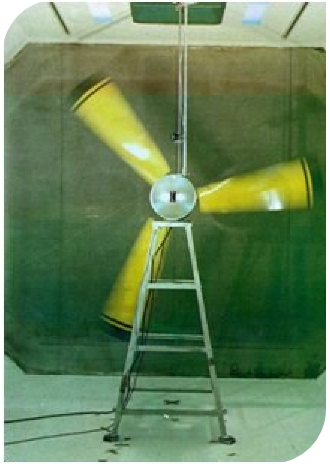
Section	Width (m)	Height (m)	Max. speed (m/s)
1	4.5	3.5	9.5
2	3.5	2.5	17.0
3	1.8	1.4	60.0

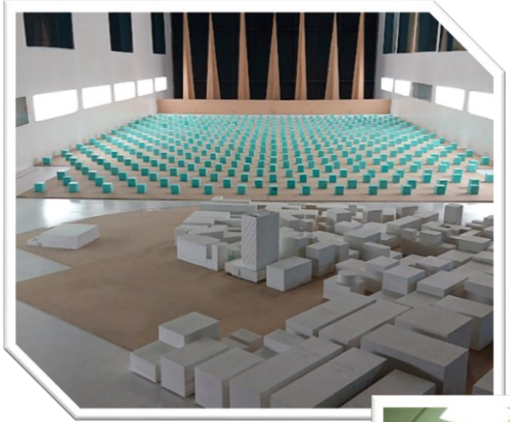
- Section 1 **(4.5x3.5m)** suitable for small propellers, wind turbine rotors and fans

- Section 2 **(3.5 x 2.5 x 12 m)** suitable for buildings, bridges, wind turbine siting, pollutant dispersion and large model wake studies.
  It is equipped with remotely controlled turn table floor and 3D motor driven traversing mechanism.
  It's the atmospheric boundary layer test section

- Section 3 **(1.8x1.4)** for airfoils, aircraft wings, fuselages, model aircrafts, light and heavy vehicles.
  It's the high speed test section (up to ~50 m/s)

3 bladed HAWT model (D=2m) in section 1





City model in section 2

Aircraft model in section 3

TWEET-IE Twin Wind tunnels for Energy & the EnvironmenT INNOVATIONS - EXCELLENCE

The NTUA Wind Tunnel

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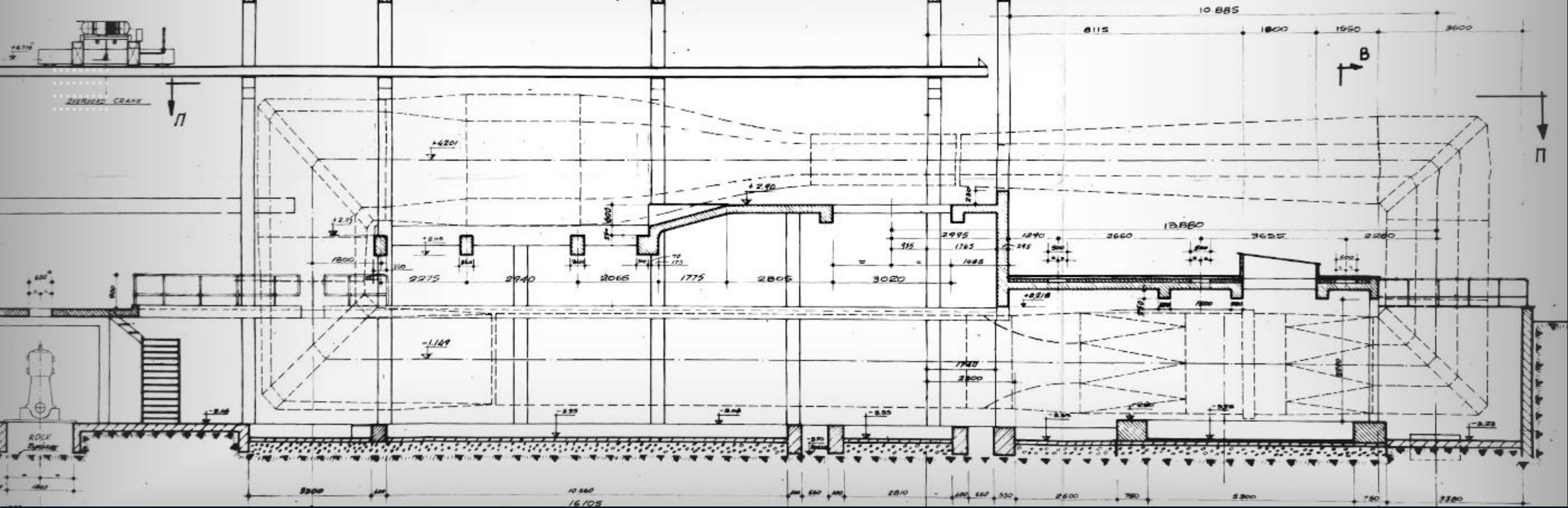
NTUA Wind Tunnel

Aerodynamics and Wind Energy Applications

WIND TUNNEL
NATIONAL TECHNICAL UNIVERSITY OF ATHENS

Marinos Manolesos
Assistant Professor, School of Mechanical Engineering

Wednesday, 26 June 2024



Technical Specifications

Closed loop, closed test sections

Large Test Section

- 3.5 m x 2.5 m x 12 m,
- Max speed 17 m/s,
- T.I. 2% - 6%

Small Test Section

- 1.4 m x 1.8 m x 2.5 m
- Max speed 60 m/s,
- T.I. 0.2%

Equipment

- Force Balances
- Pressure Scanners
- Hot Wire Anemometry
- Stereo Particle Image Velocimetry

✓ **Workshop**

✓ **Prefit Area**

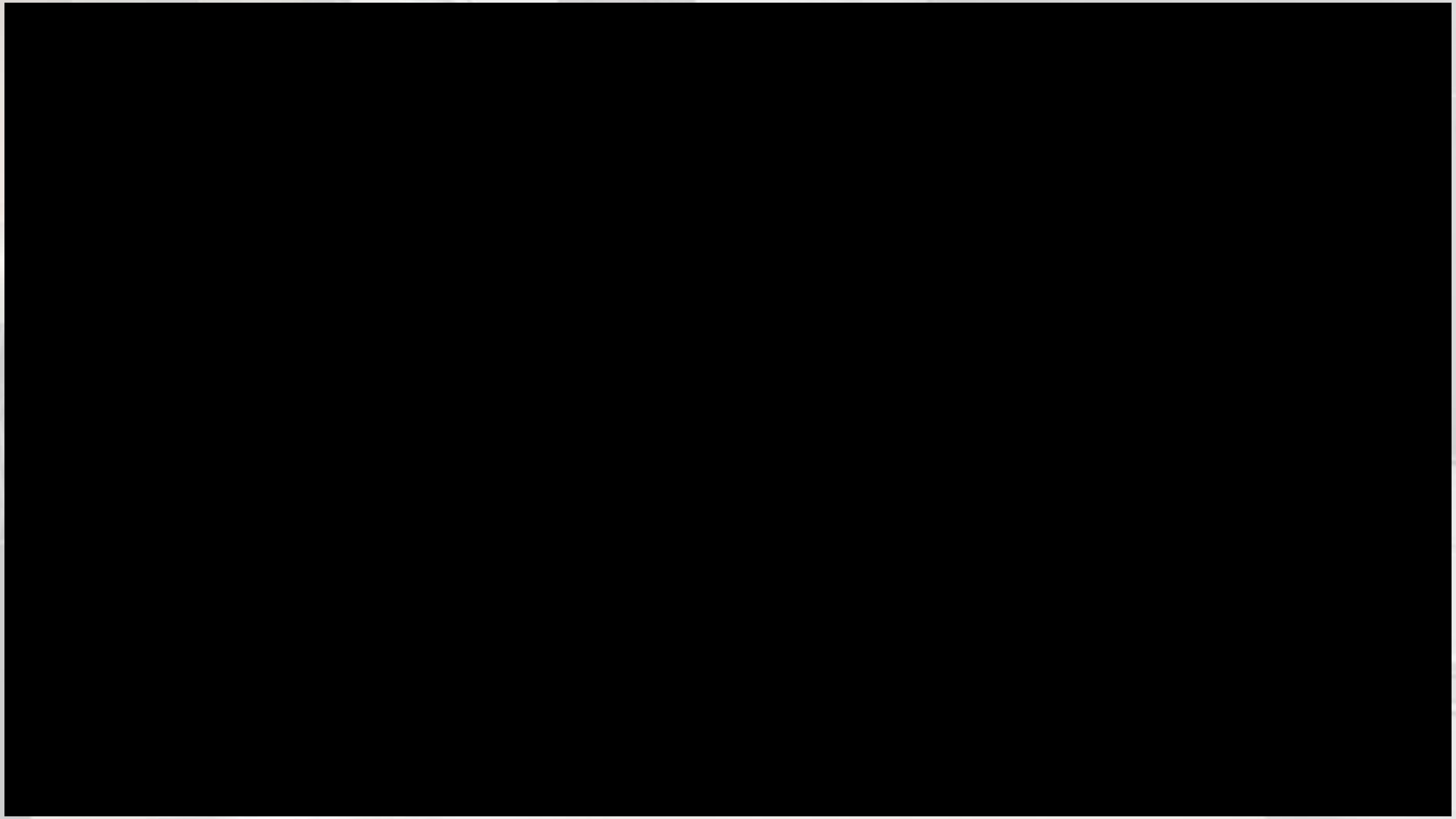
Large Test Section **Applications**

- Small Wind Turbines
- Wind Farm Modelling
- Sports (Cycling)
- Component Testing
  (Tents, Umbrellas, Parachutes)

Horizontal Axis Wind Turbines

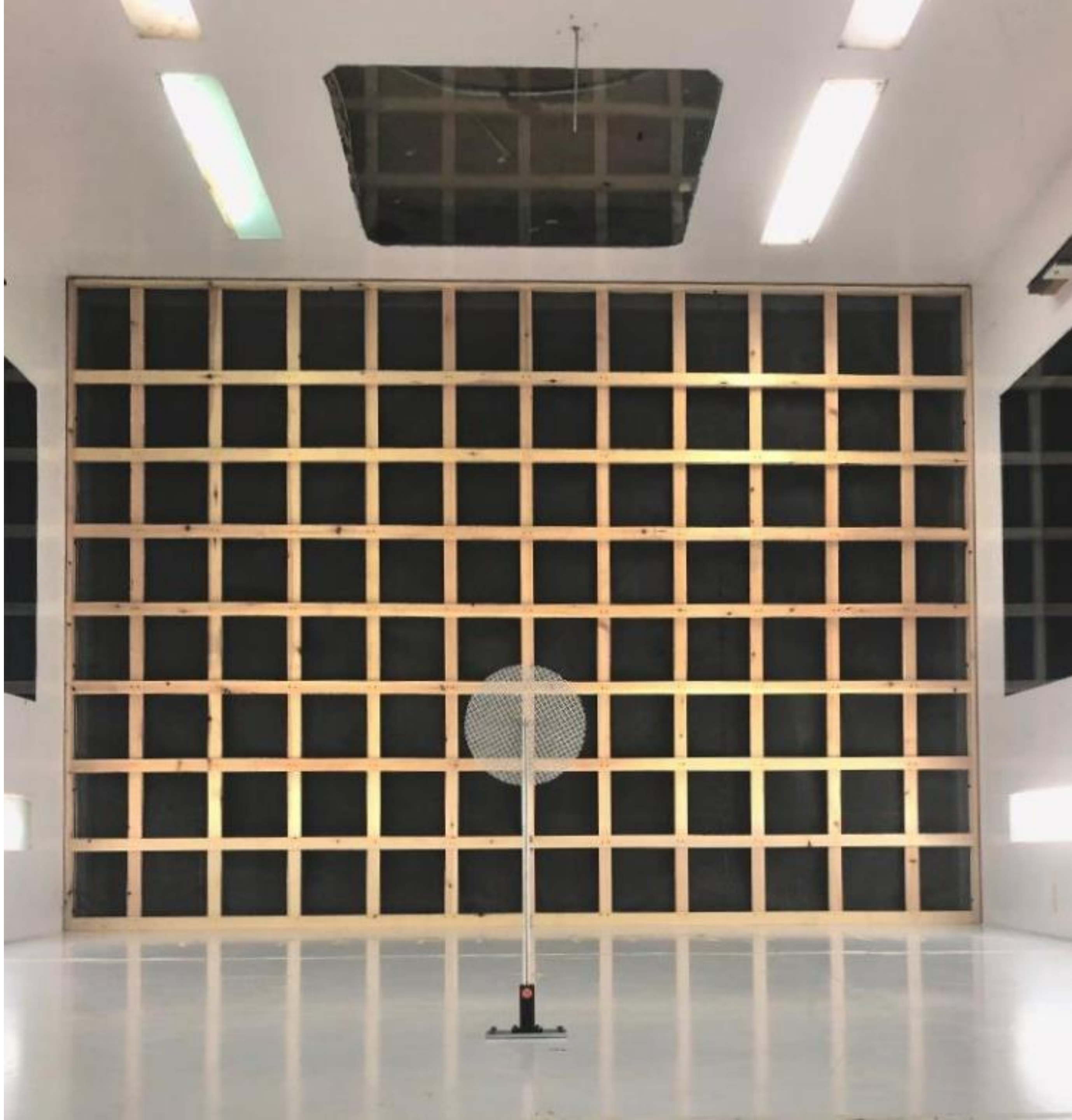
- Power
- Loads
- Wake / Blade Aerodynamics
- Component Testing
- Up to D=1.1 m

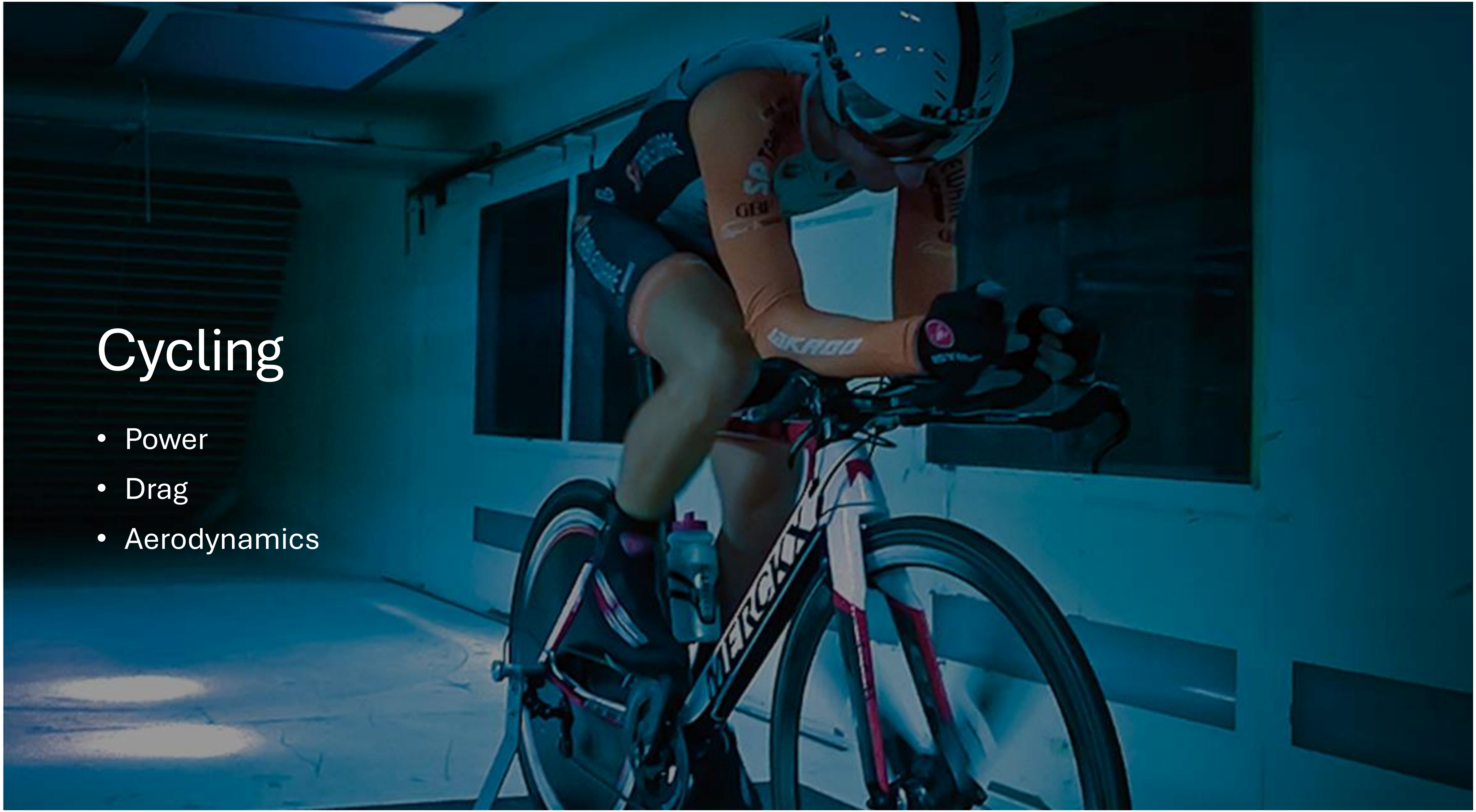
From two weeks ago..



Wind Farm modelling

- Perforated disk models
- Different levels of inflow turbulence





Cycling

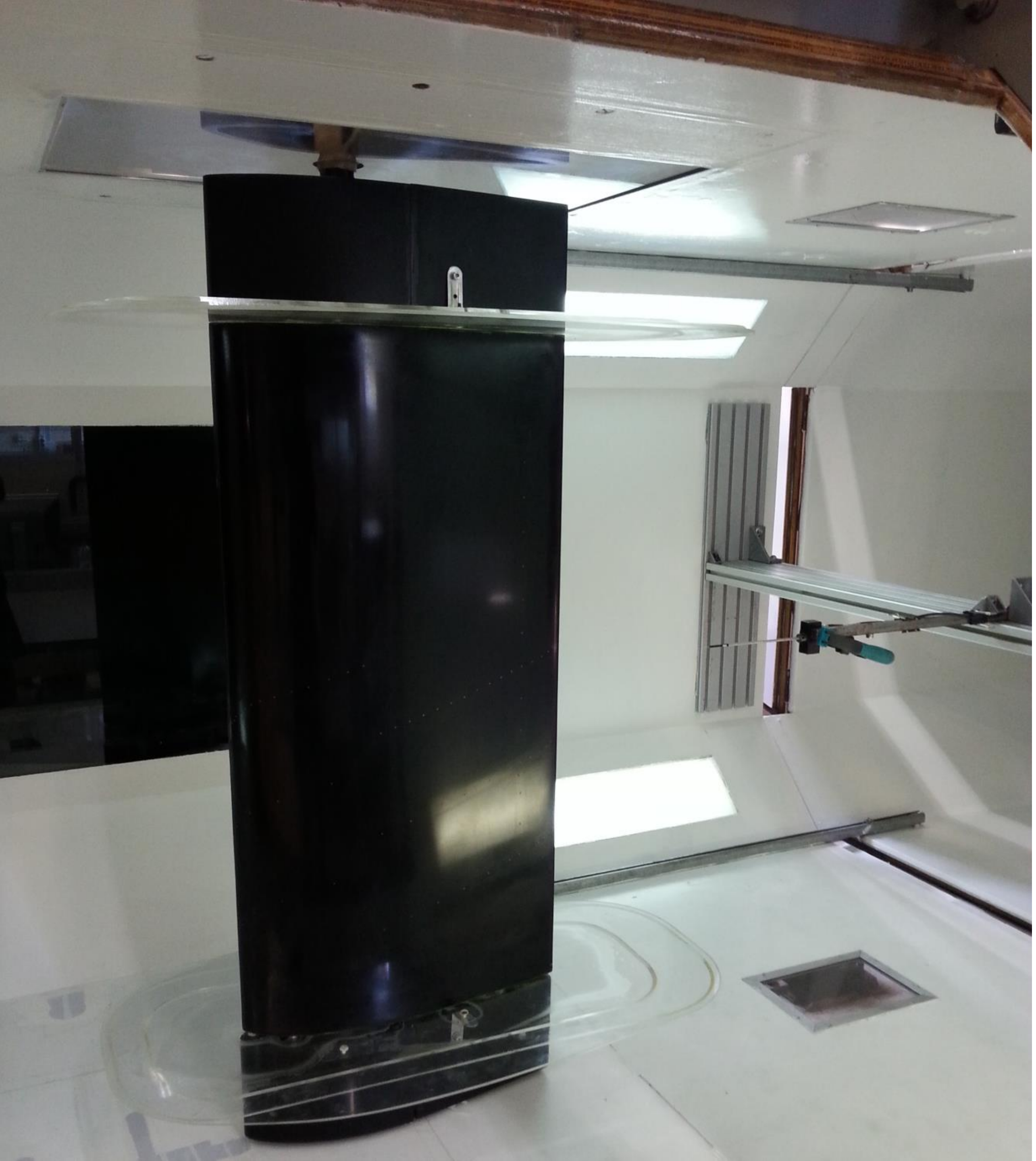
- Power
- Drag
- Aerodynamics

Wind Turbine Nacelle Testing

- Forces
- Vibrations
- Aerodynamics

Small Test Section Applications

- Airfoil Testing
- Gust Generation
- Flow Control Devices
- Component testing

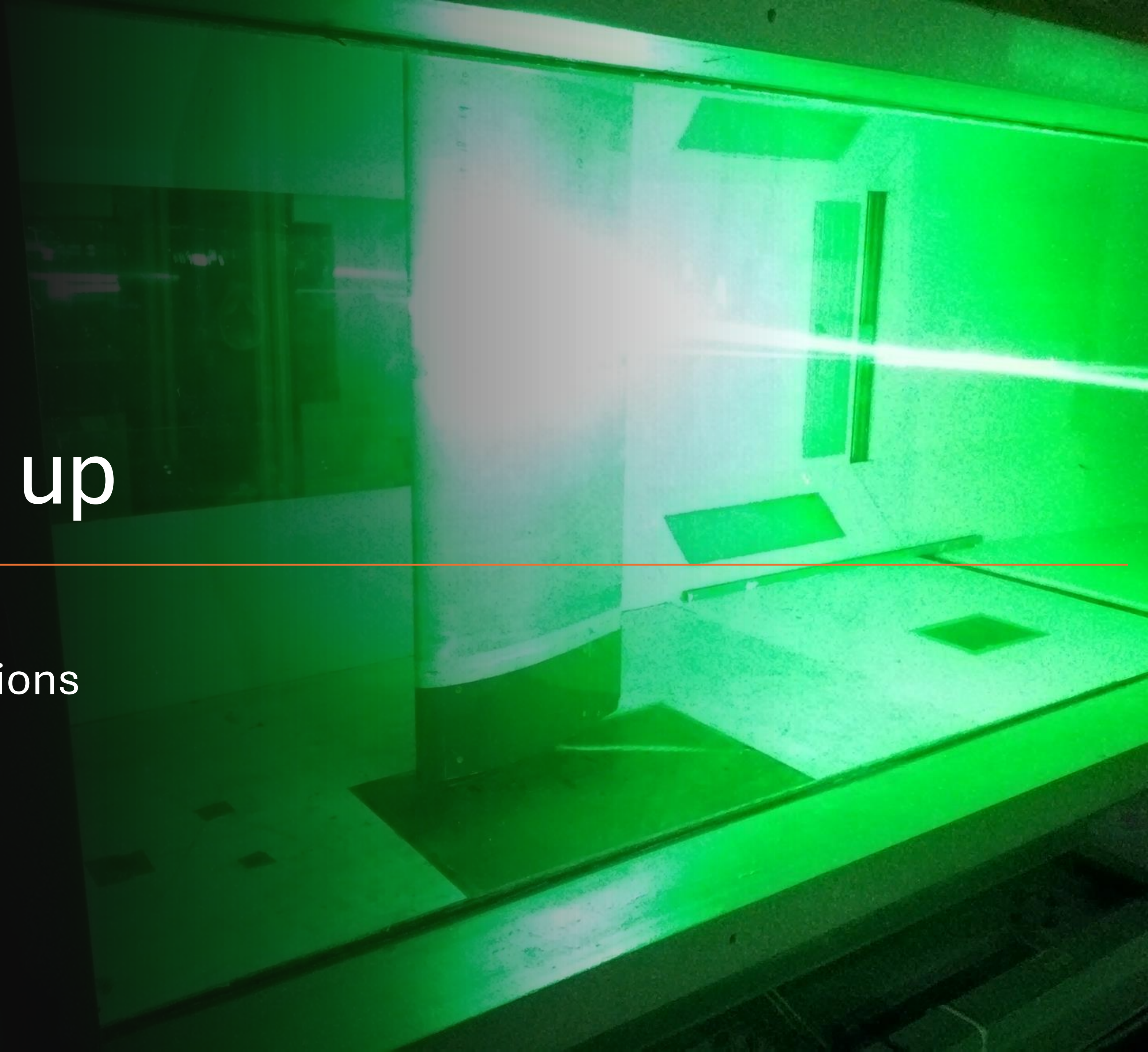


Airfoil Testing

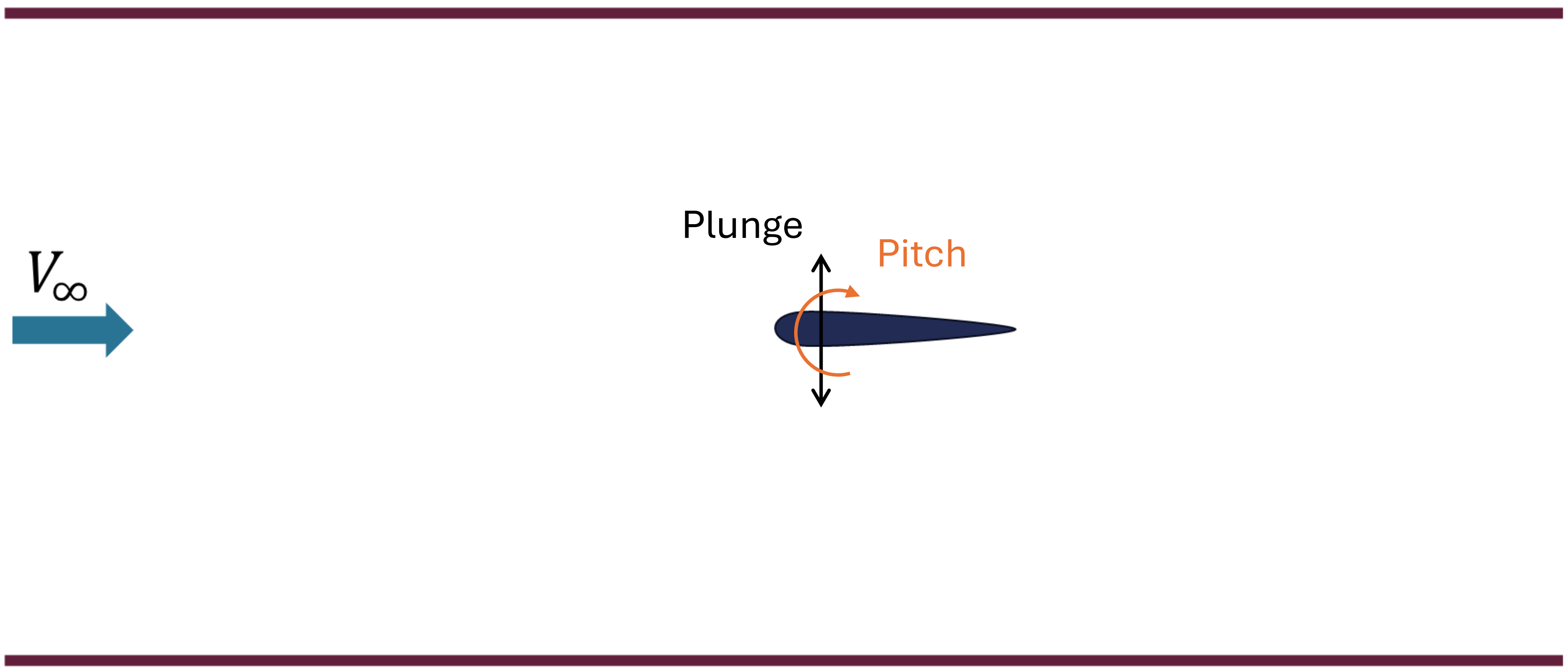
- Wind Turbine Airfoils
- Airfoil Performance
- Flow Control Devices
- Reynolds number up to 1.8M

Aeroelastic Set up

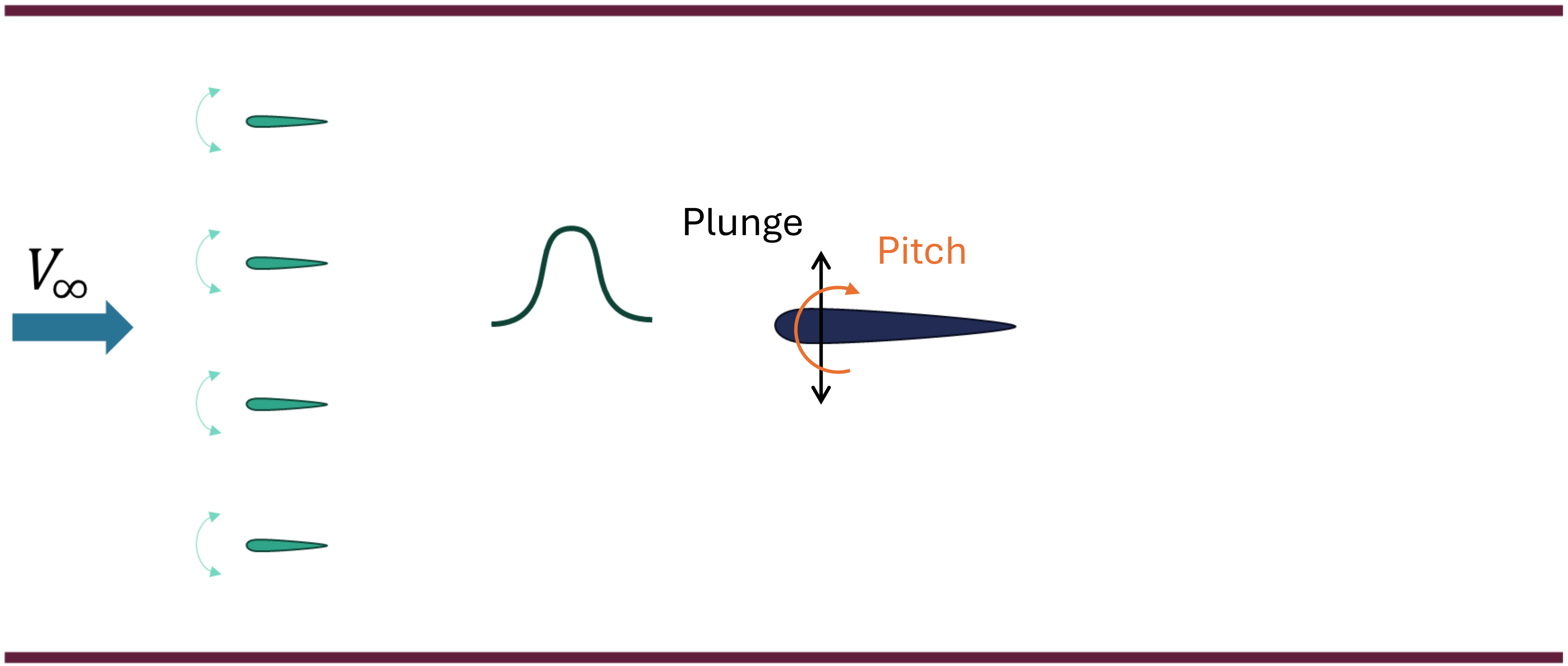
Models can pitch or plunge
under free and/or control motions



Aeroelastic Set up

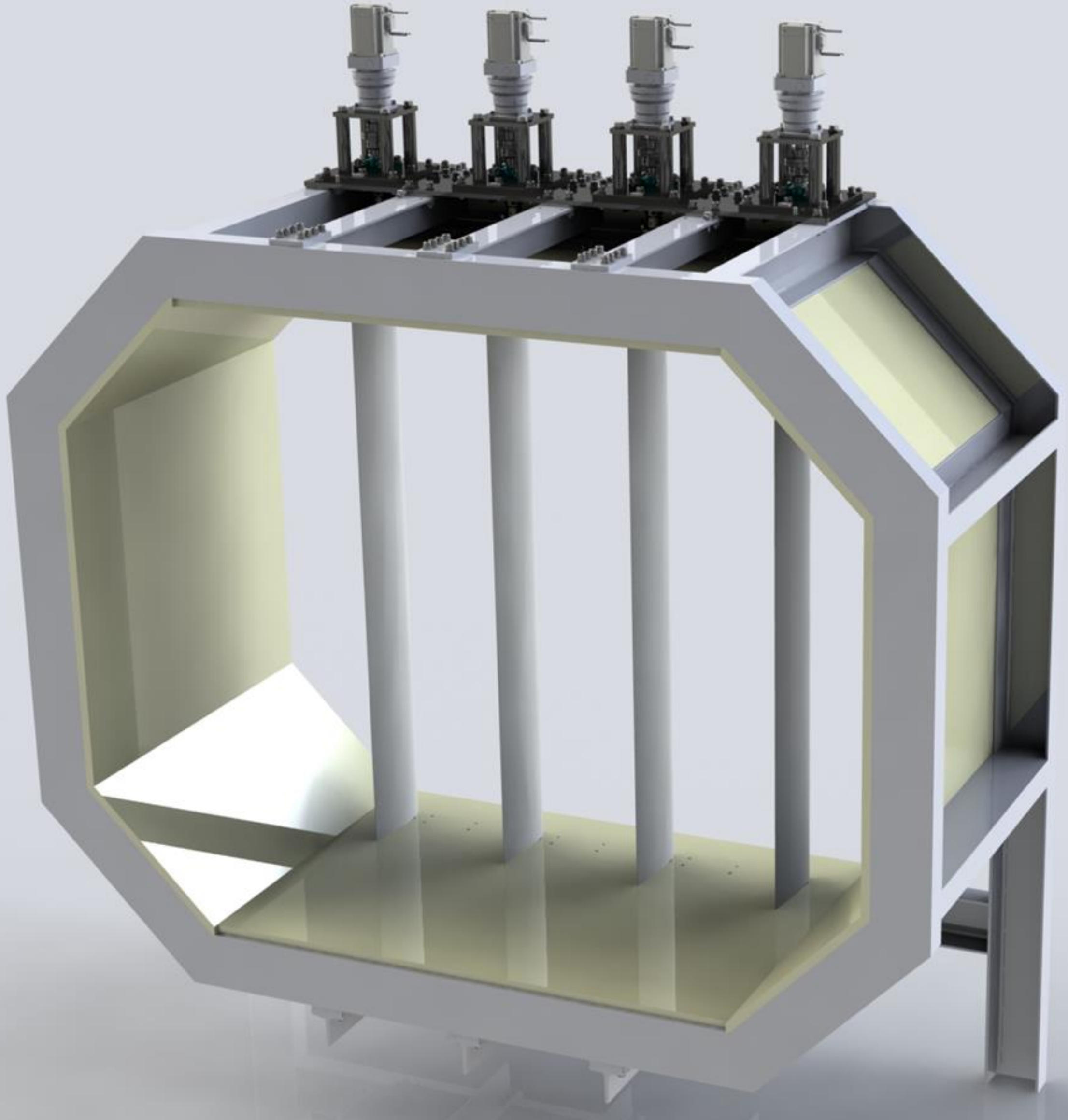


Gust Generation



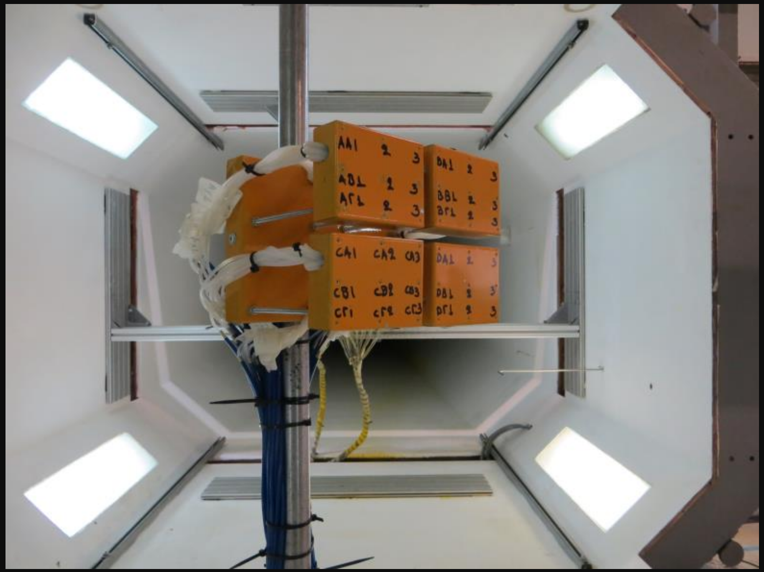
Gust Generation

One of the few facilities
in the world to achieve gusts
and Reynolds numbers
of this magnitude



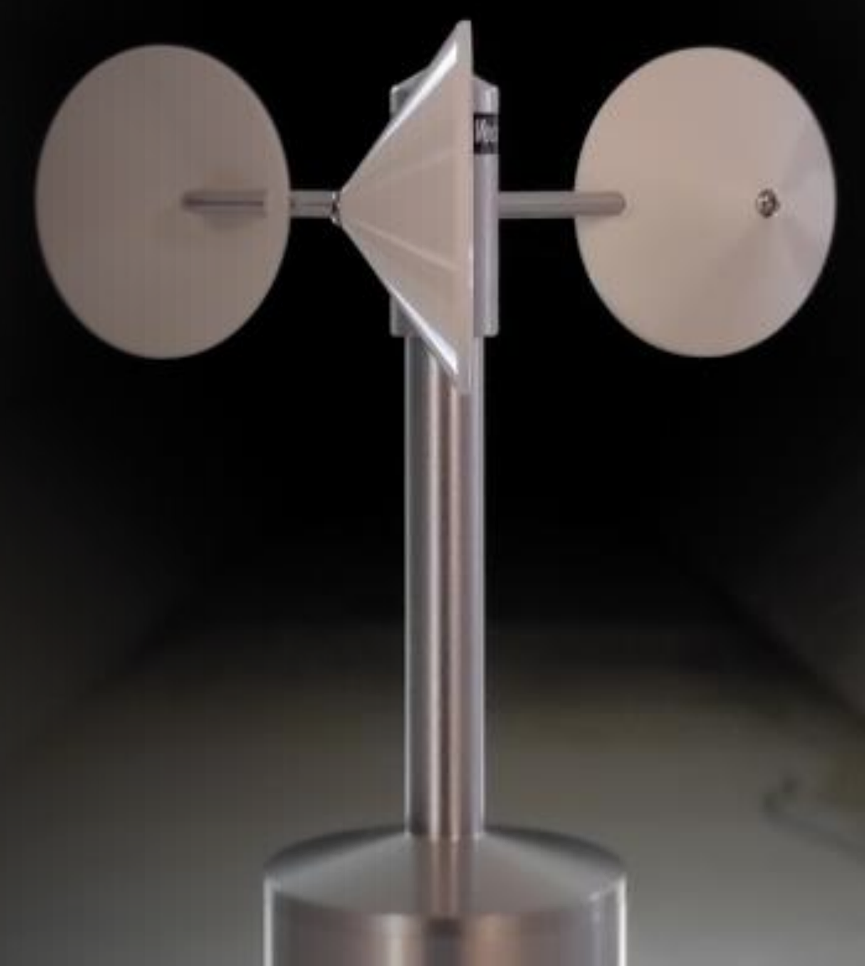
Component testing

- Survivability
- Forces
- Sealing



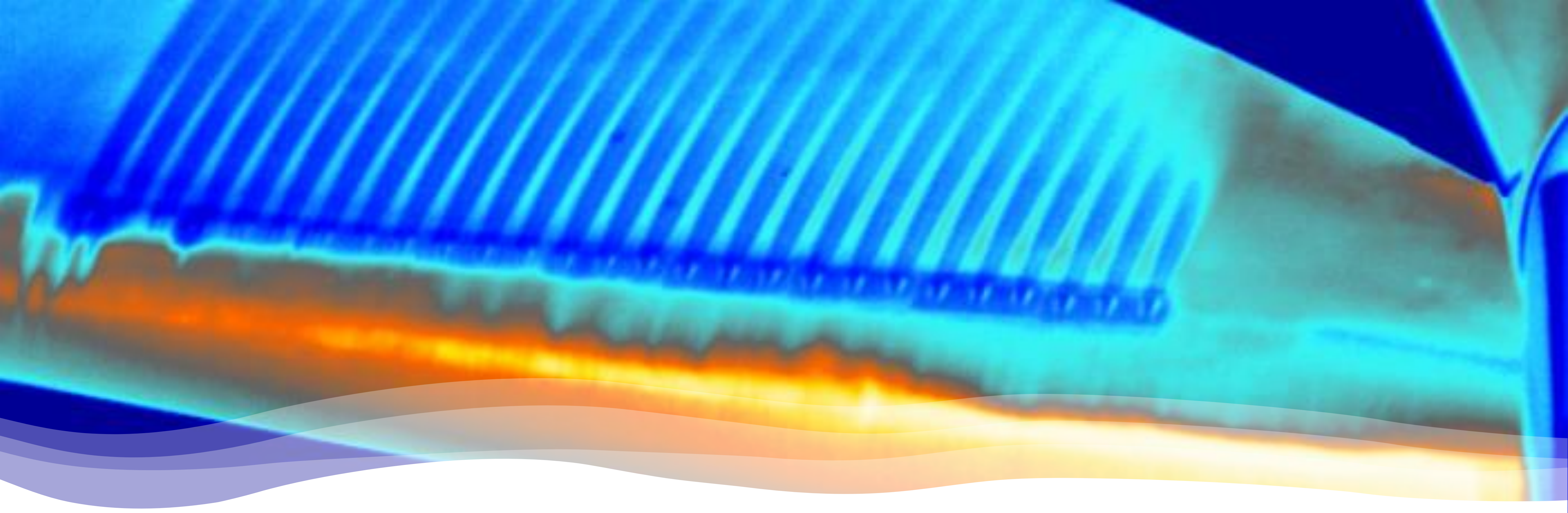
Anemometer Calibrations

- International Wind Engineering
- MEASNET Certification



Student Teams

- PROM Racing
- EUROAVIA
- Aiolos



Application:

Designing Flow Control Devices on Wind Turbines

The project:
Demonstration of Enhanced Vortex Generators

Can we (commercially) design better VGs than the existing ones?

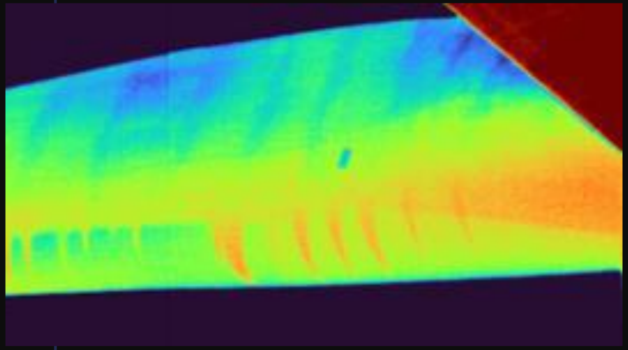
- Improved shape/configuration
- Improved positioning
- Blade specific

- Higher AEP

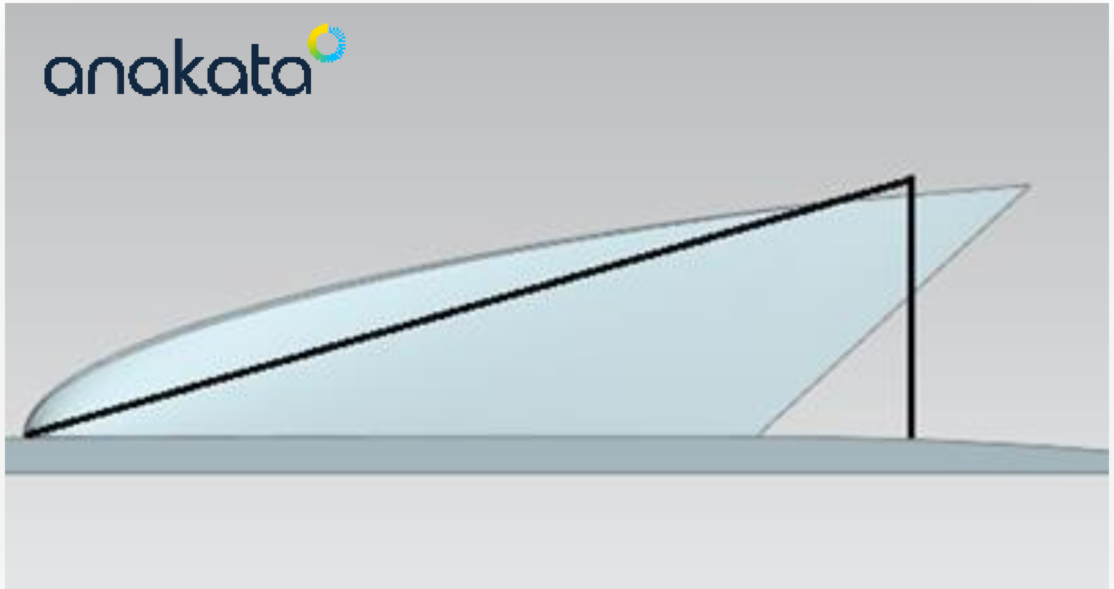
Application on two turbines:

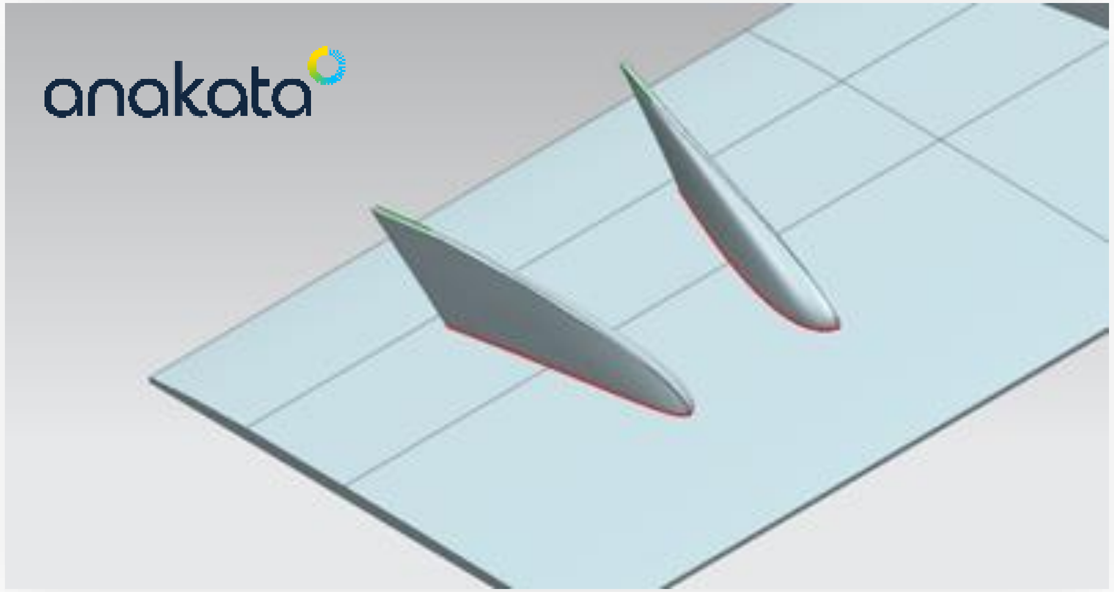
- 850kW Vestas V52 ($D = 52\ m$)
- 7MW Levenmouth Demonstration Turbine ($D = 171\ m$)

What we did



- Wind Tunnel Testing
- RANS CFD simulations
- BEM calculations
- Infrared Thermography
- Field tests

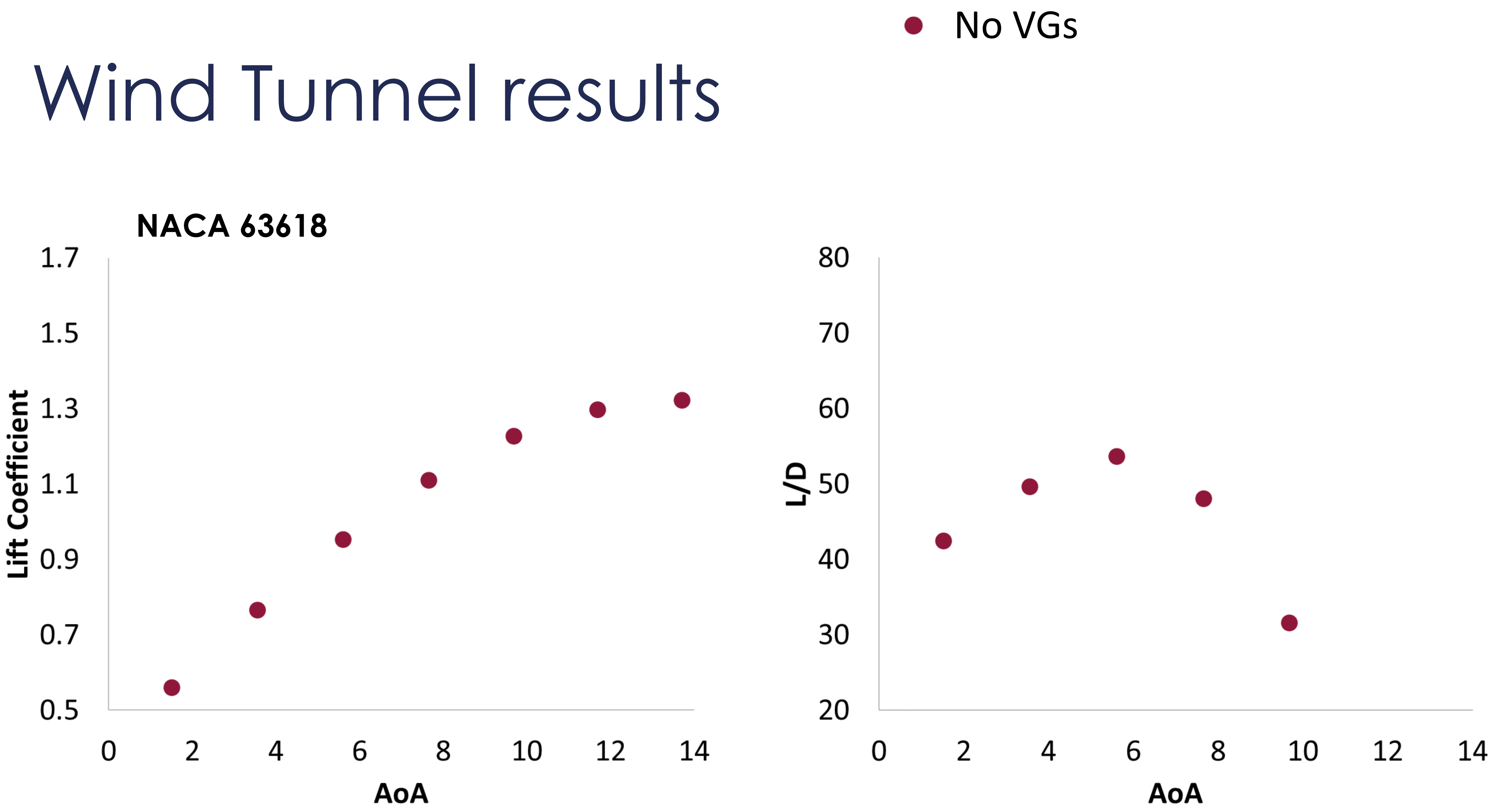




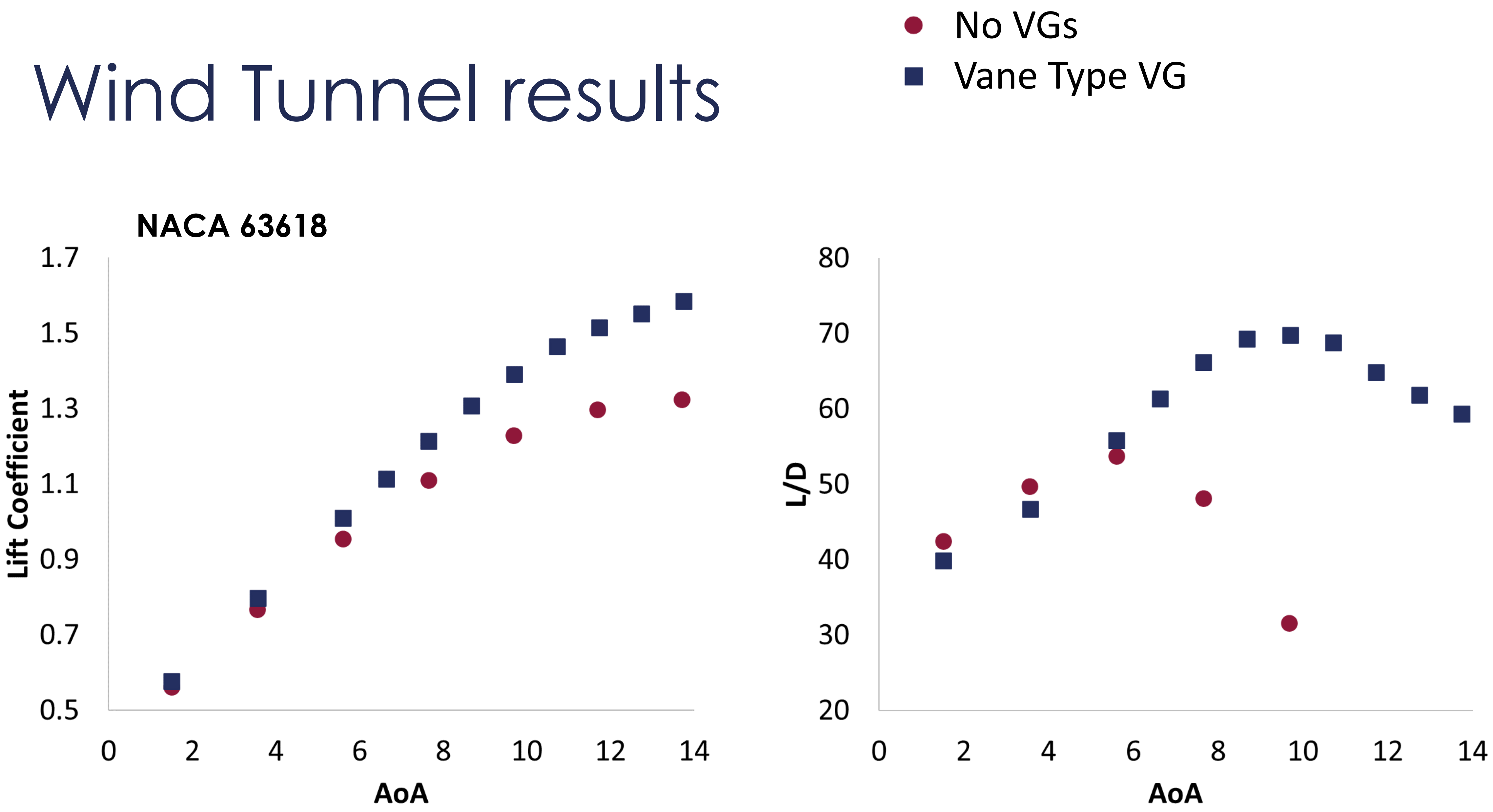
VG Design

- A single VG design performed best for all airfoil profiles.
- Best performing shape
  - is 3D
  - has a cambered airfoil outline and
  - has variable twist
- $h_{VG} = 0.01c$
- Located at
  - $0.4c$ for the 18% thick airfoil
  - Both sides on the 35% thick airfoil

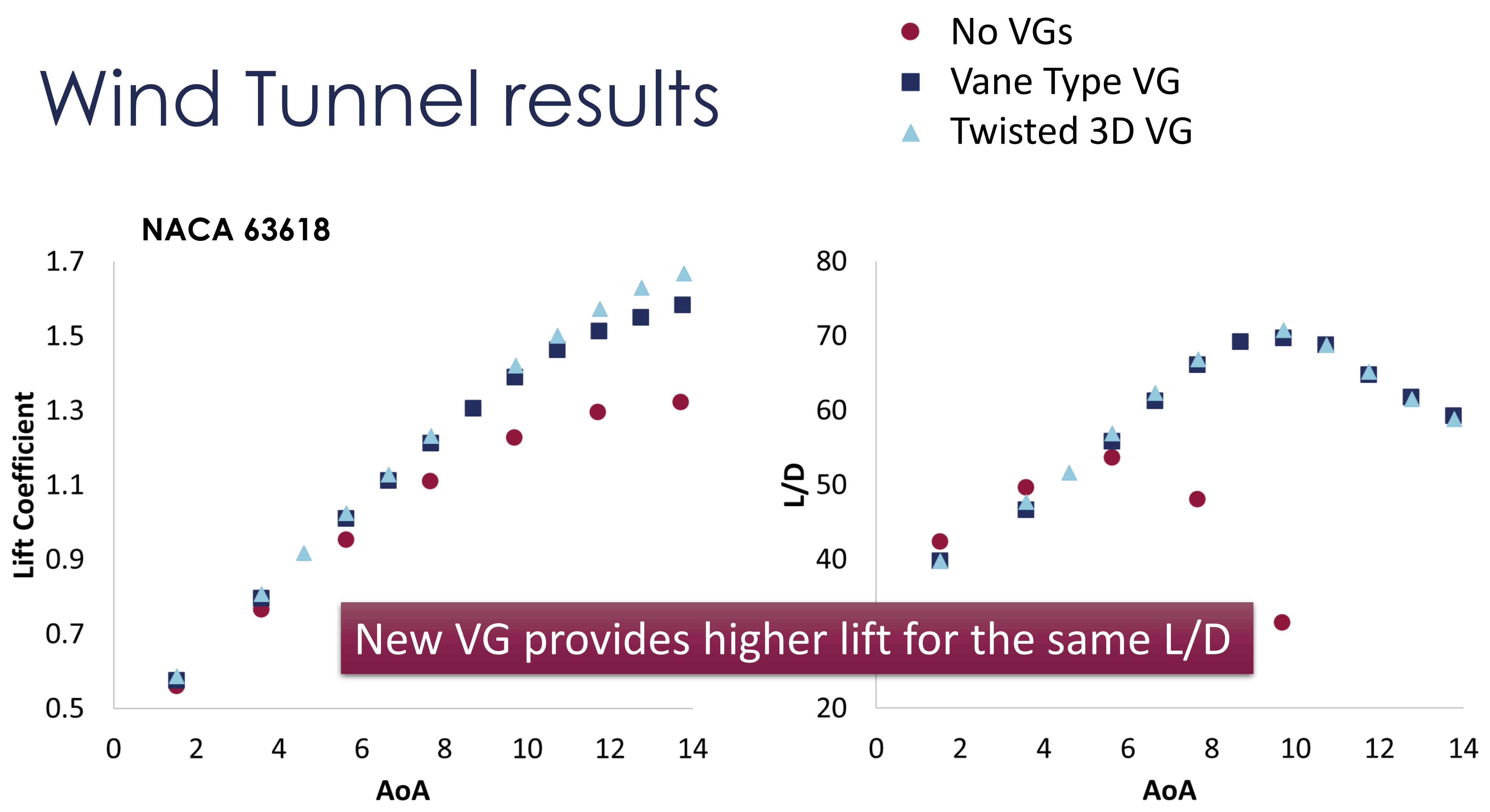
Wind Tunnel results



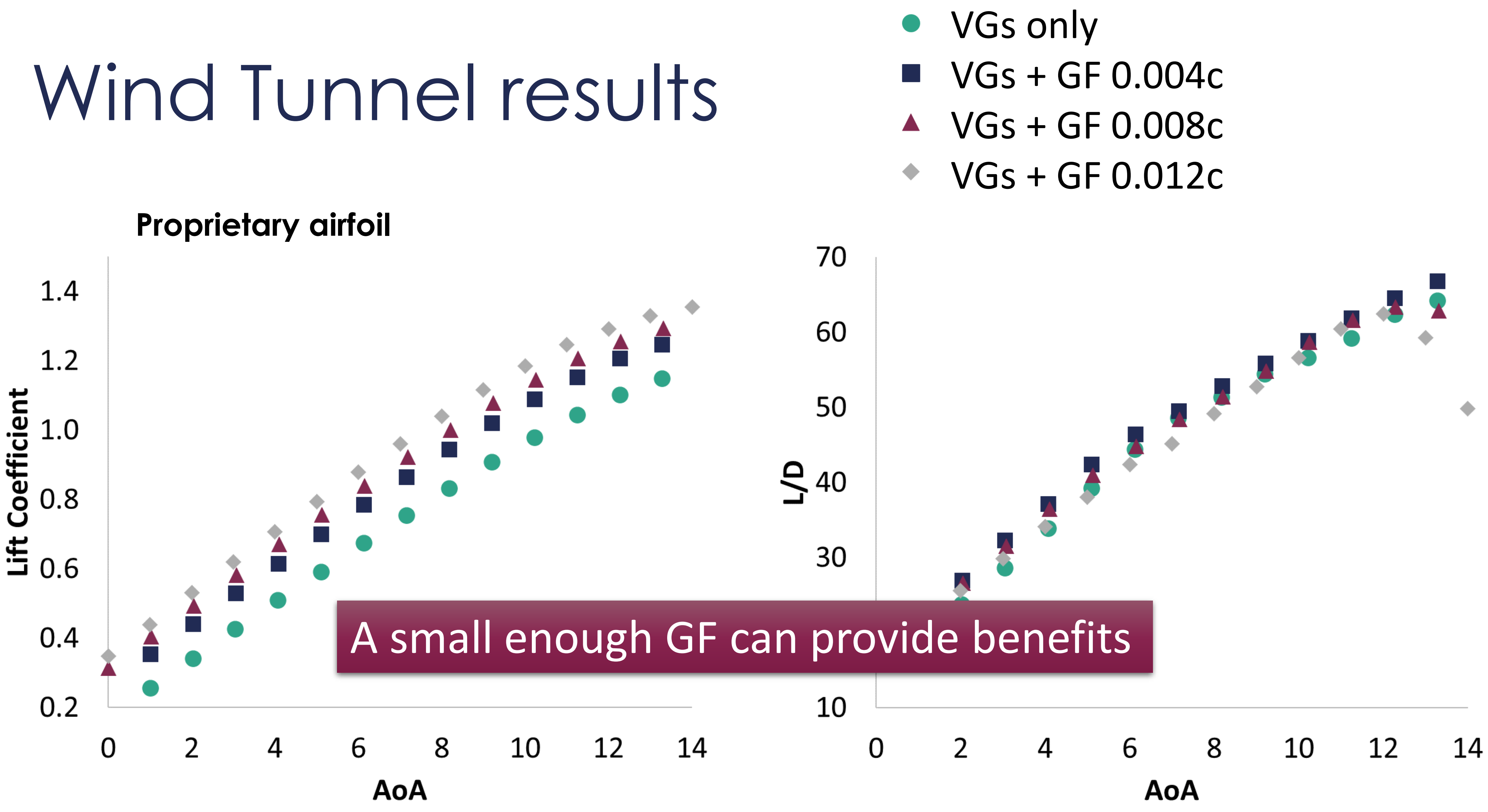
Wind Tunnel results



Wind Tunnel results

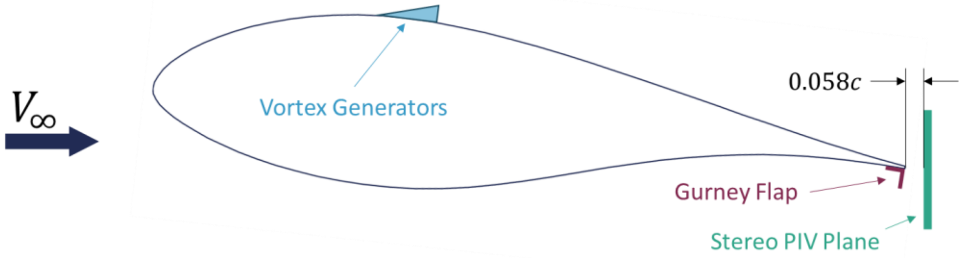


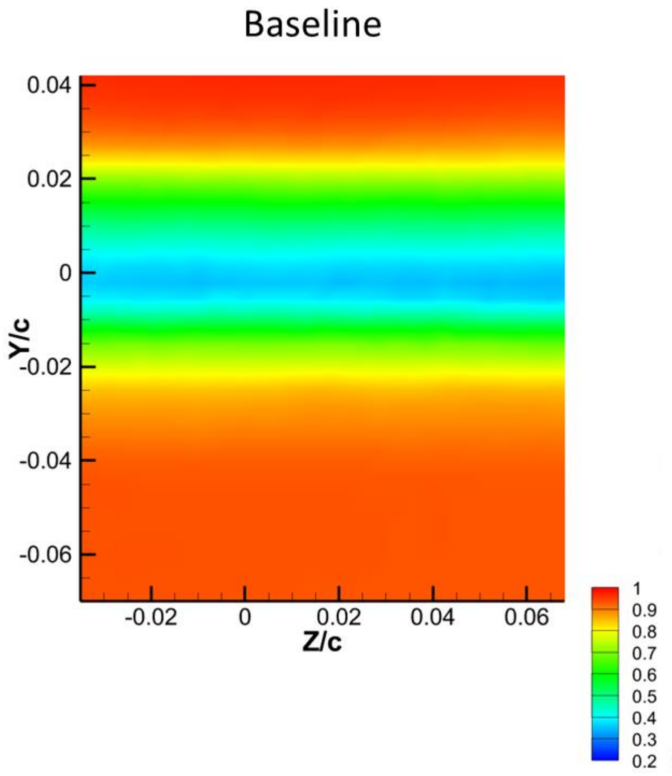
Wind Tunnel results



JoP: Conf Series, vol. 2265, no. 3, p. 032040. IOP Publishing, 2022

PIV





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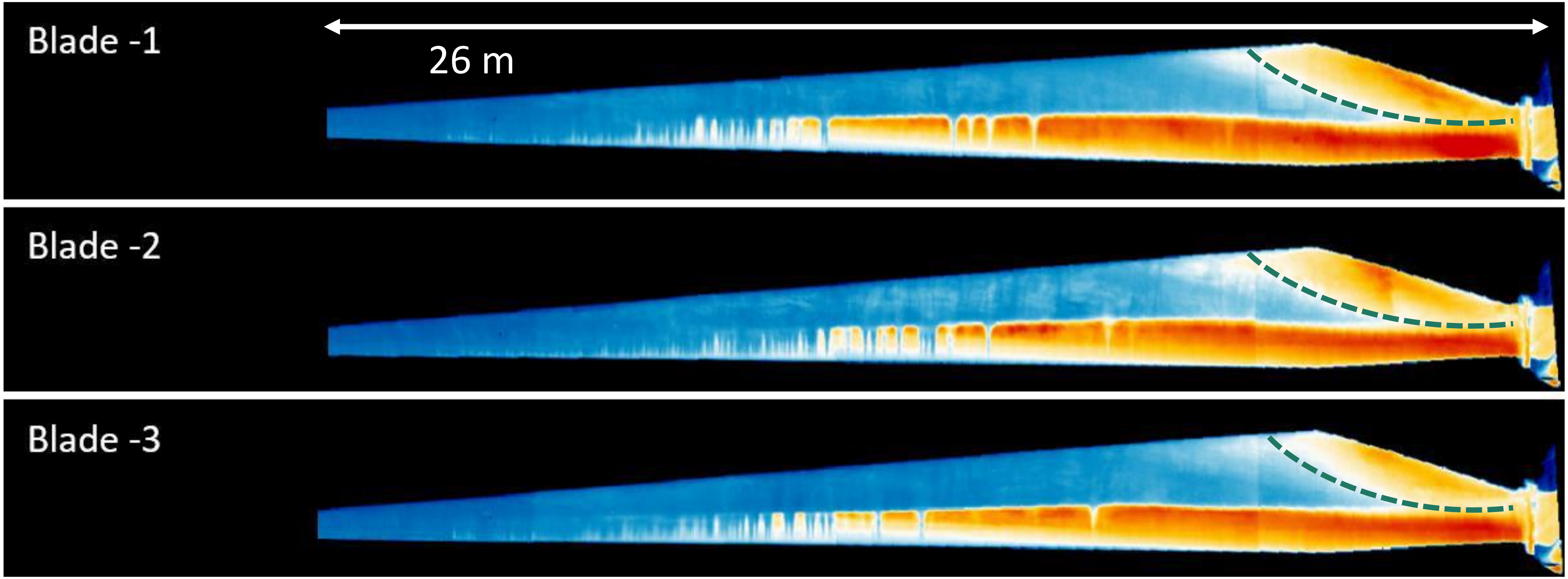
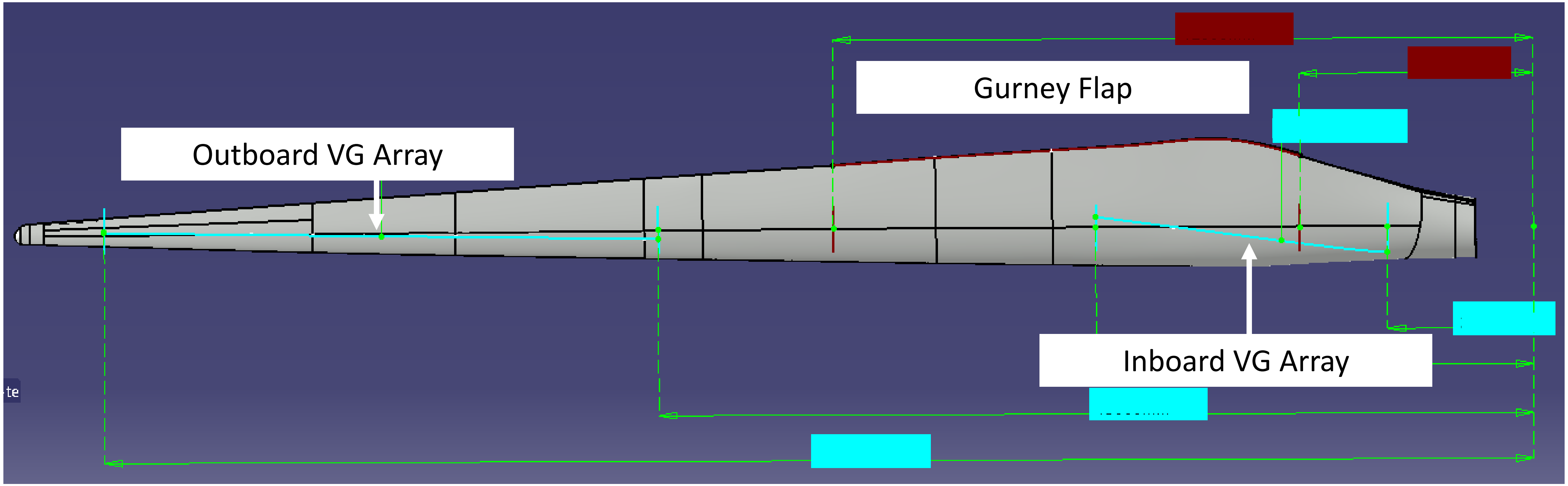
Wanstrow – Vestas V52 850kW

Suction Side Features

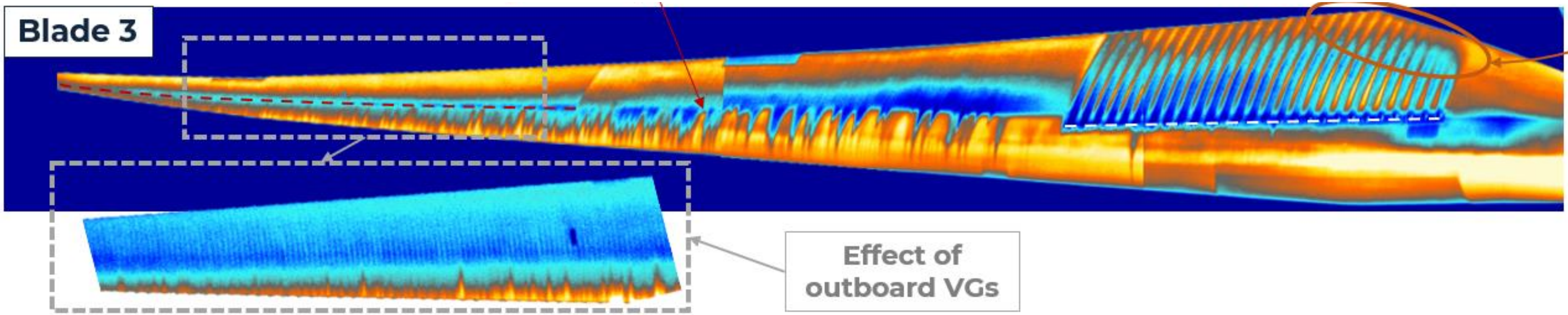


V52 Flow control configuration

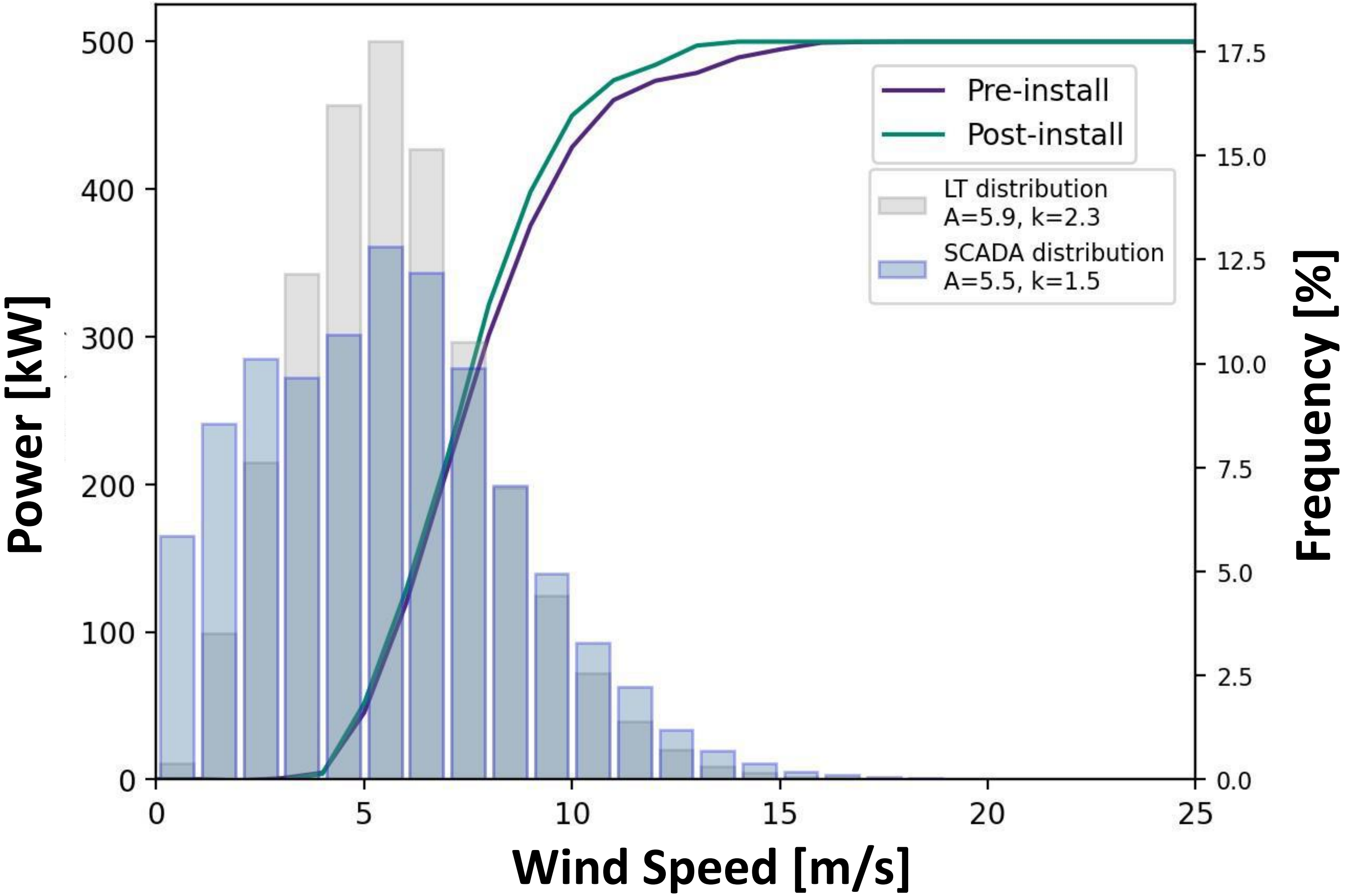


Field Assessment

Region of flow separation near blade root mitigated with VGs



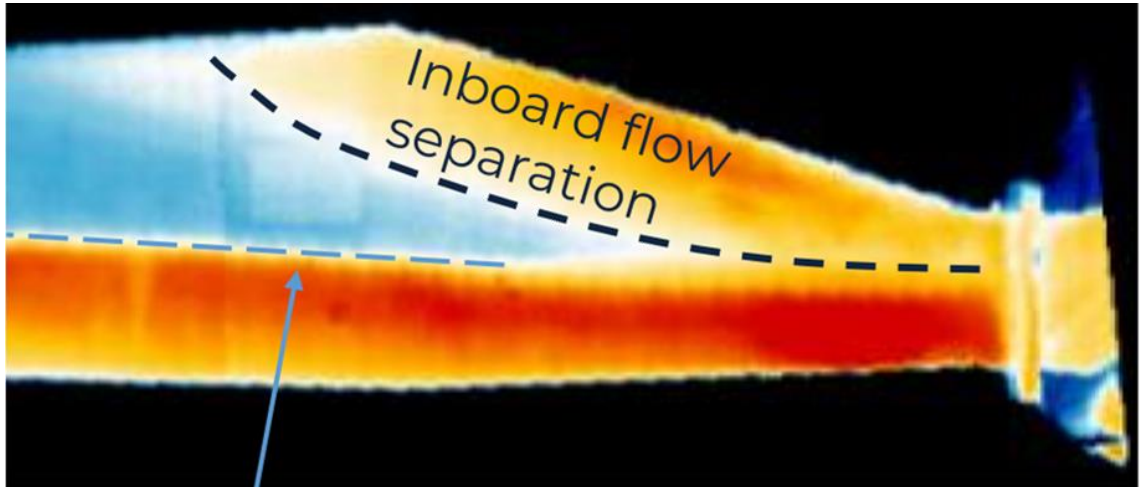
Field Assessment **+5.4% to +5.8% AEP**



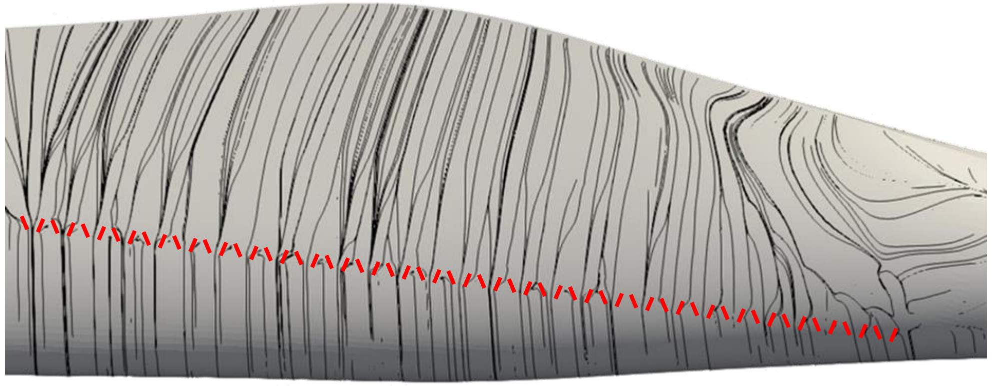
natural power

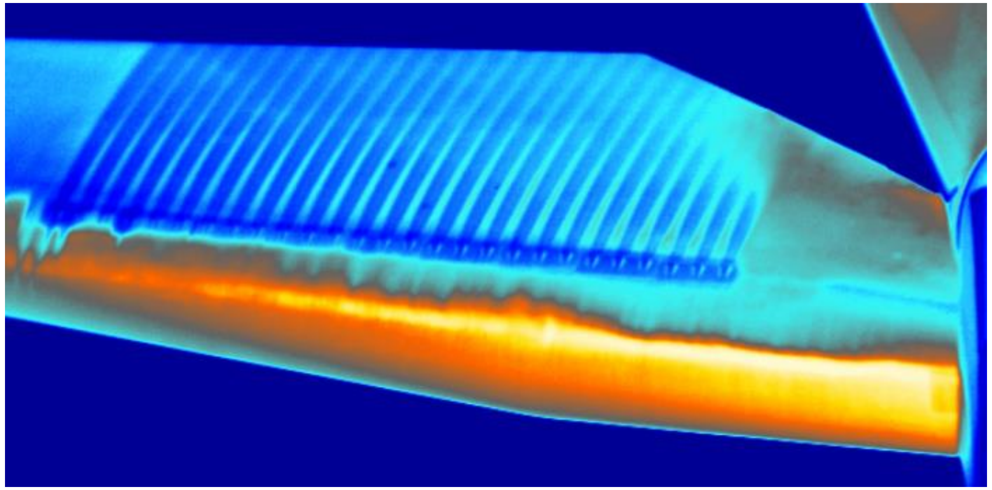
Results – Retrofitting Flow Control Devices

Before



After





[1]

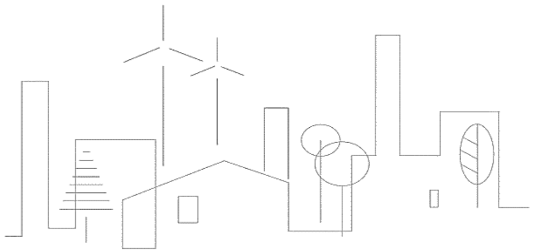
Thank you for your attention

Questions?

marinos@fluid.mech.ntua.gr

References

1. Papadakis, G. and Manolesos, M.: The flow past a flatback airfoil with flow control devices: benchmarking numerical simulations against wind tunnel data, Wind Energ. Sci., 5, 911–927, https://doi.org/10.5194/wes-5-911-2020, 2020.
2. Manolesos, M., Celik, Y., Ramsay, H., Karande, R., Wood, B., Dinwoodie, I., ... & Papadakis, G. (2024, June). Performance improvement of a Vestas V52 850kW wind turbine by retrofitting passive flow control devices. In *Journal of Physics: Conference Series* (Vol. 2767, No. 2, p. 022027). IOP Publishing.



Aerodynamics and Wind Energy: Computational Fluid & Structural Dynamics

Vasilis Riziotis

TWEET-IE Technical Event, 26 June 2024

Co-funded by the European Union

Computational Aerodynamic & Fluid Structure Interaction research activities related to Wind Energy applications:

- Aerodynamic and hydro-aero-elastic design/optimization and analysis of wind turbines
- Wind turbines noise emission and propagation
- Wind farms layout optimization and wake effects assessment

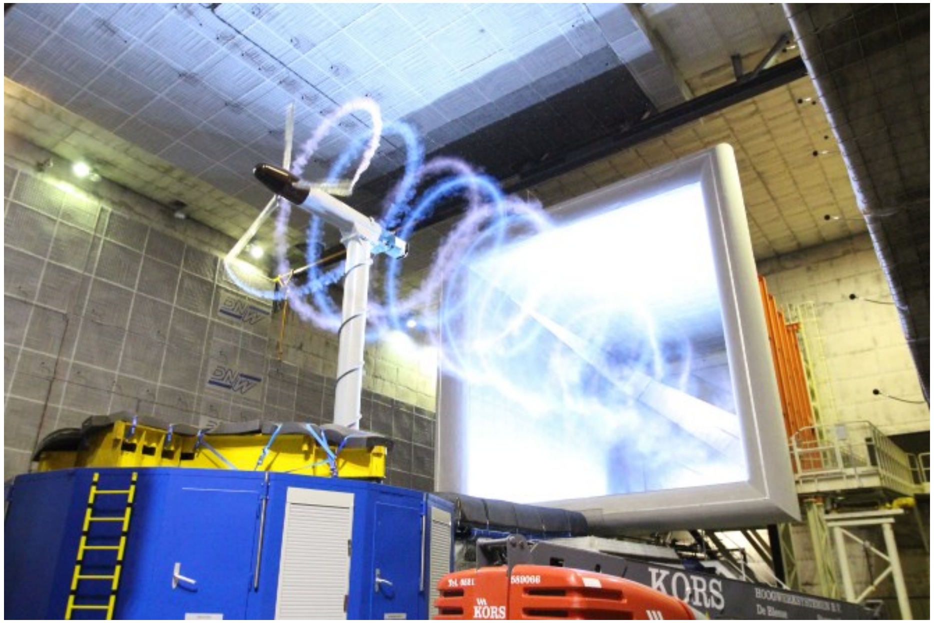
A wide range of in-house aerodynamics analysis tools have been developed over the years:

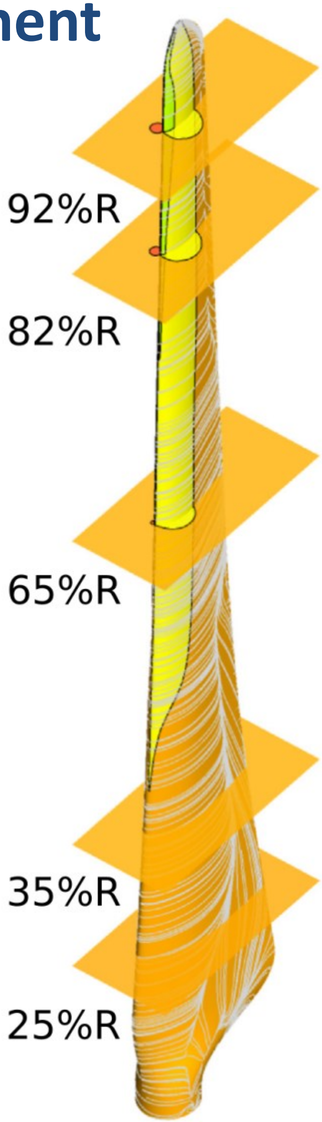
- Enhanced Blade Element Momentum (BEM) models
- Lifting line / lifting surface / panel free wake vortex models
- Actuator disk and line CFD URANS/DDES/LES models
- Fully resolved CFD URANS/DDES/LES models
- Hybrid CFD models (Eulerian – Lagrangian)

Modelling of New MEXIXO experiment

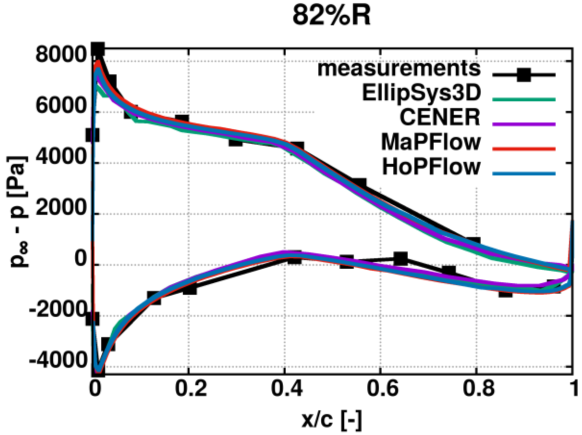
MEXICO 2012 → New MEXICO 2015

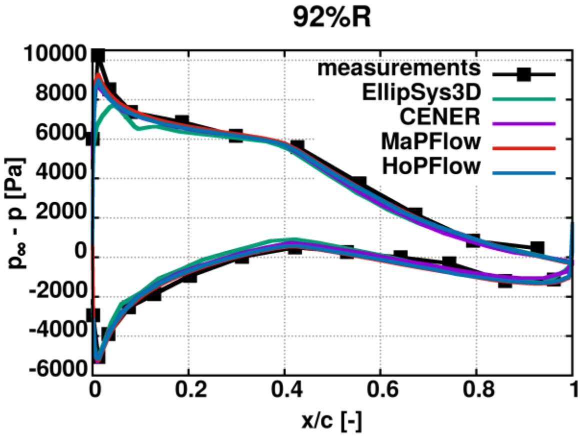
U_∞	14.7 m/s	20-45%R	DU91-W2-250
Ω	425 rpm	55-65%R	RISØ A1-21
Yaw, Tilt	0°	75-100%R	NACA 64418

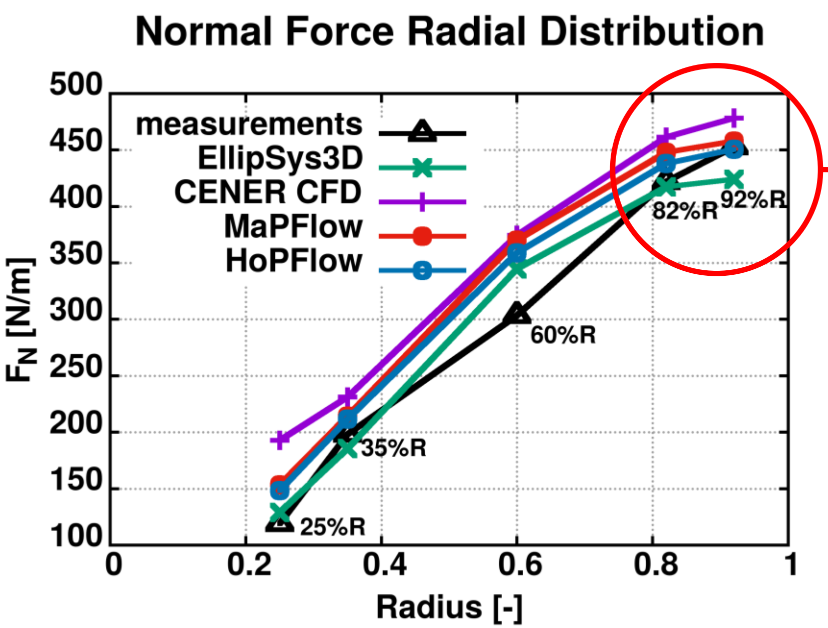


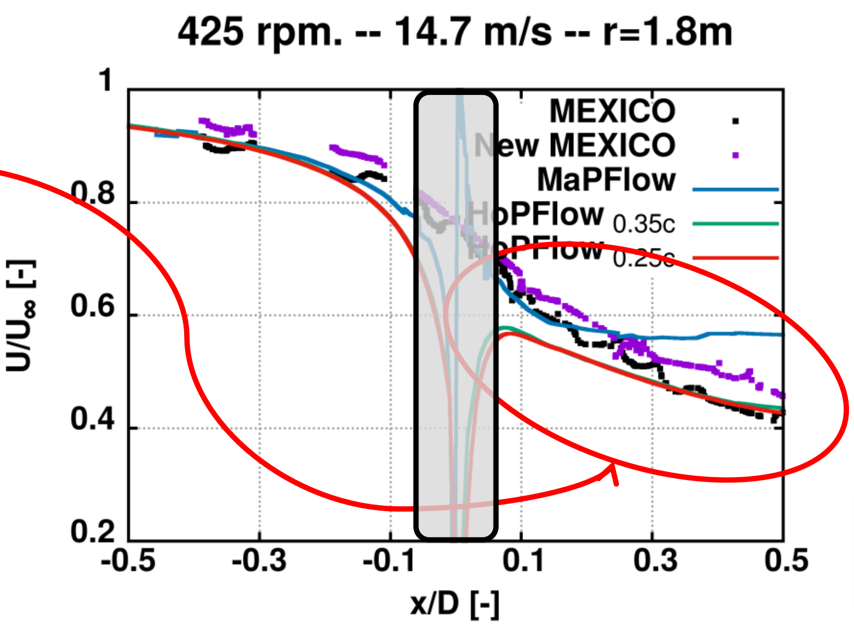


Wind Turbine Aerodynamics

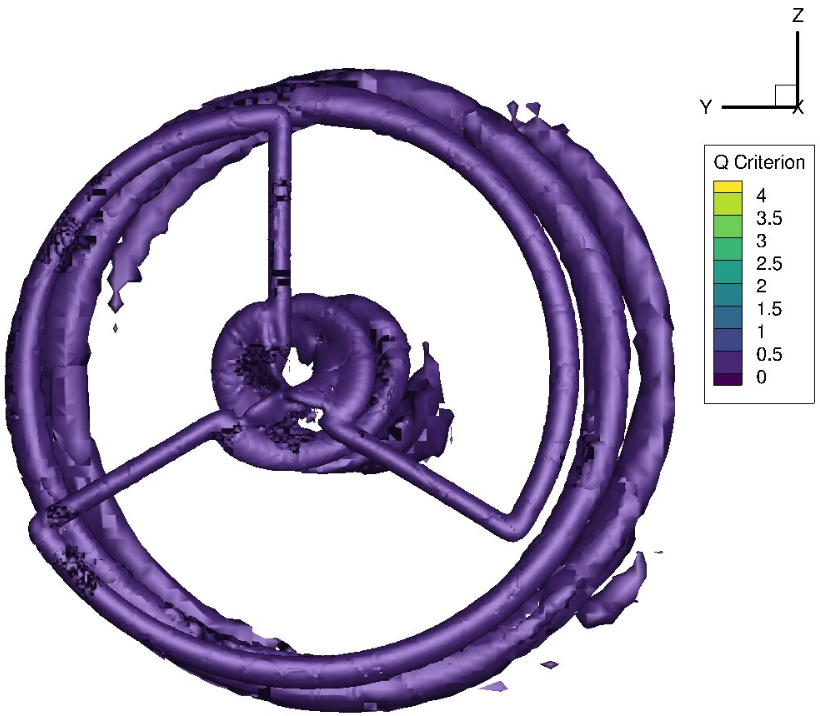




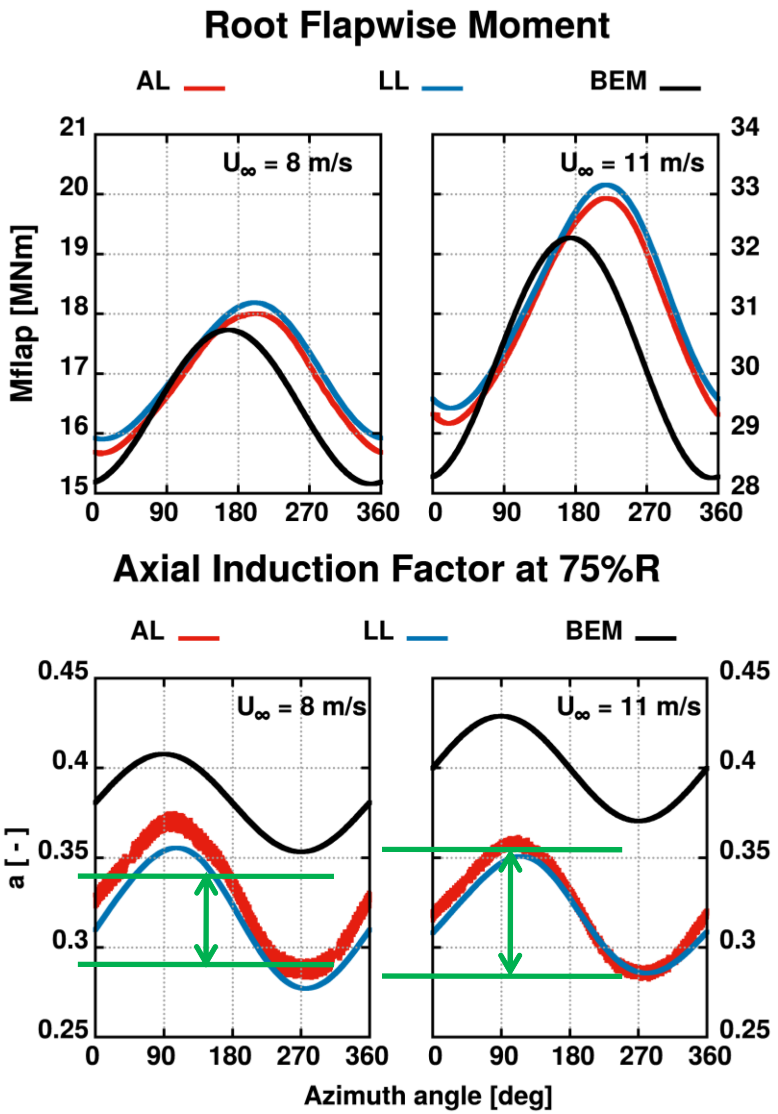




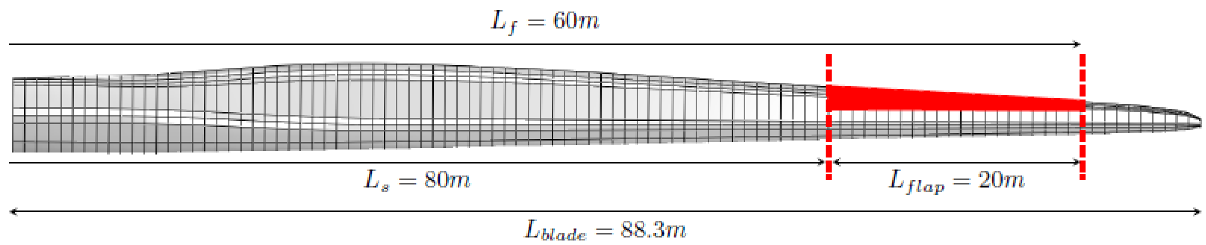
Modelling of yawed flow conditions



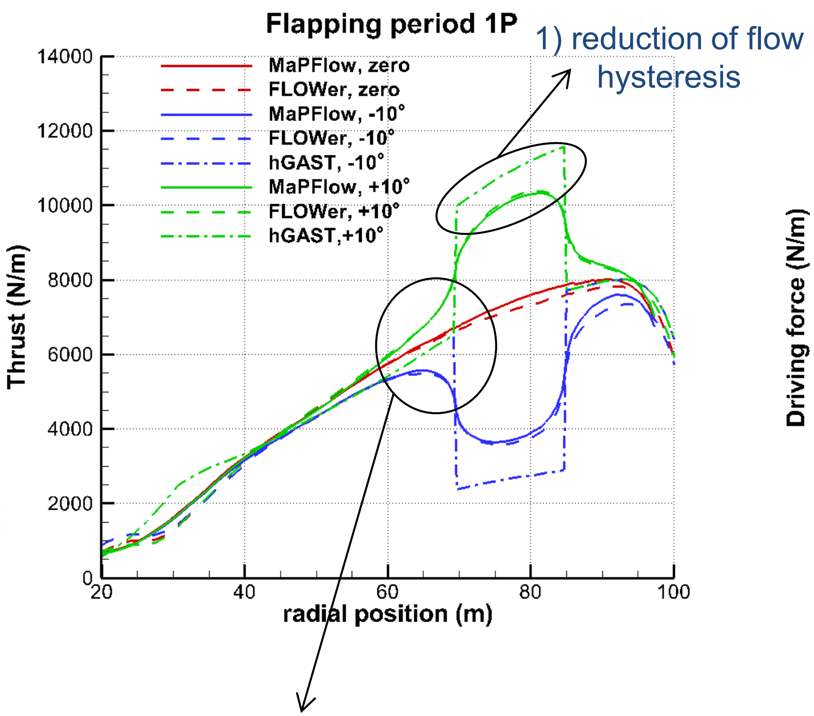
Yaw 15°

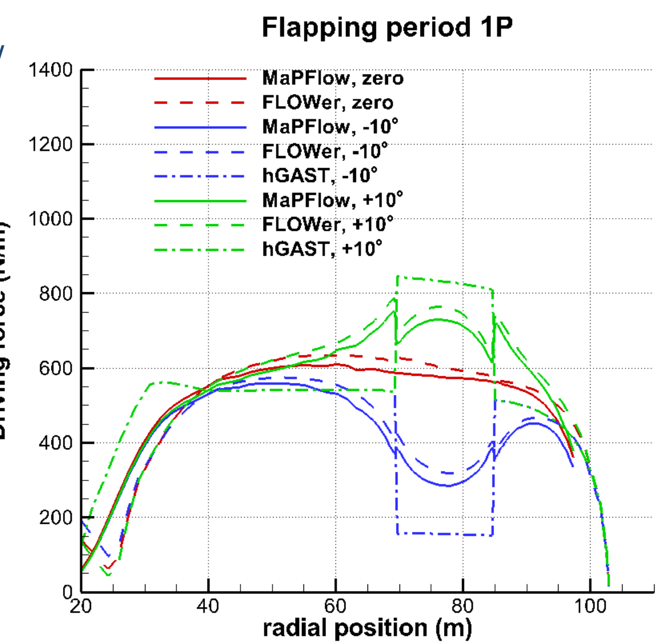


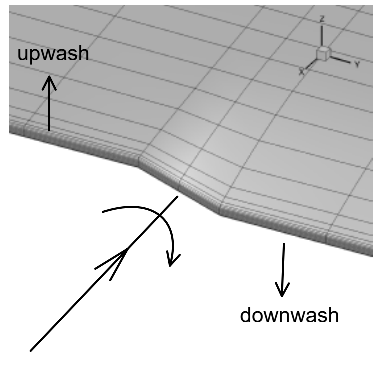
1P flap deflection - radial distribution of loads for +-10deg flap deflection



AVATAR AdVanced Aerodynamic Tools for lArge Rotors



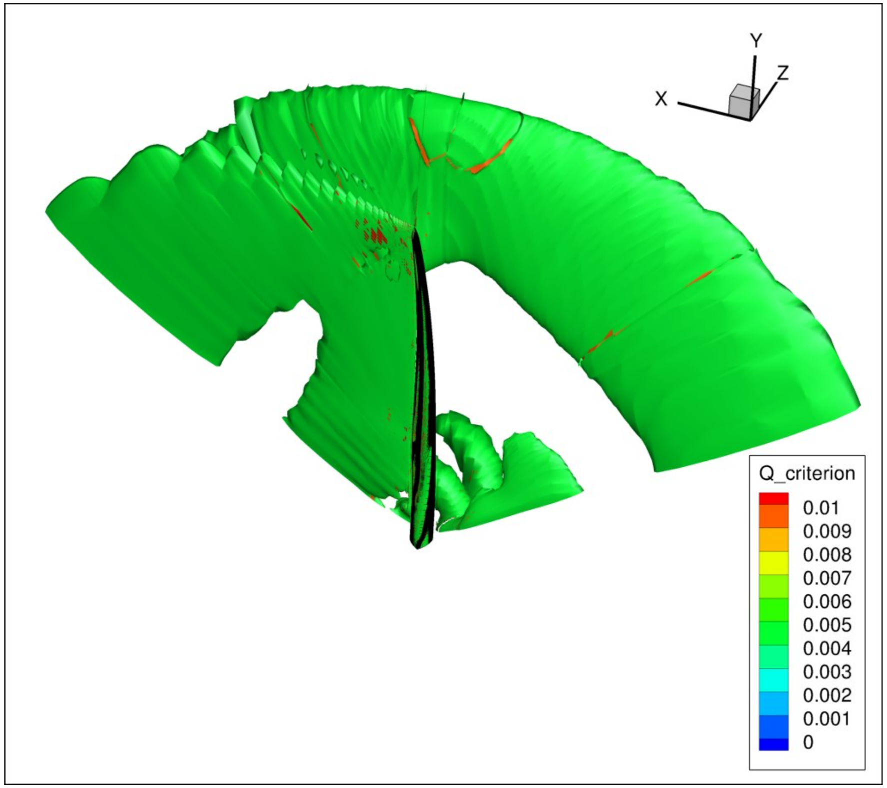




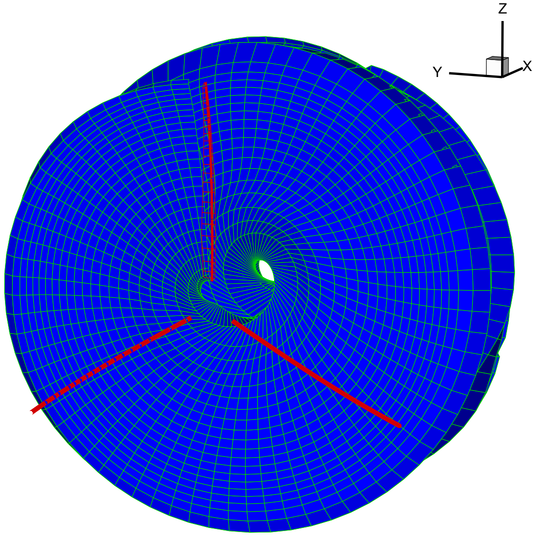
2) expansion of flap influence beyond the flap region

3) off-center appearance of maximum

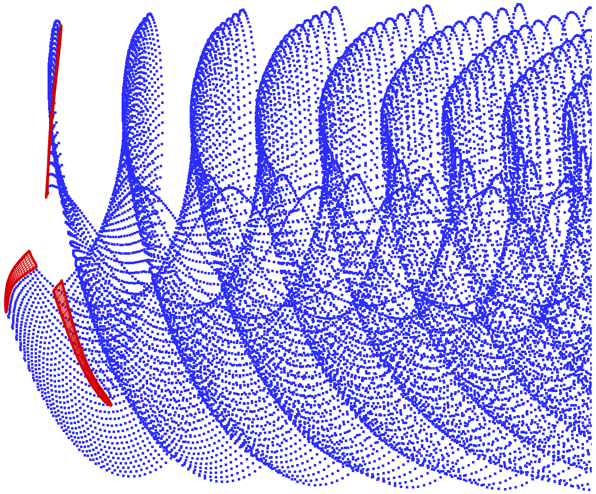
Wind Turbine Aerodynamics



3D CFD (Q criterion)

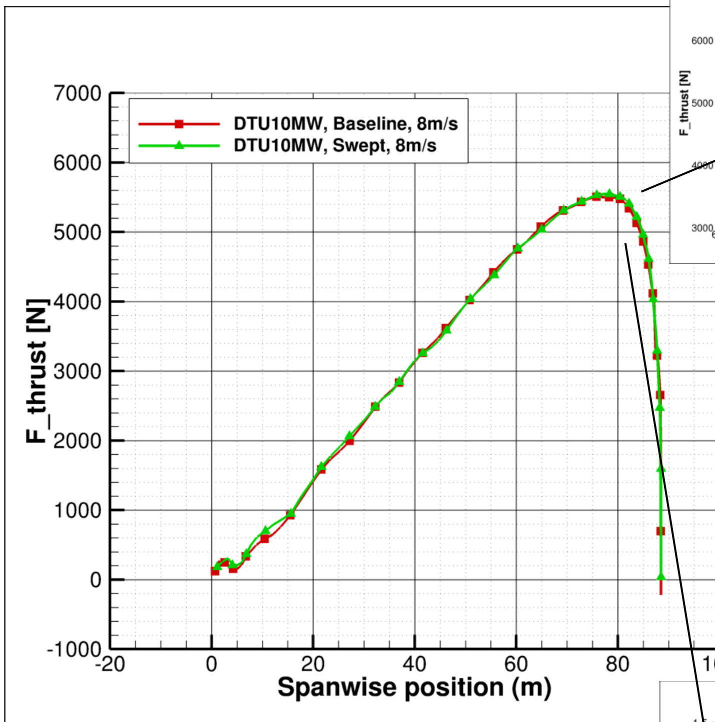


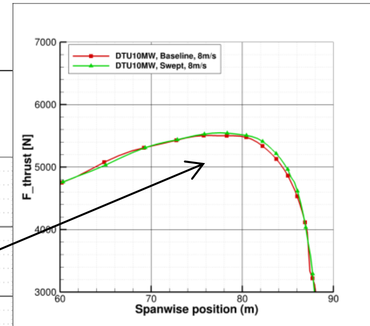
3D free wake lifting line (wake pattern)

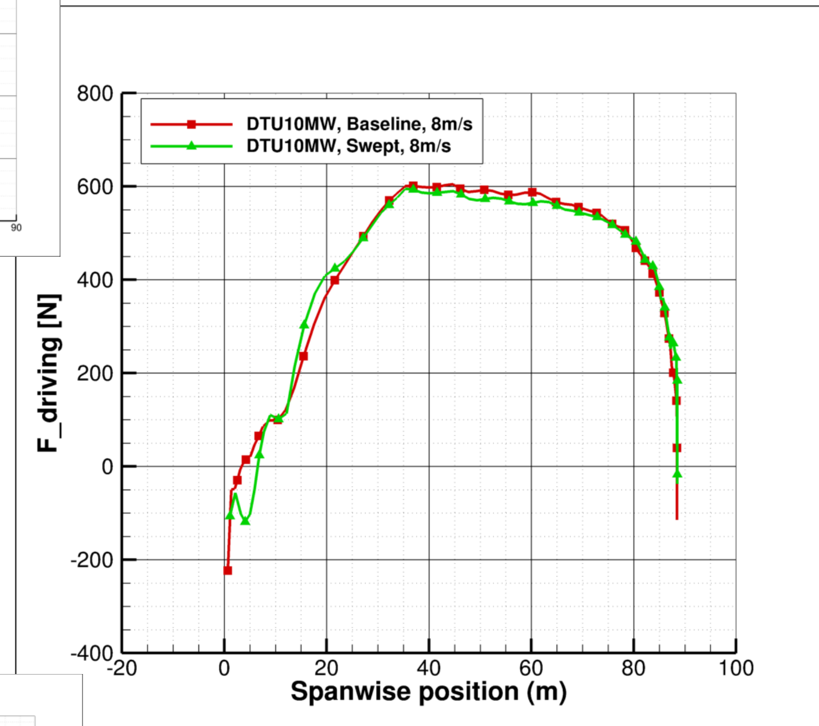


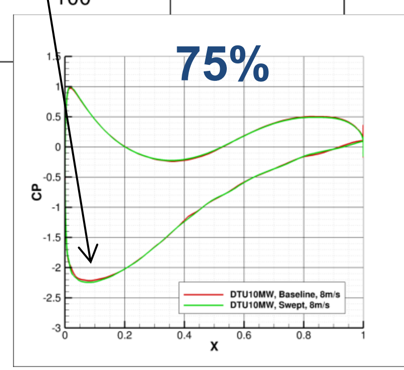
3D free wake aeroelastic (wake pattern)

3D CFD





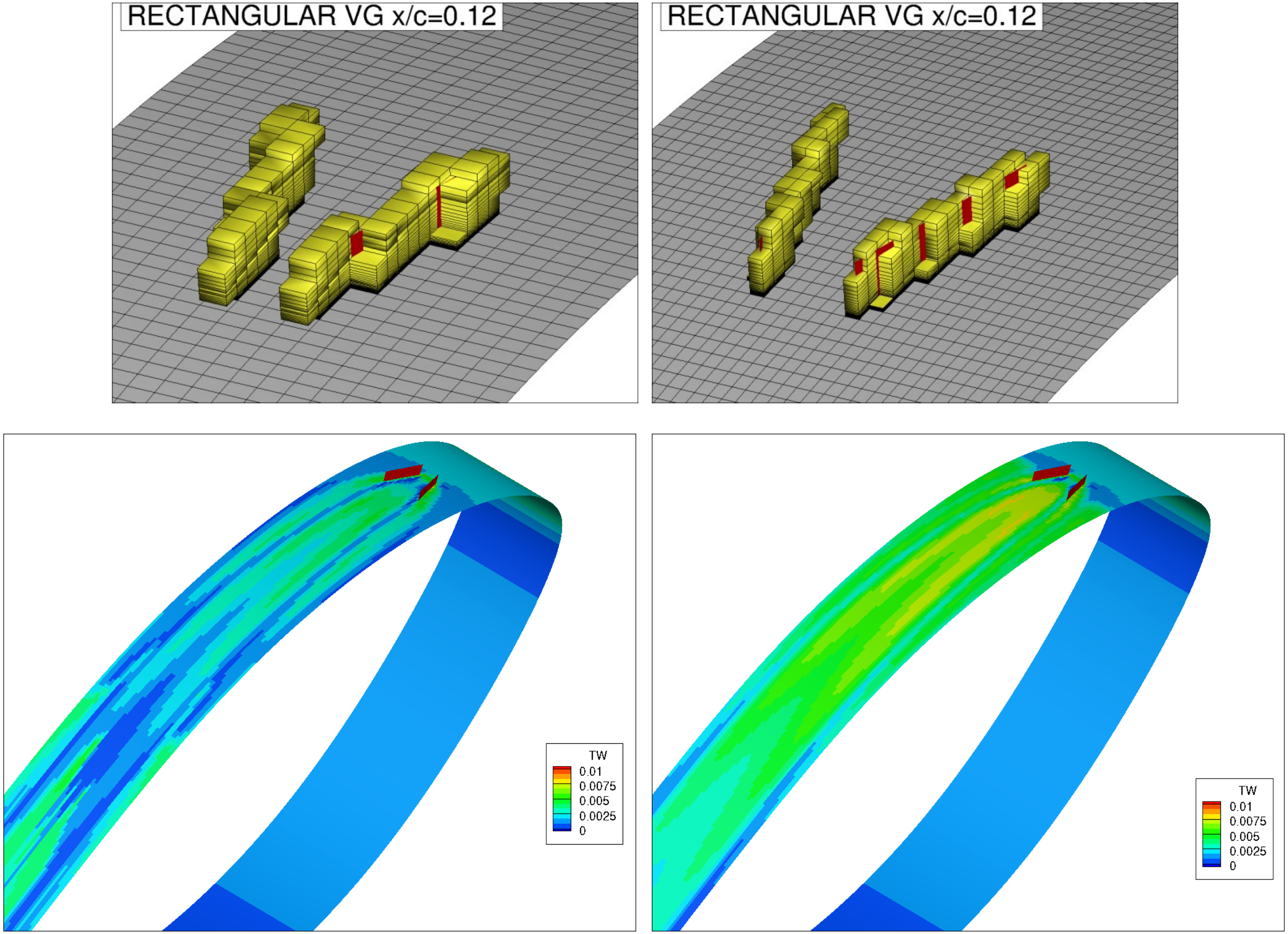




Thrust +0.25%

Power +0.46%

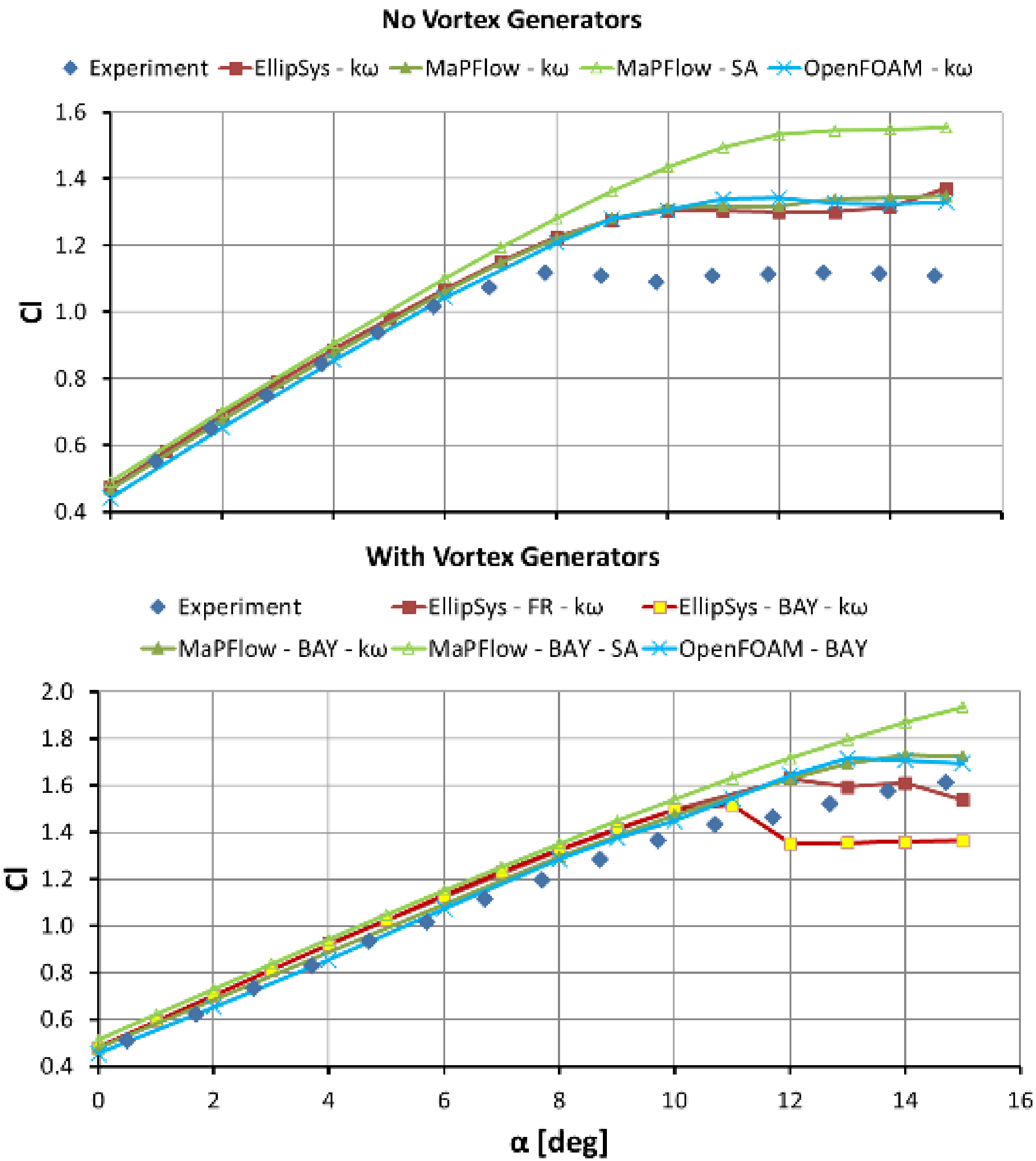
Wind Turbine Aerodynamics



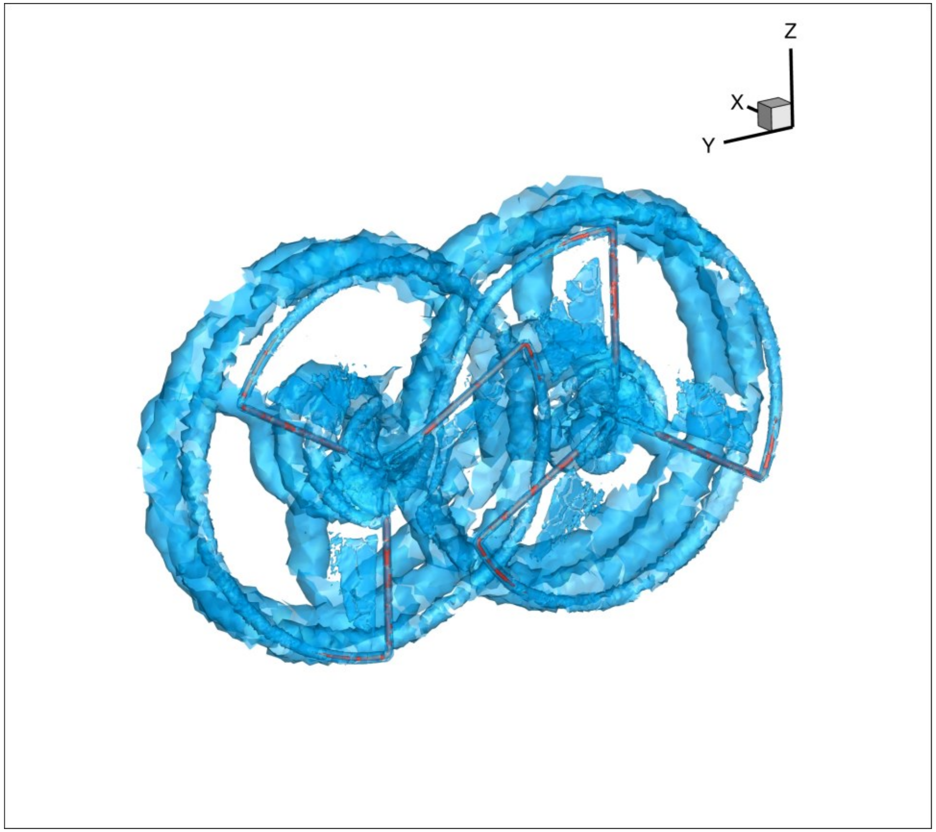
Free transition

Forced transition

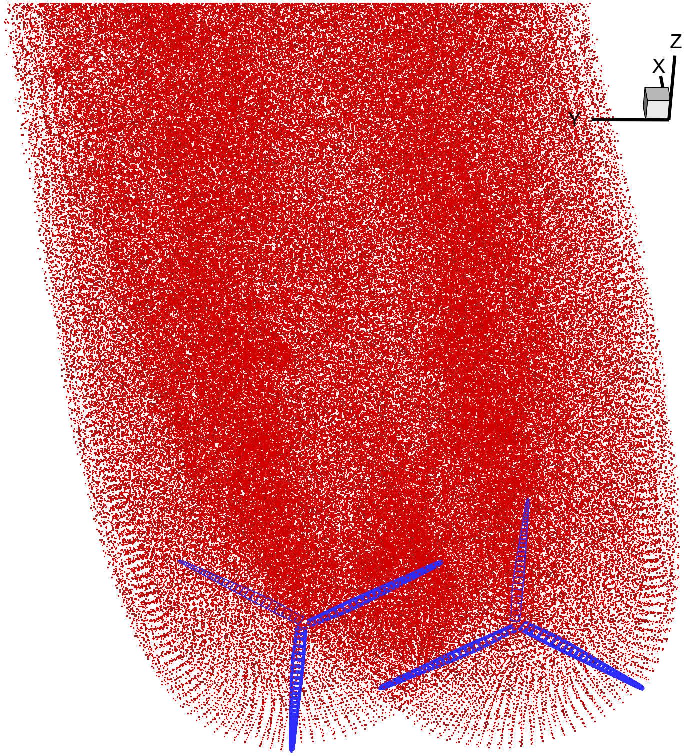
Wind Turbine Aerodynamics



Multi-Rotors

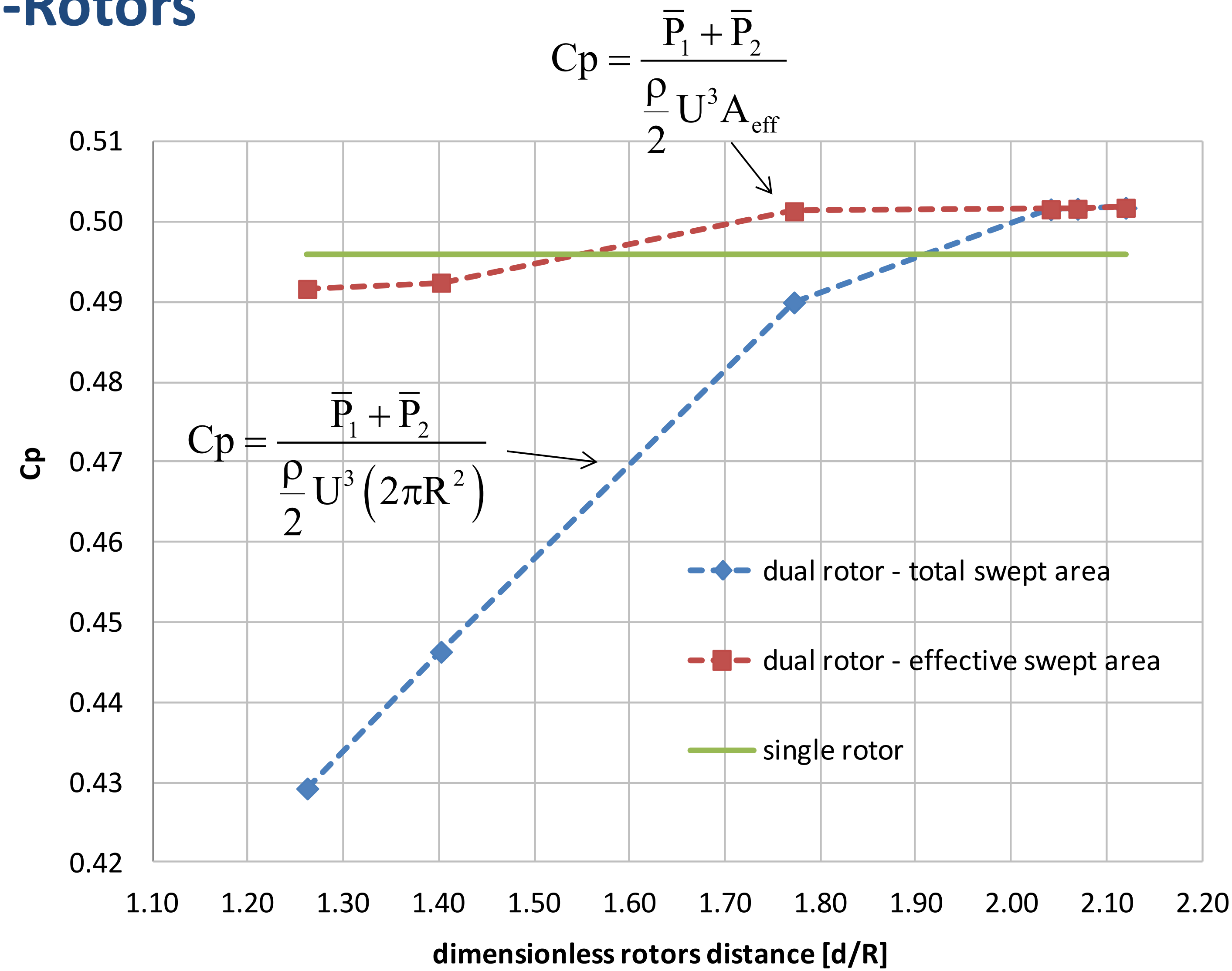


Actuator Line CFD simulations



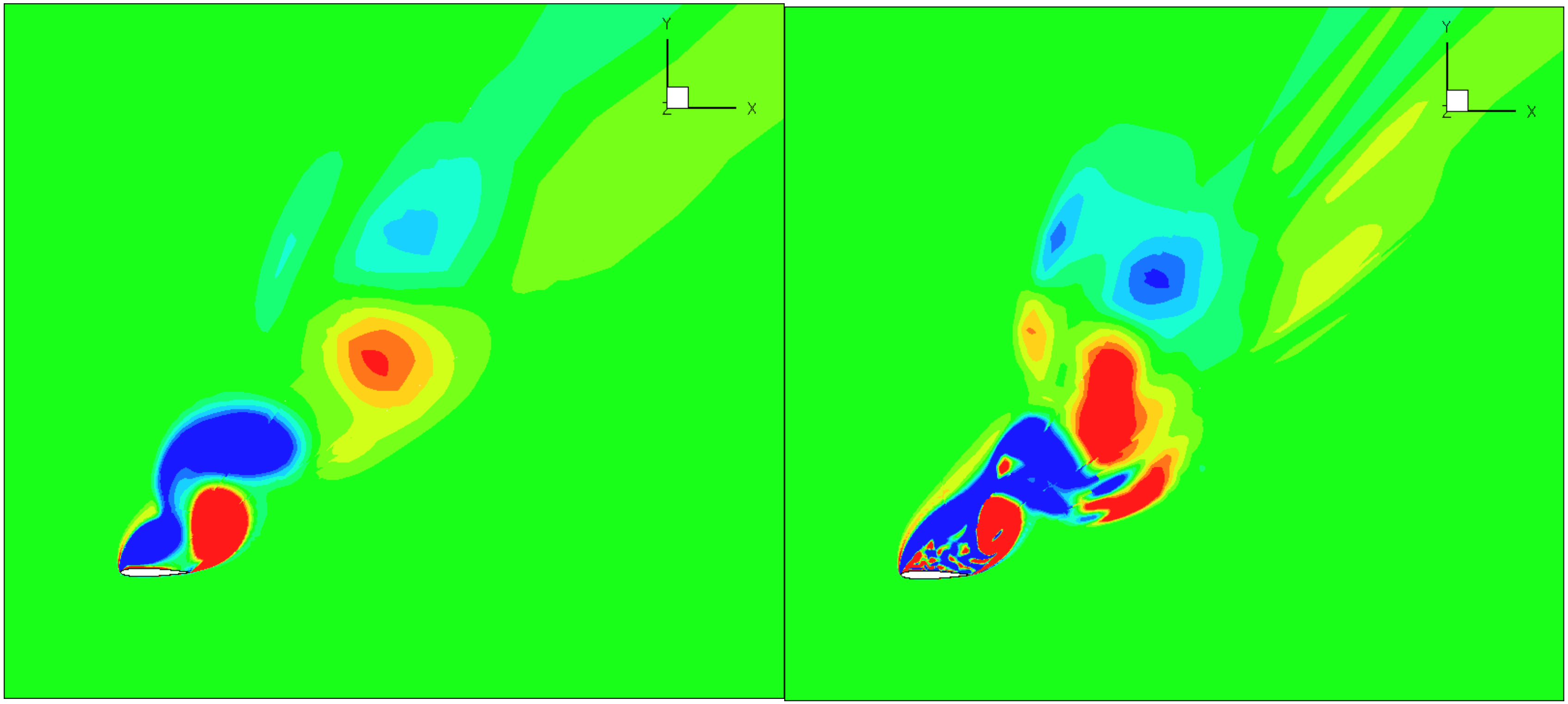
Vortex Free Wake simulation

Multi-Rotors



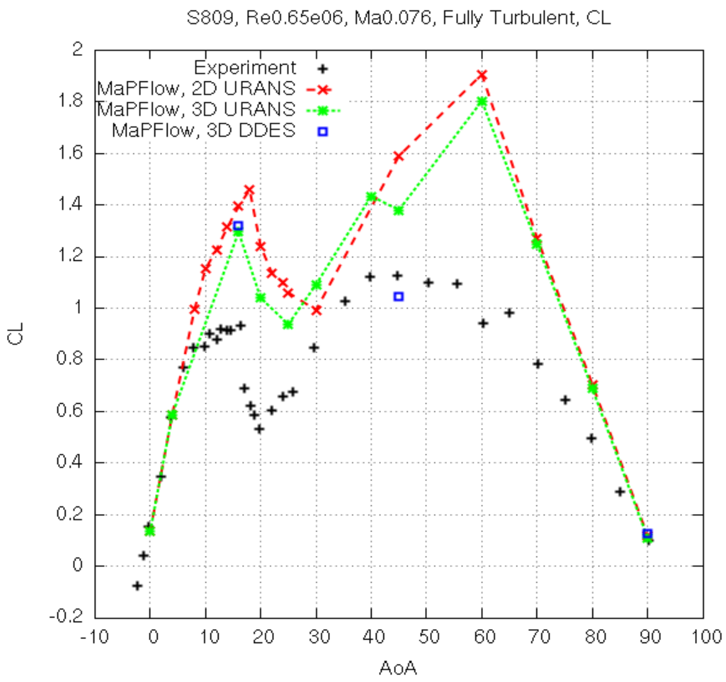
vortex shedding past an extruded airfoil section

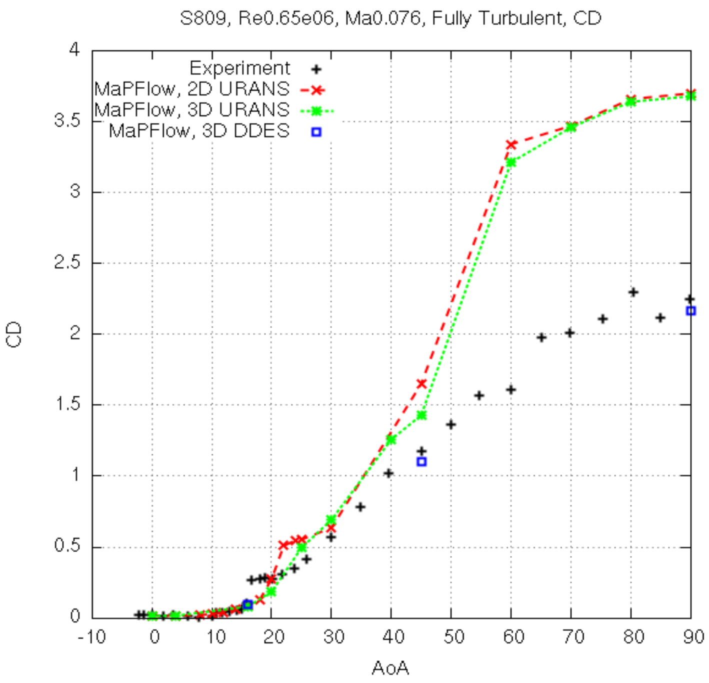
URANS vs DES



vortex shedding past an extruded airfoil section

URANS vs DES

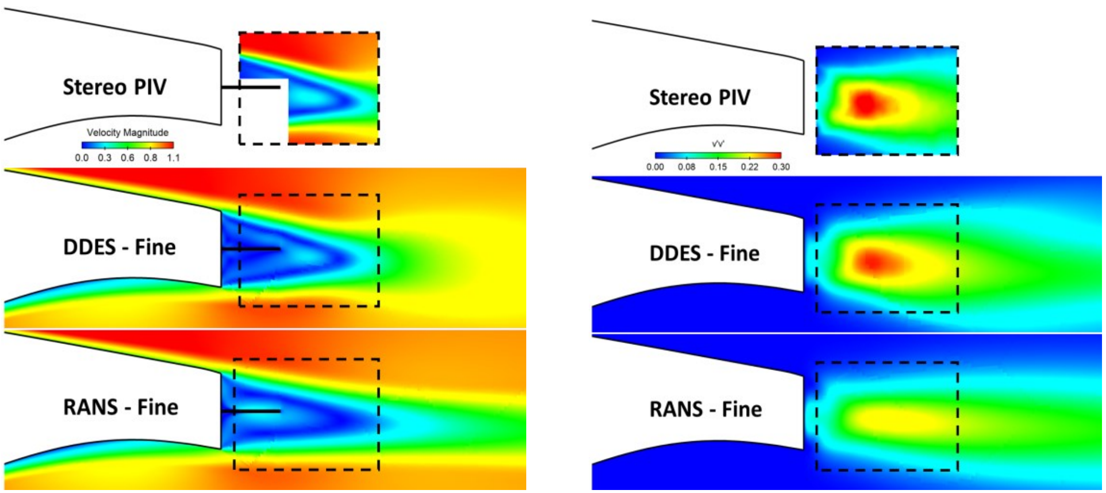


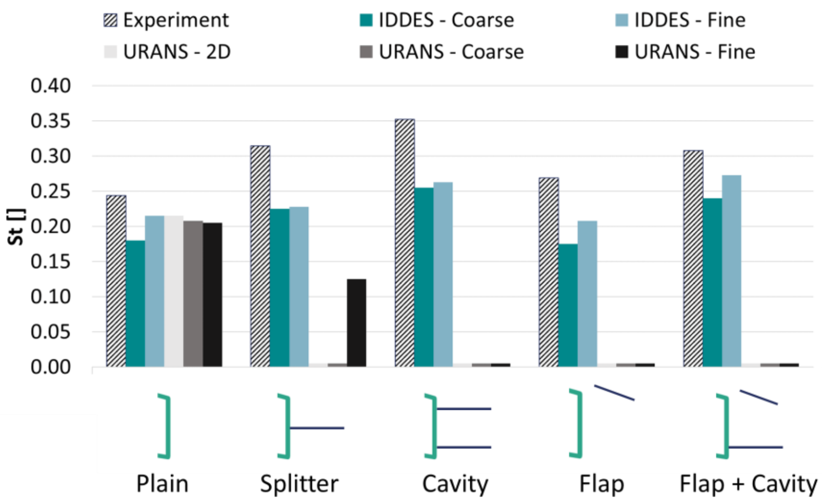


S809 airfoil

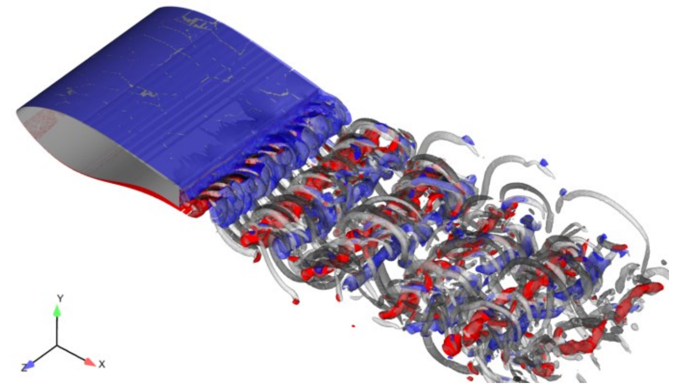
- Reynolds 0.65e06, Mach 0.076
- SA turbulence model, original and DDES versions
- 200x100 2D grid, 200x100x25 3D grid with AR=1

Modelling of flatback airfoils

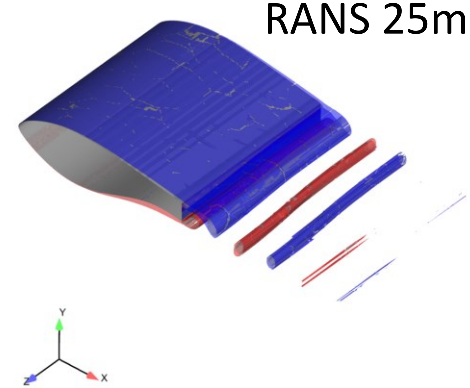




IDDES 25m cells



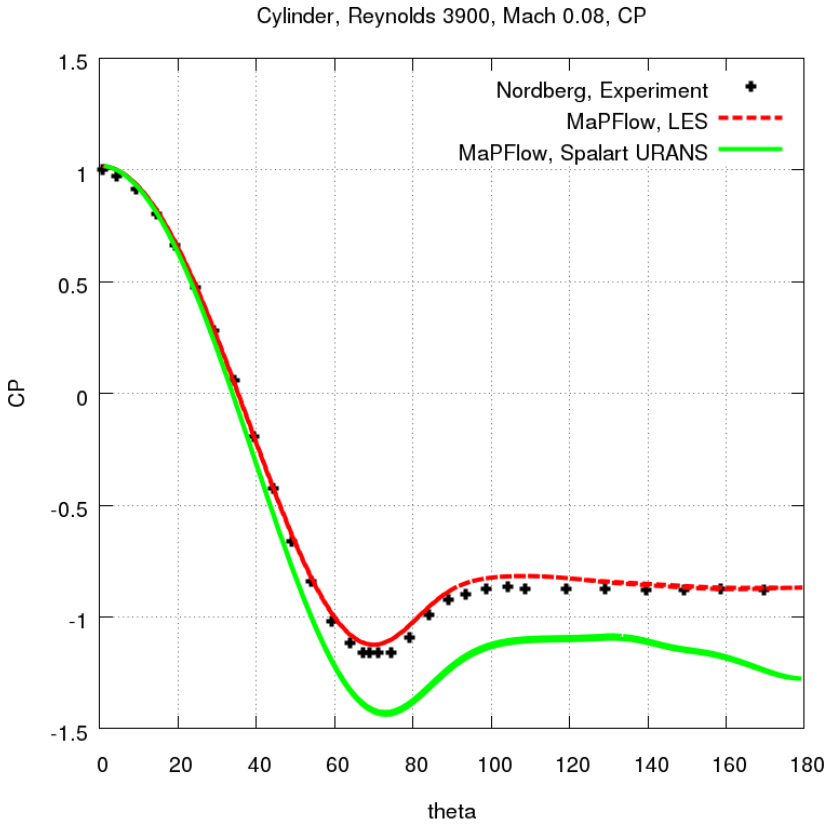
RANS 25m cells

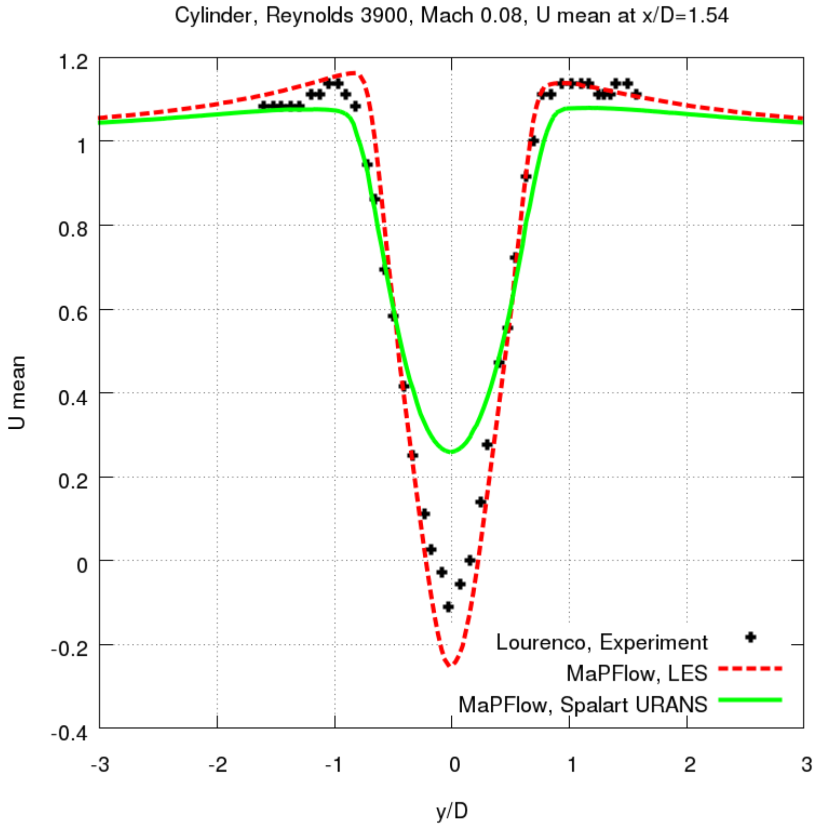


Different Unsteady Characteristics between the IDDES and RANS

Cylinder pressure distribution and wake velocities

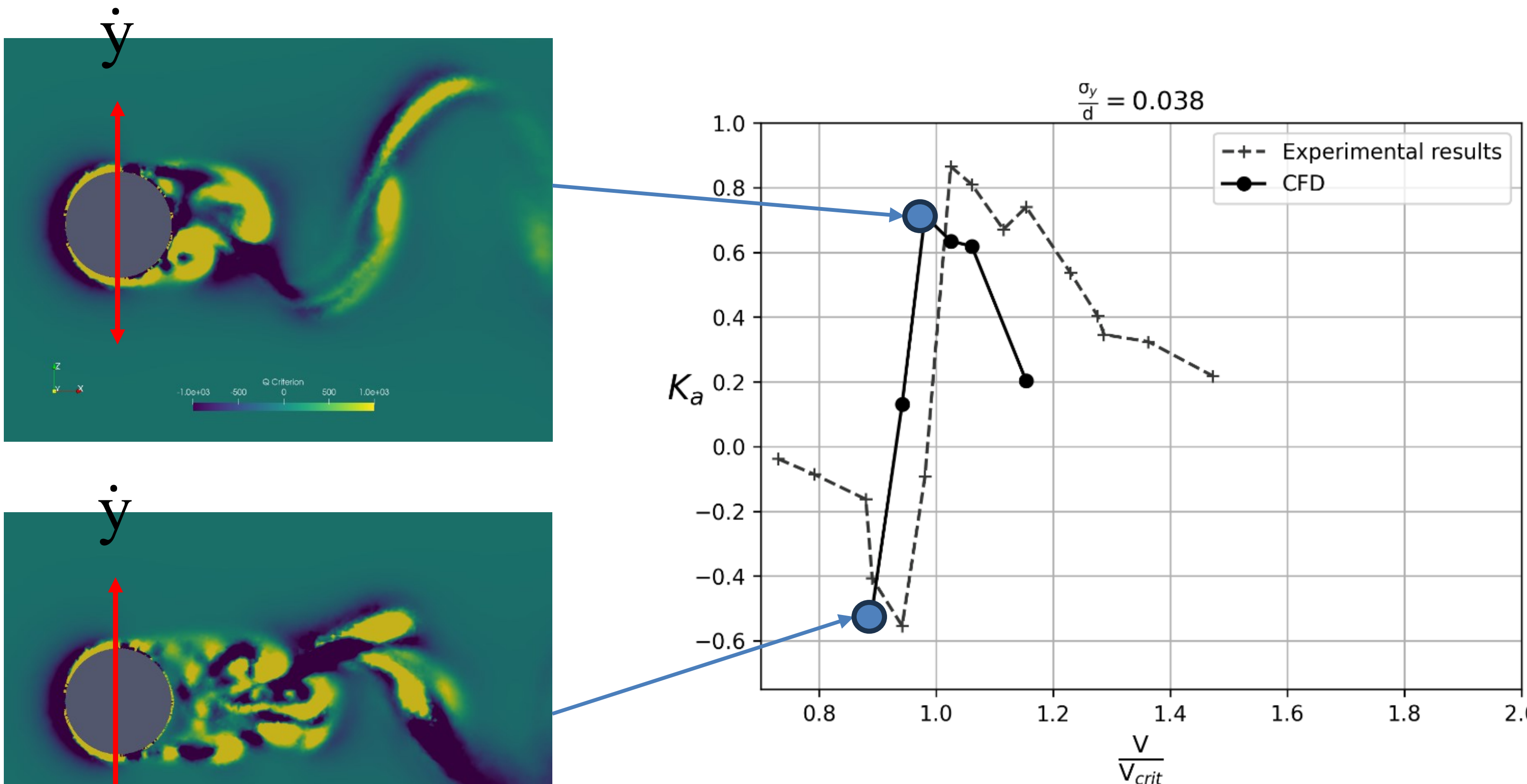
LES vs URANS





Cylinder wake, Re3900

Prediction of Vortex Induced Vibrations on Wind Turbine Towers

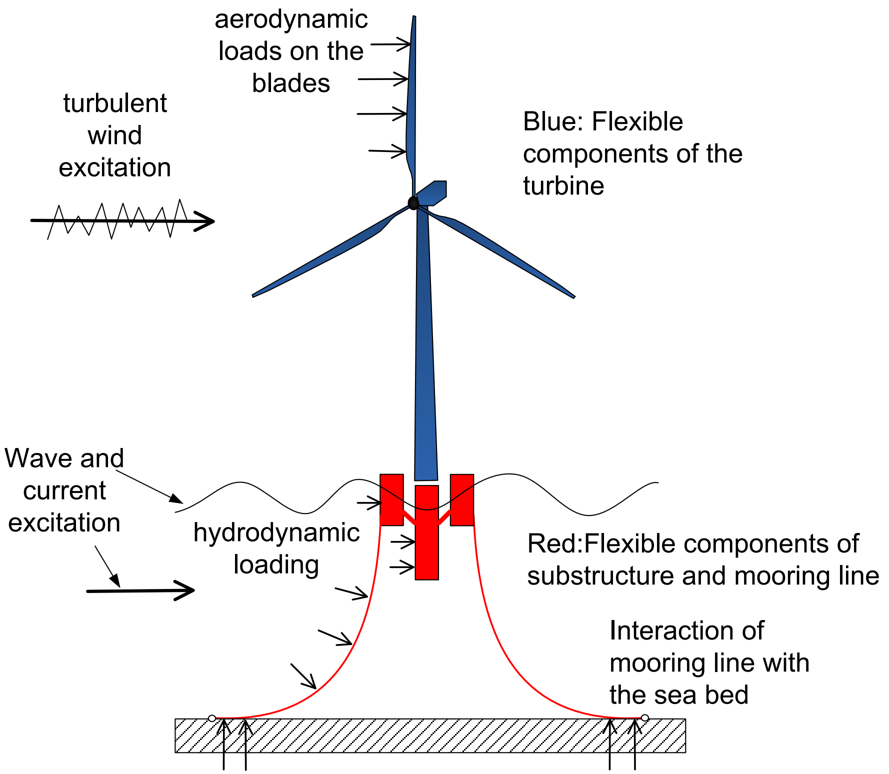


$$P = \int_0^T F_a(t)\ \dot{y}(t)\,dt$$

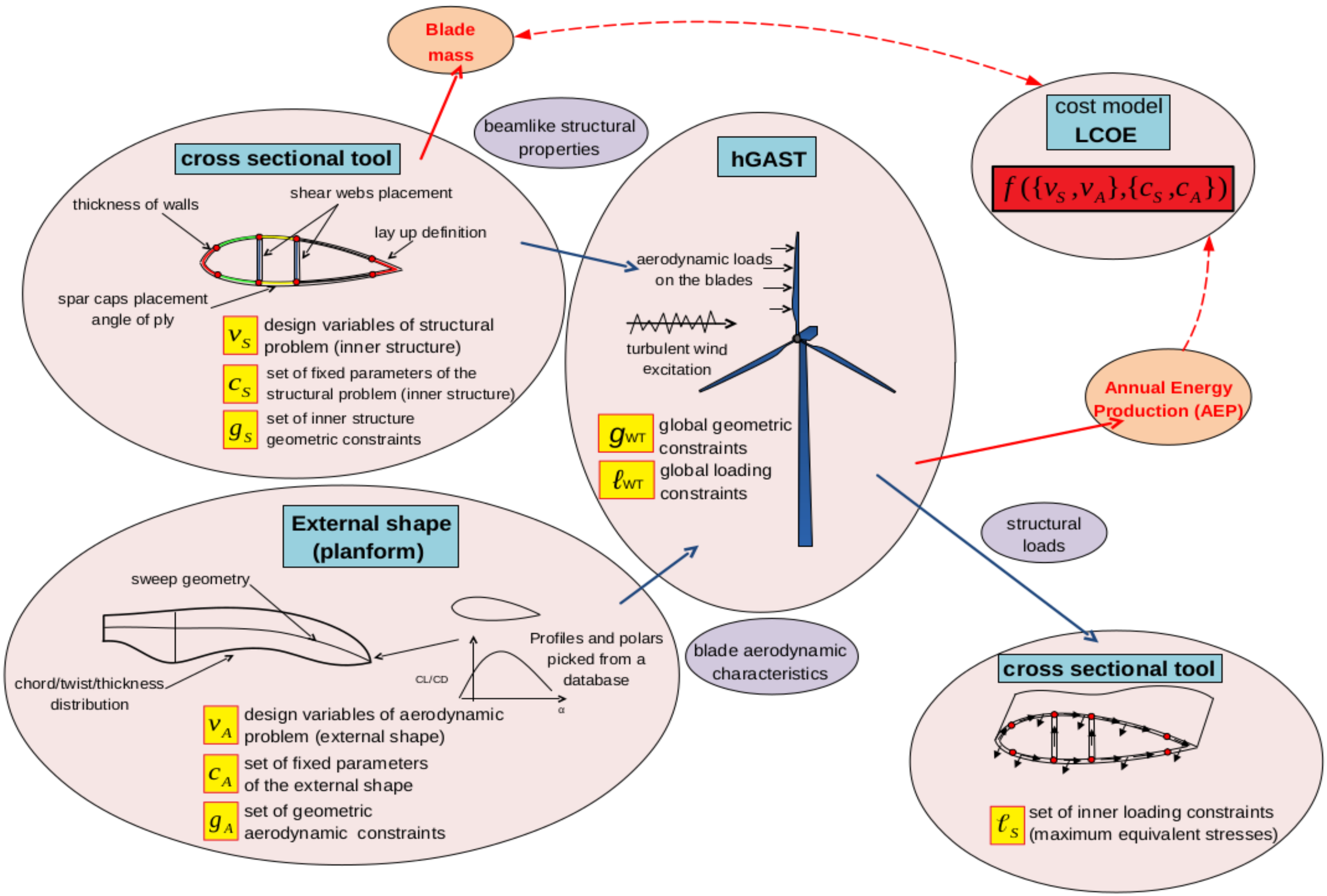
Wind Turbine Hydro-Servo-Aeroelasticity

The in-house code **hGAST** is used in the aeroelastic analysis of rotor and combined rotor-pylon problems.

- hydro-servo-aero-elastic tool which besides the structural dynamics is also able to model the controls of the system and the wave loading for offshore (including floating WTs).
- In the modeling of the flexible bodies higher order beam models and multibody dynamics are applied using a FEM discretization.
- It can be used for non linear time domain analysis and linear eigenvalue stability analysis

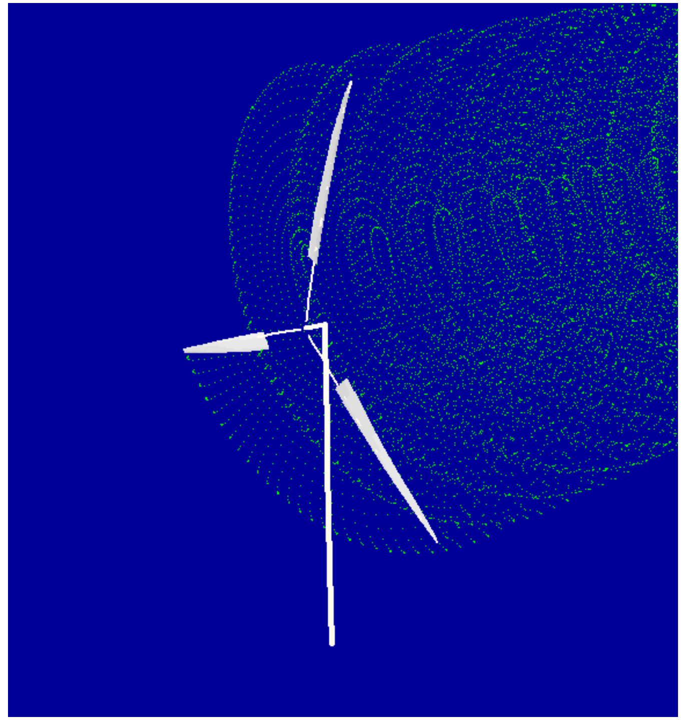


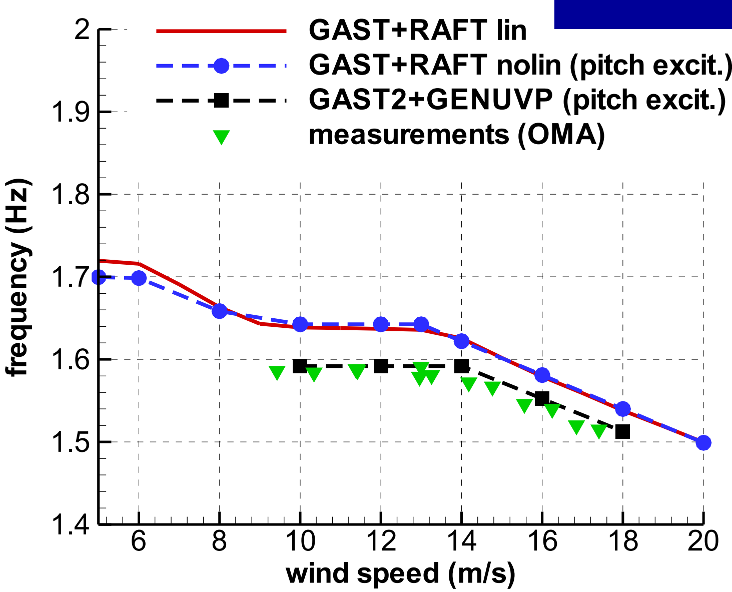
Multi-Disciplinary-Optimization tools

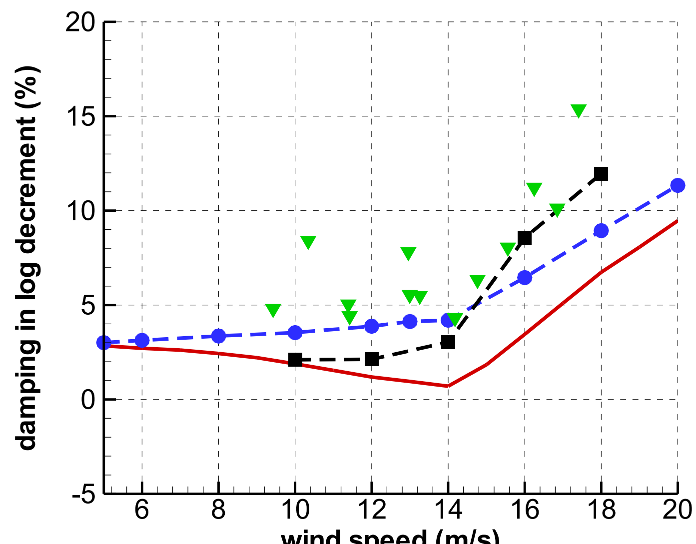


Wind Turbine Hydro-Servo-Aeroelasticity

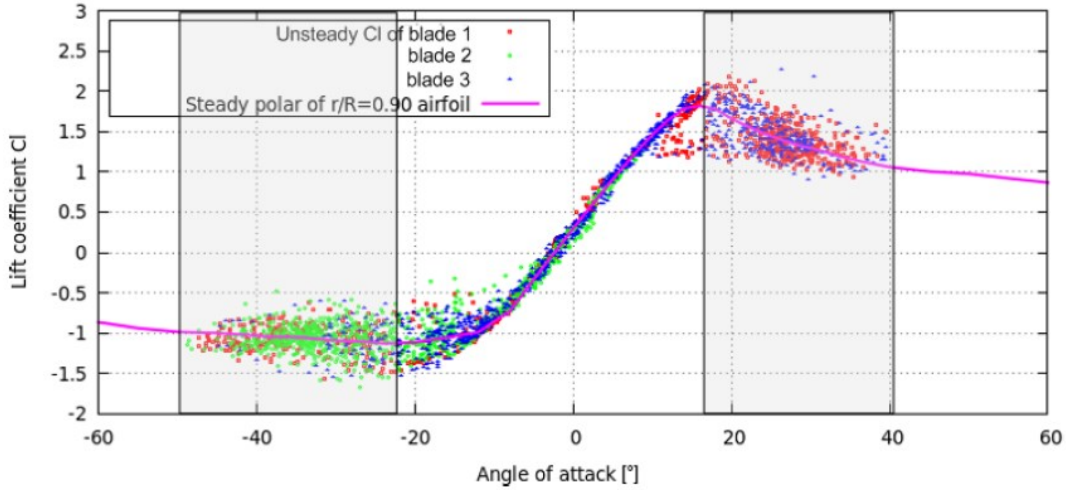
Stability Analysis Tools

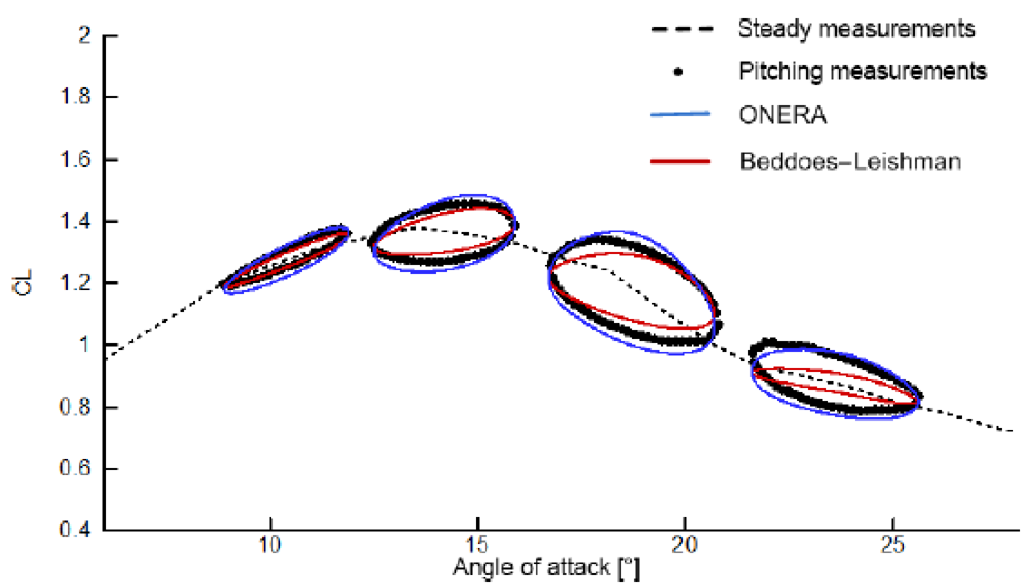




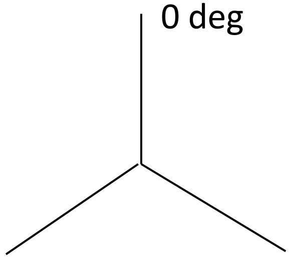


Stall Induced Vibrations during idling or parked state



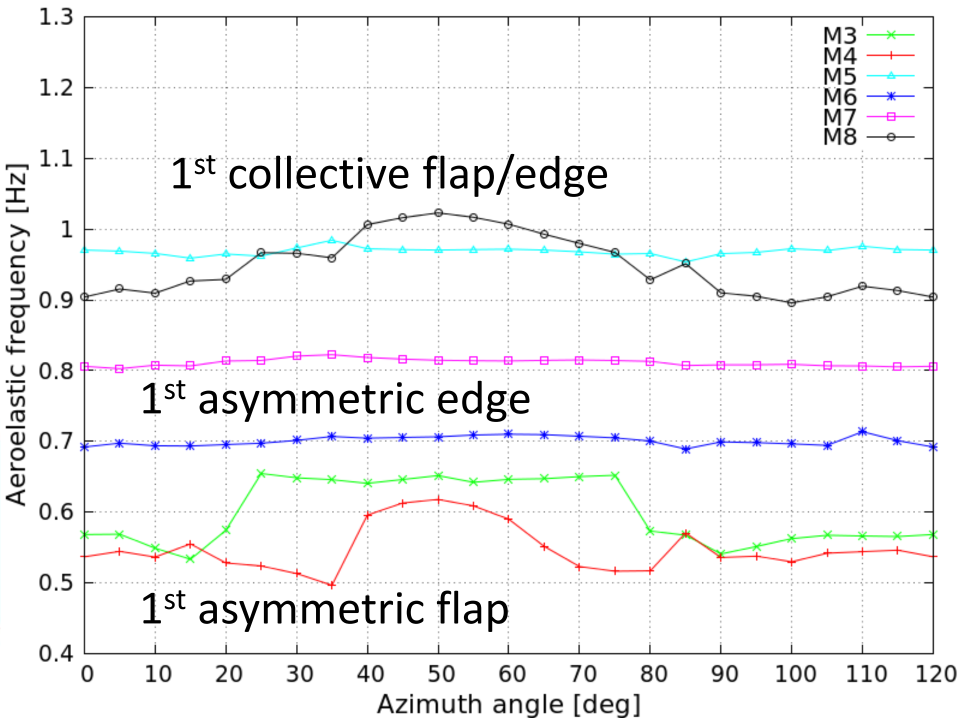


Stall Induced Vibrations during idling or parked state

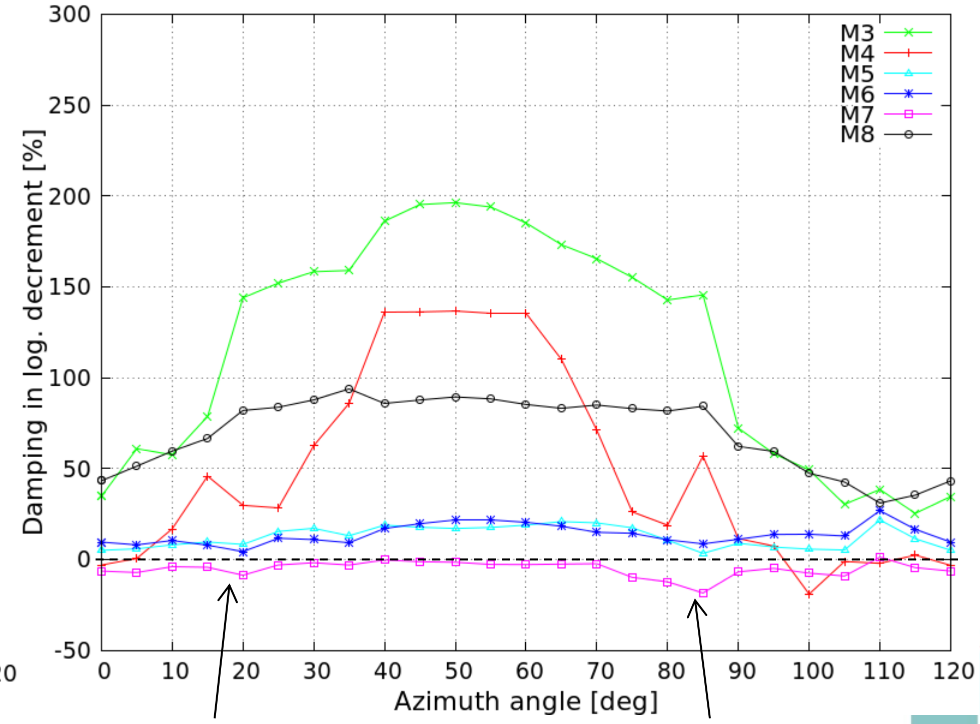


Wind speed=42.5 m/s, yaw=30deg

modal frequency



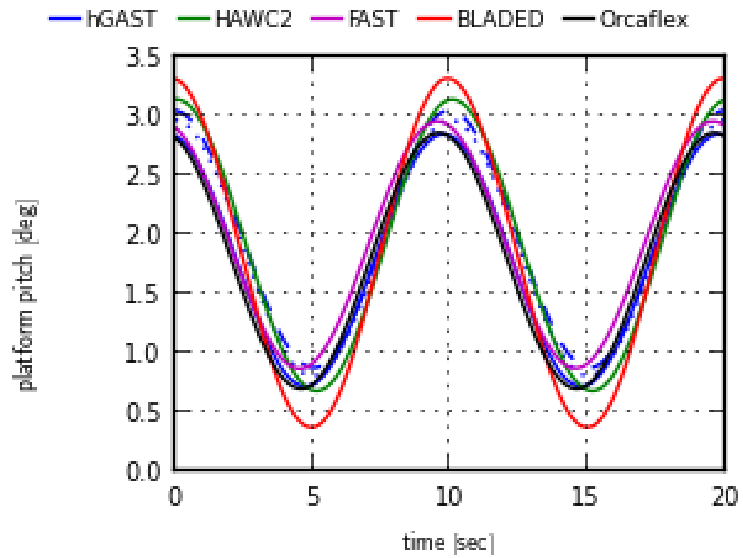
modal damping

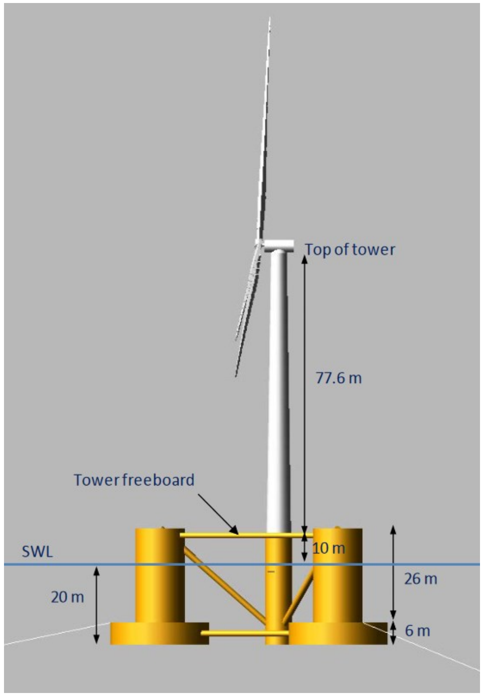


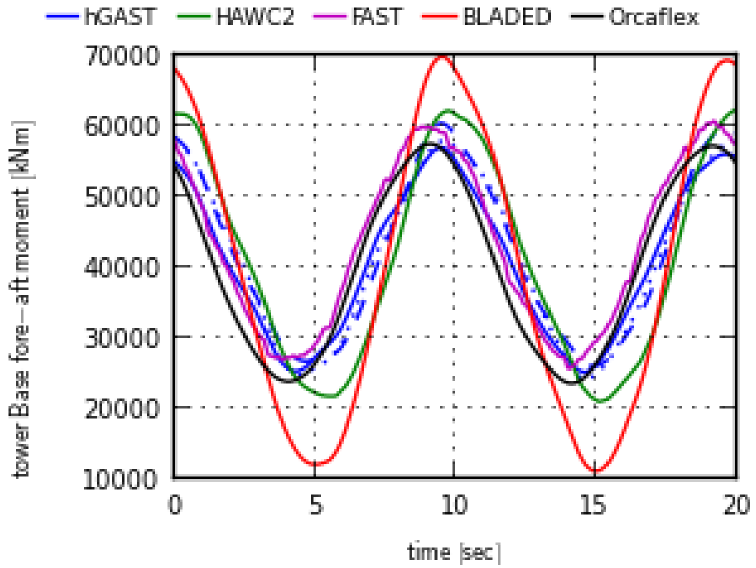
negative damping values of M7 in the vicinity of 20deg and 80deg azimuth angles

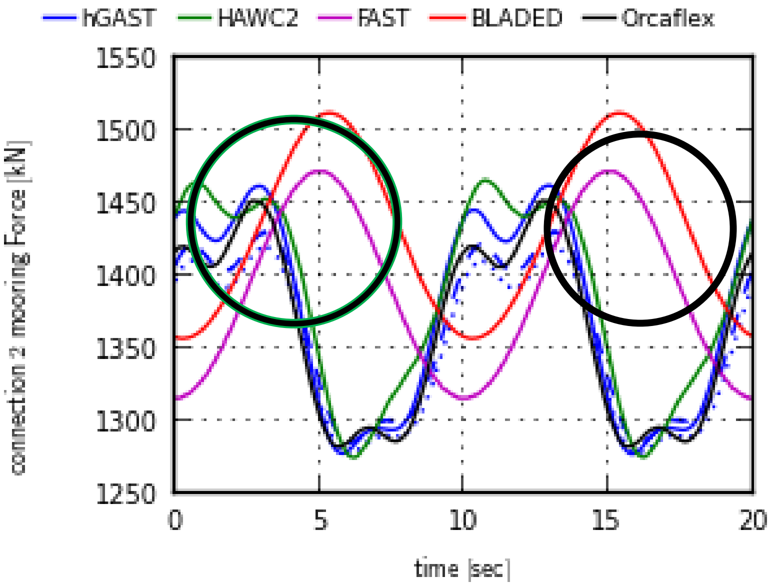
Wind Turbine Hydro-Servo-Aeroelasticity

IEA - OC4

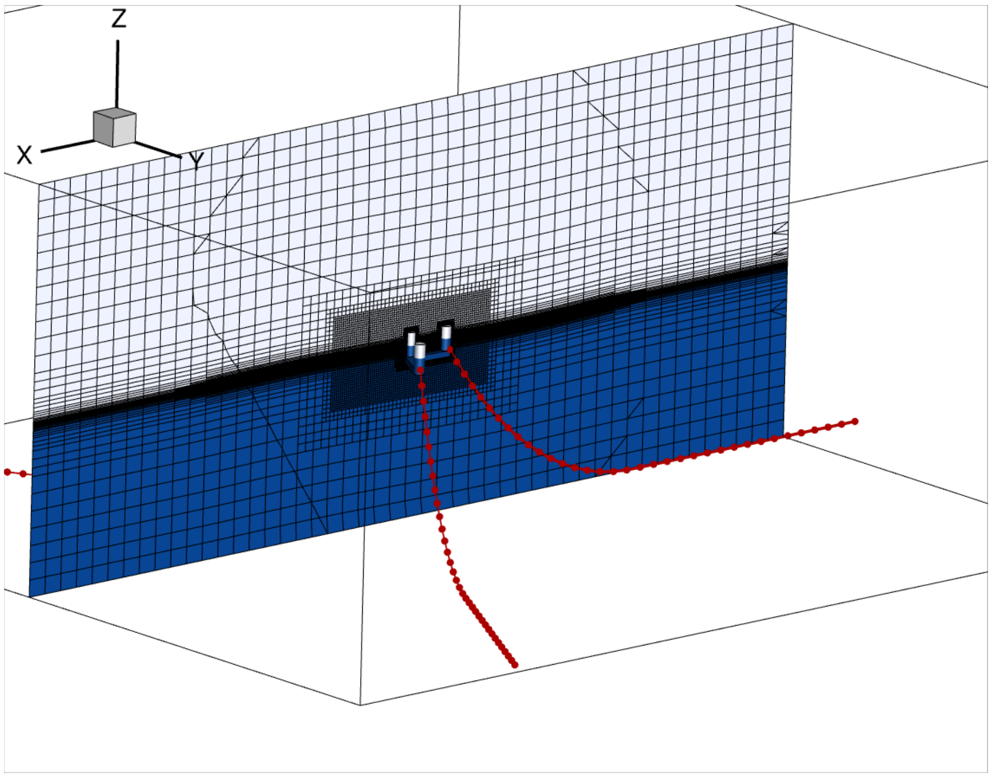




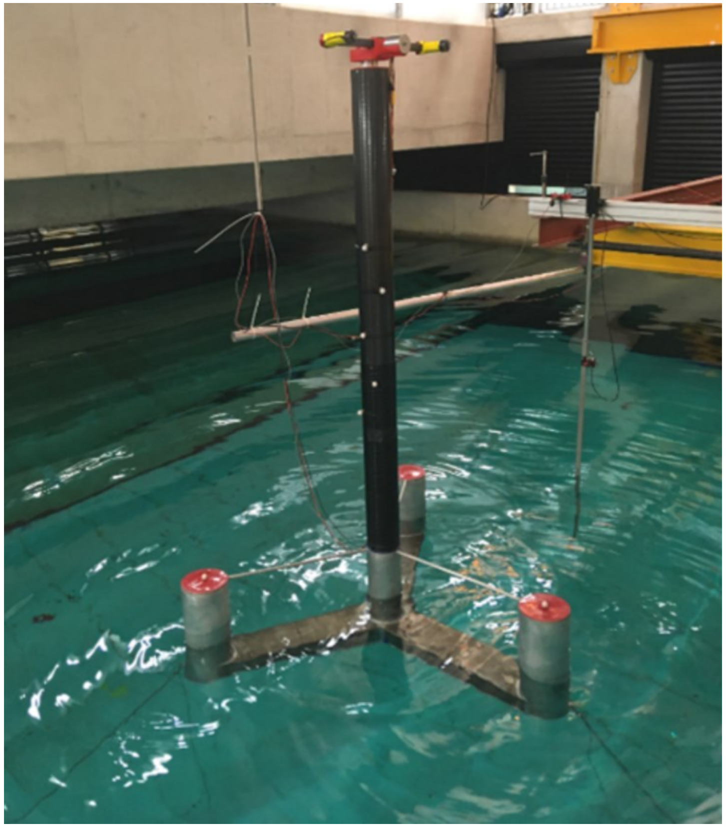




Wind Turbine Hydro-Servo-Aeroelasticity



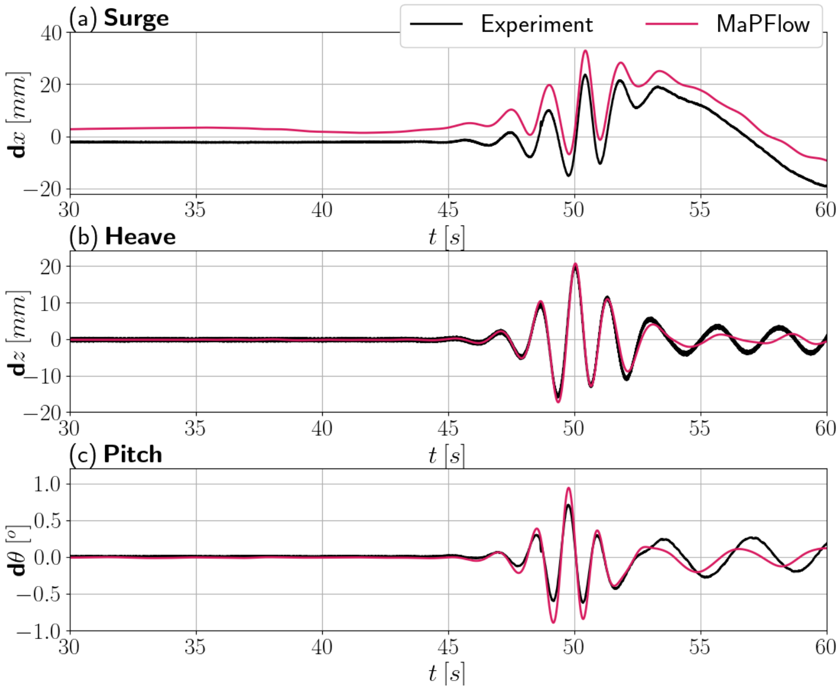
Numerical wave tank



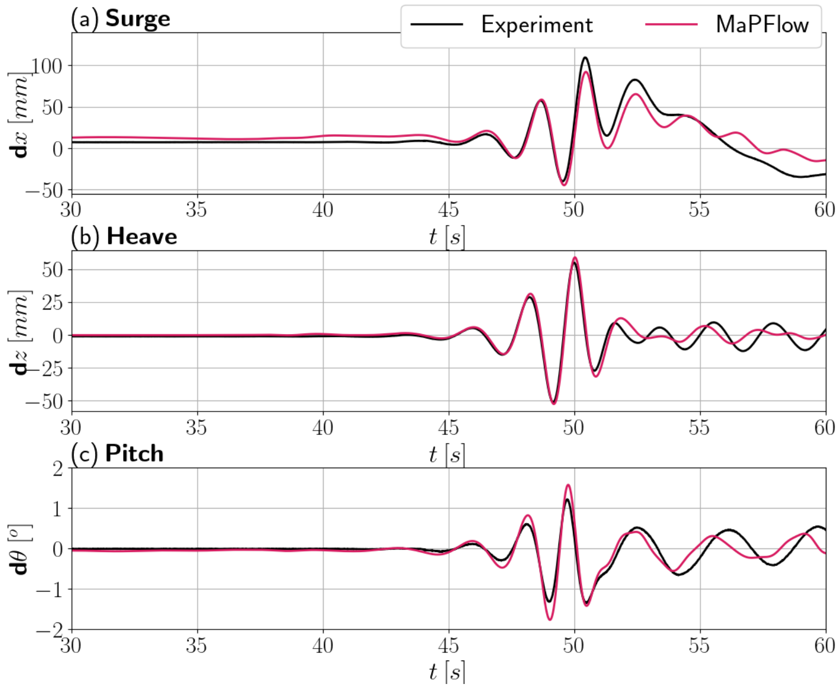
Floater UMaine VolturnUS-S
Scale 1:70

Wind Turbine Hydro-Servo-Aeroelasticity

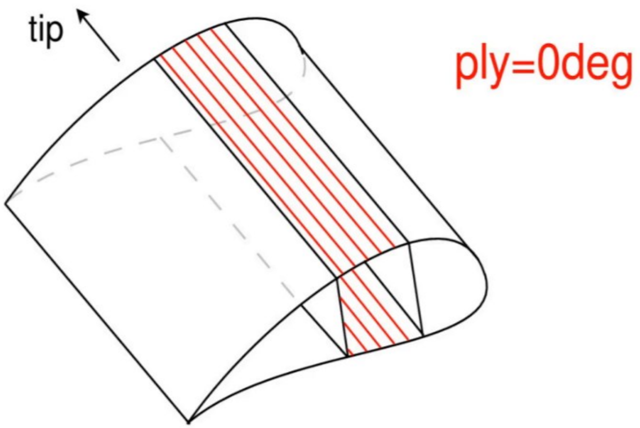
Benign wavetrain

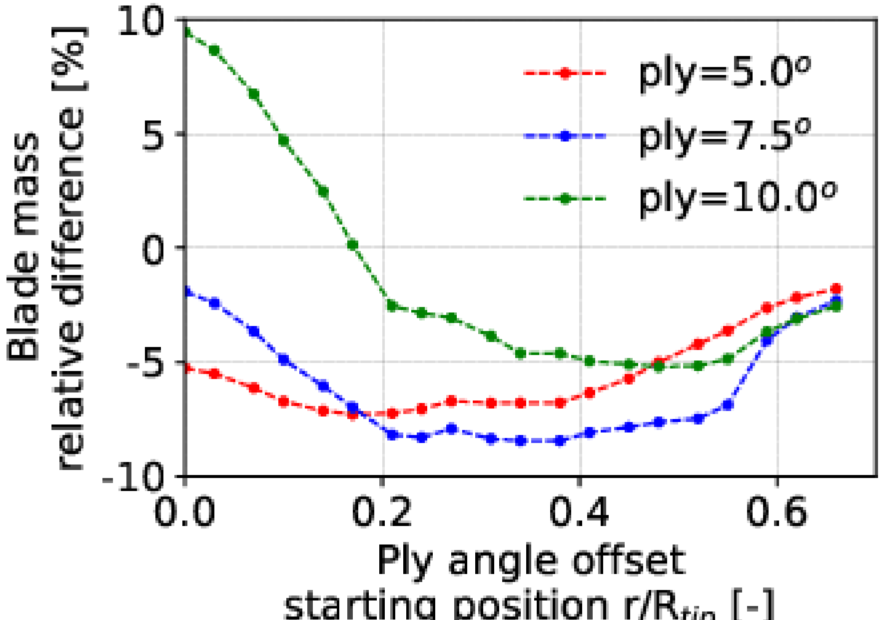


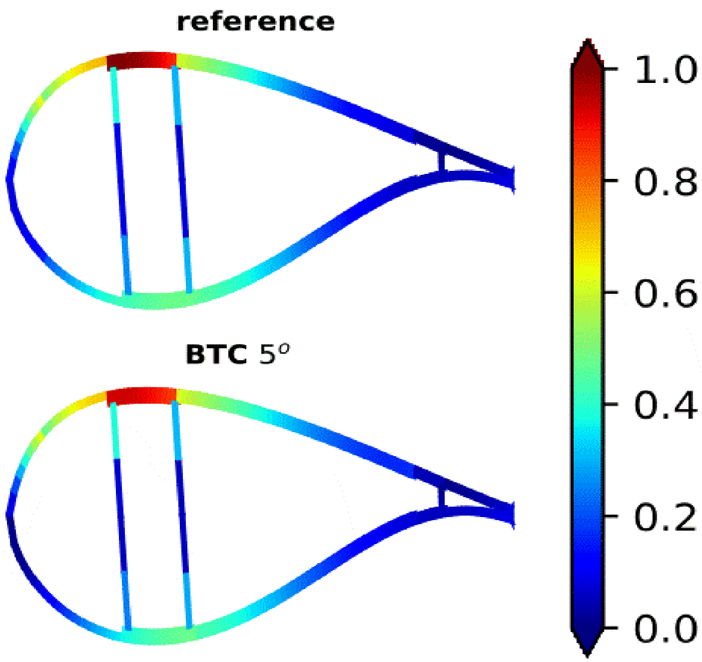
Extreme wavetrain



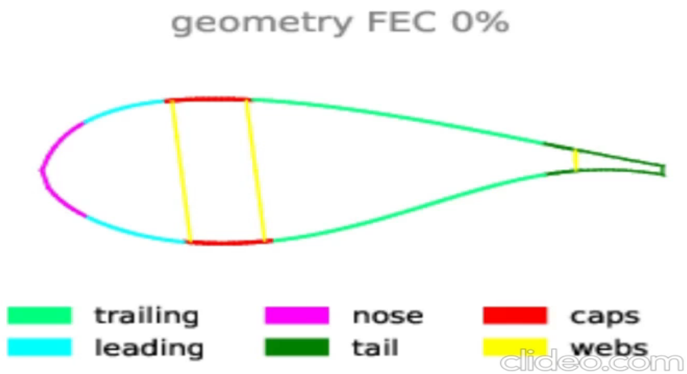
Optimization of the use of passive control of loads – Bend Twist Coupling

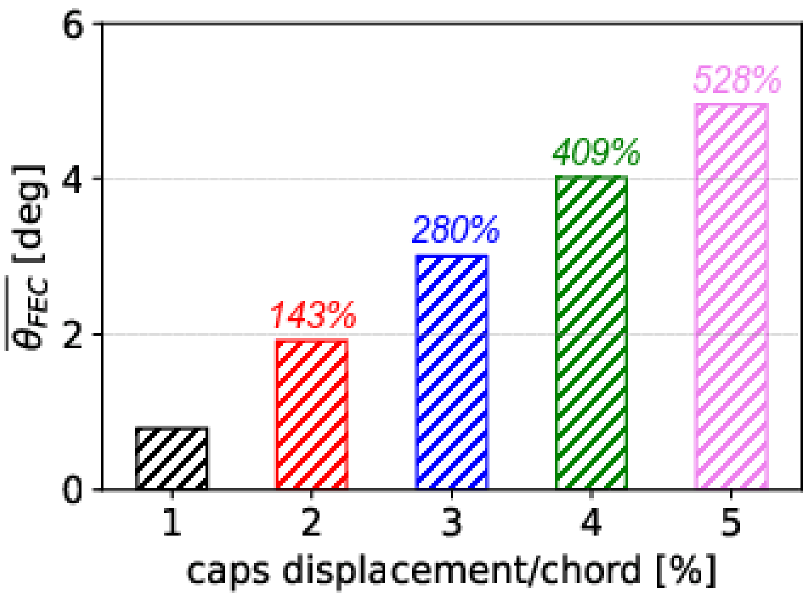


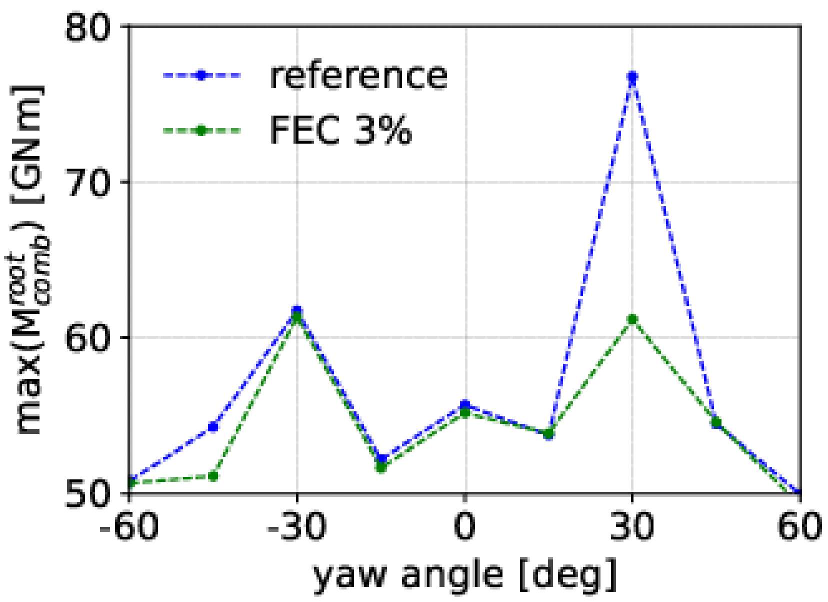




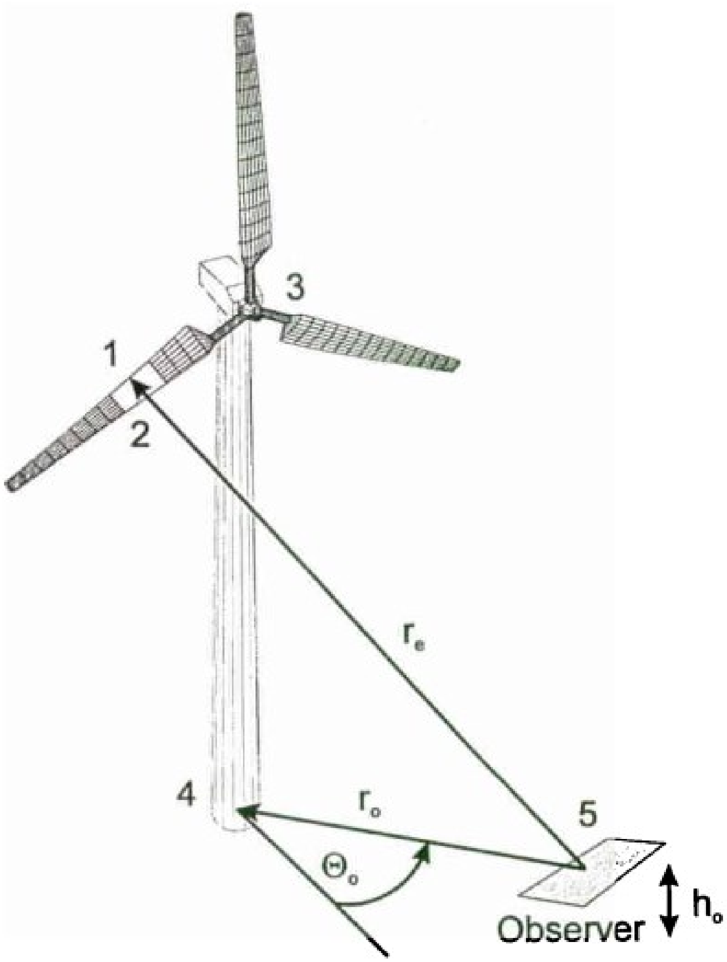
Optimization of the use of passive control of loads – Flap Edge Coupling







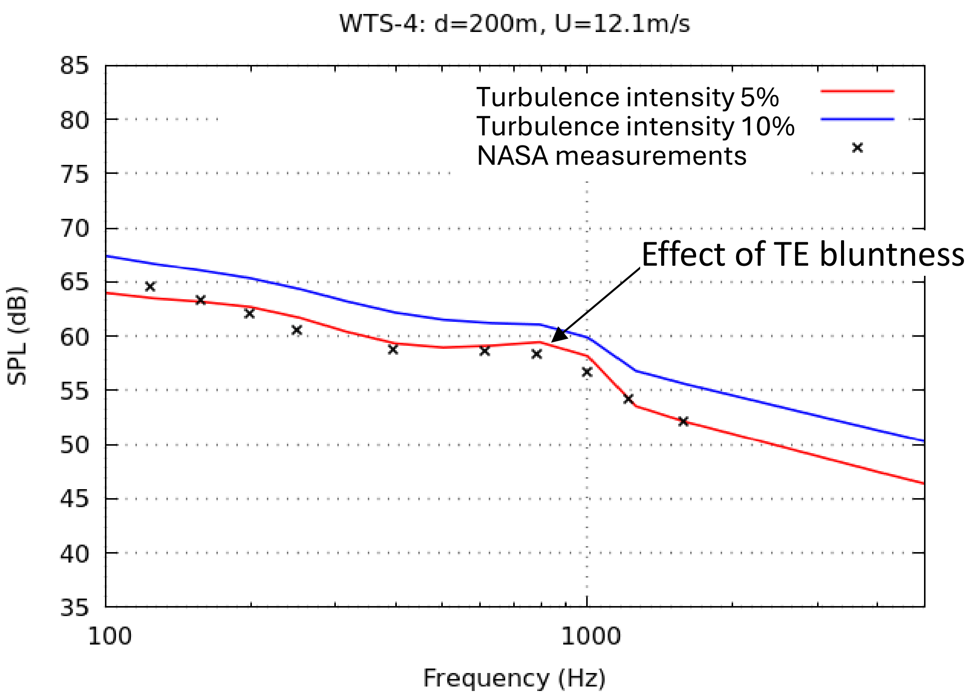
Wind Turbine Aeroacoustics – Noise generation



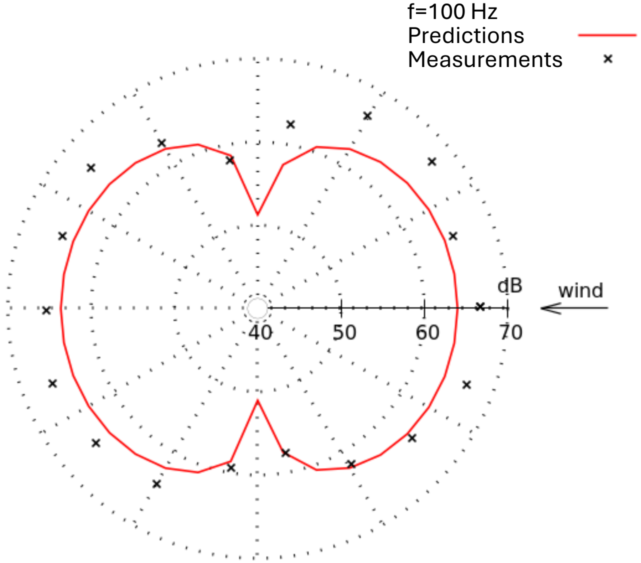
- Quasi 3-D approach
- Blades are discretized into sections
- Section by section 2D aerodynamic simulations using viscous-inviscid interaction code Foil2w → δ, δ* at trailing edge
- Each blade section is treated as an acoustic source
- Aeroacoustic caculations using semi-empirical relationships (Brooks, Pope, Marcolini)
  - ✓ Turbulent boundary layer noise
  - ✓ Turbulent inflow noise
  - ✓ Trailing edge bluntness noise
  - ✓ Laminar boundary layer noise
  - ✓ Tip noise
  - ✓ Stall and separation noise
- Total SPL is obtained by summing up all contributions:

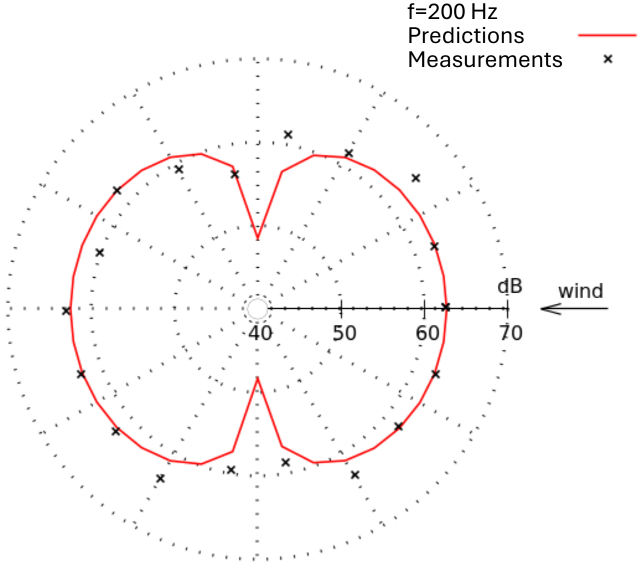
WTS-4 turbine, 4.2MW,
Diameter, hub height = 80m
Rotational speed = 30rpm

SPL spectrum, d=200m



Directivity polars, d=200m





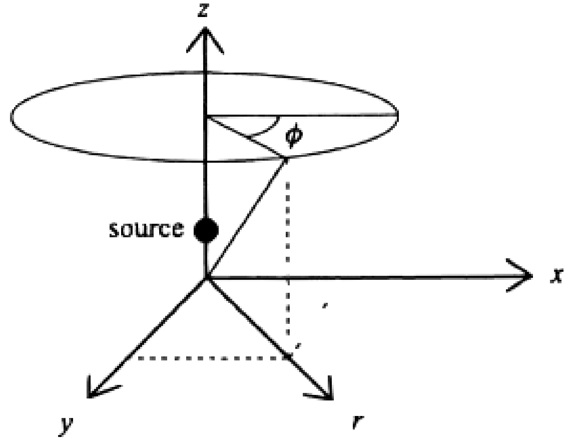
Axisymmetric approximations in frequency domain

Ray theory

- Trace eigenrays
- Calculate attenuation loss along the eigenrays through simulation of physical attenuation mechanisms
- Synthesize sound pressure level at the receiver for one or more frequencies

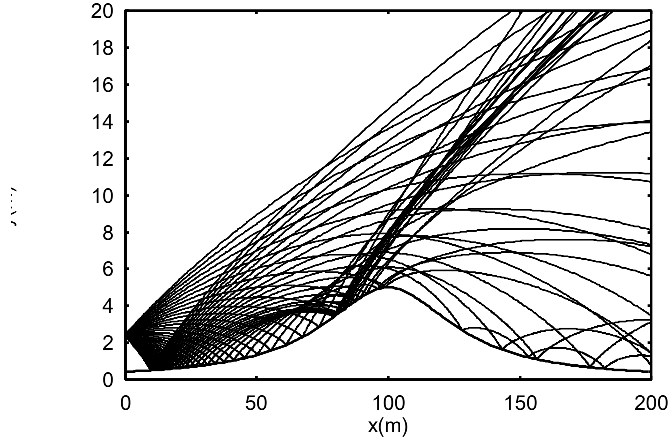
Parabolic equation

- Simplified form of the Helmholtz equation for small propagation angles
- Back scattering is ignored

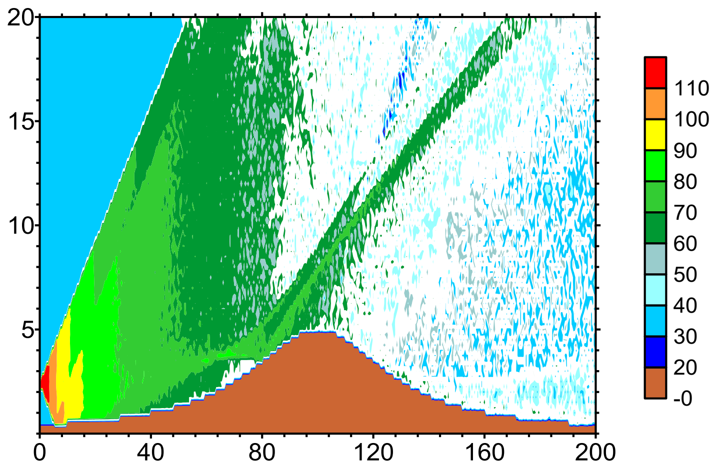


Axisymmetric approximations in frequency domain

Ray theory



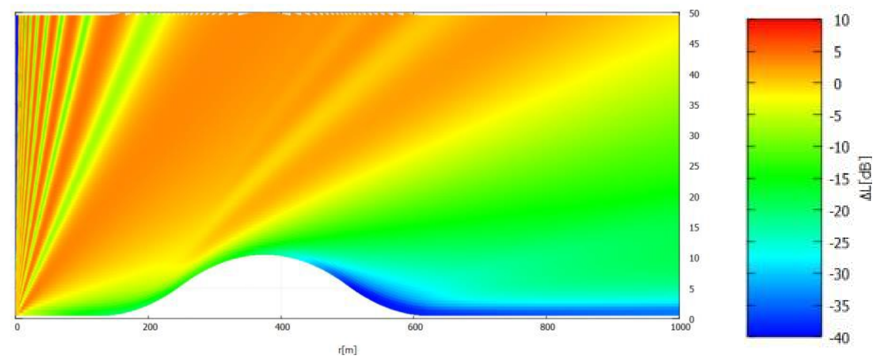
SPL contours



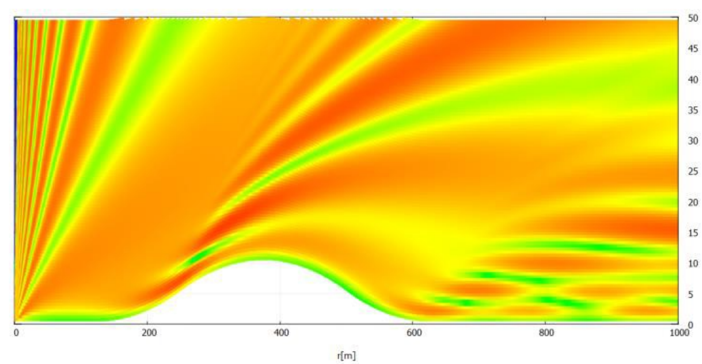
Parabolic equation

Contours of relative SPL (wrt free spherical propagation)

No wind



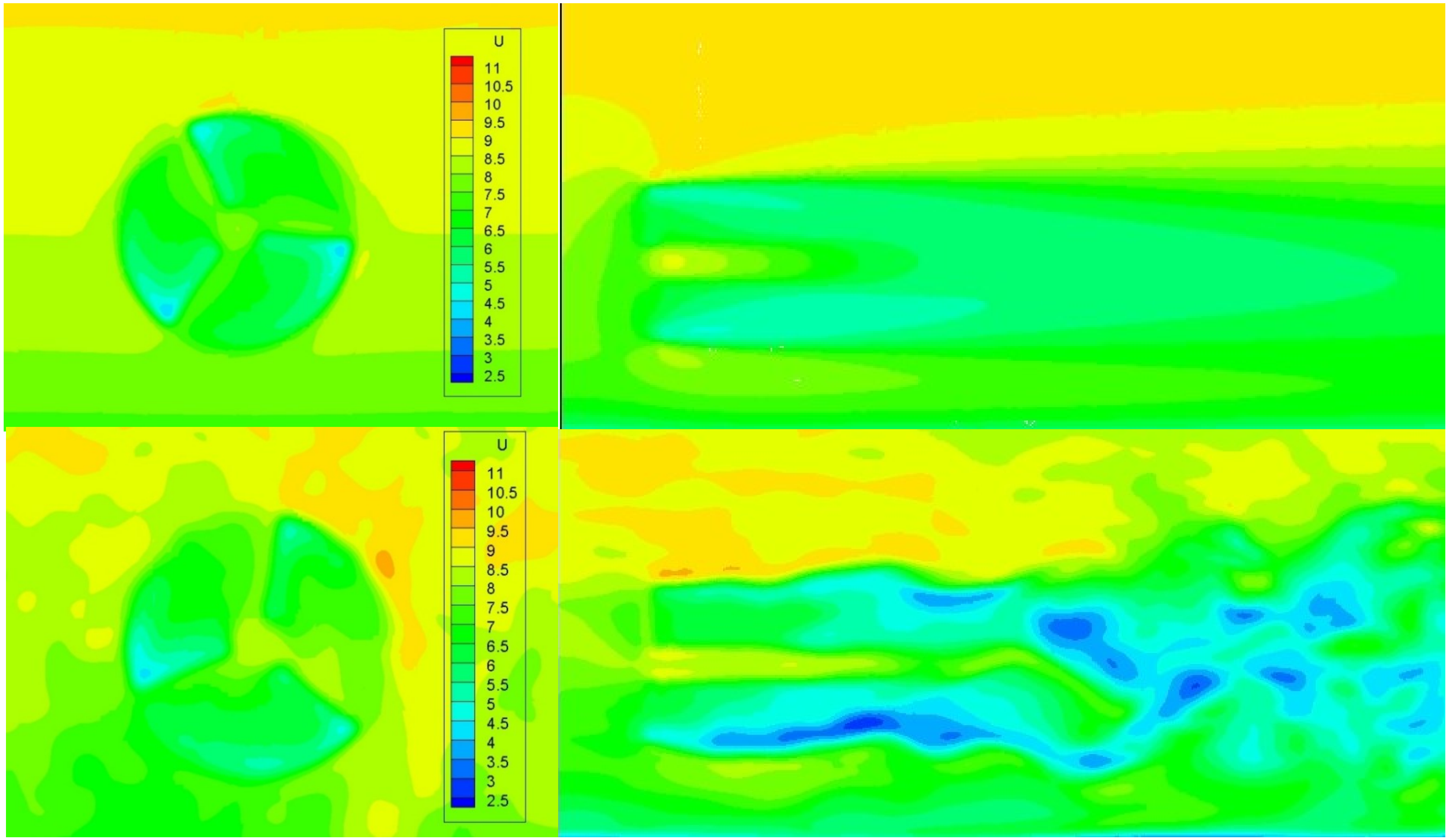
Downwind conditions



Actuator line - Velocity contours

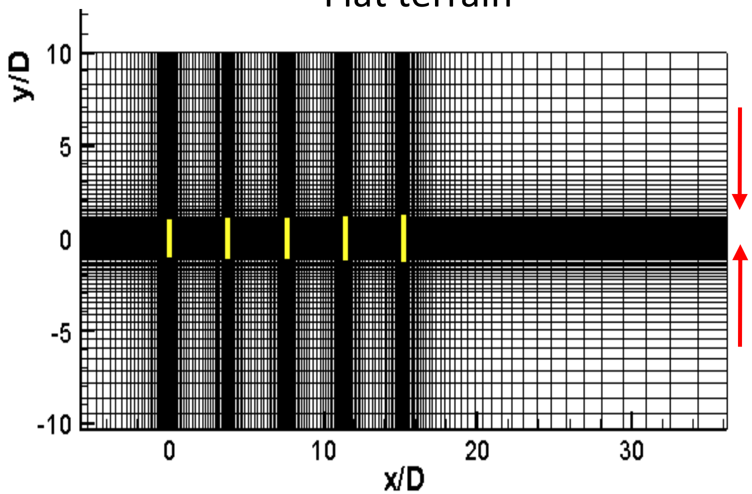
RANS

LES

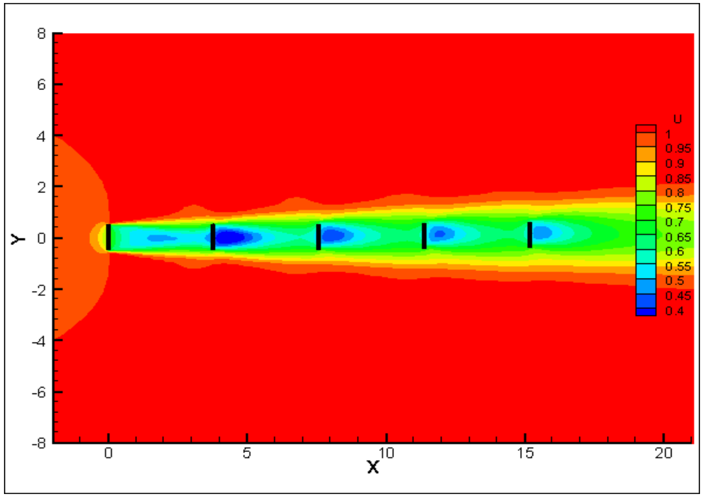


Actuator disk – Wind farms

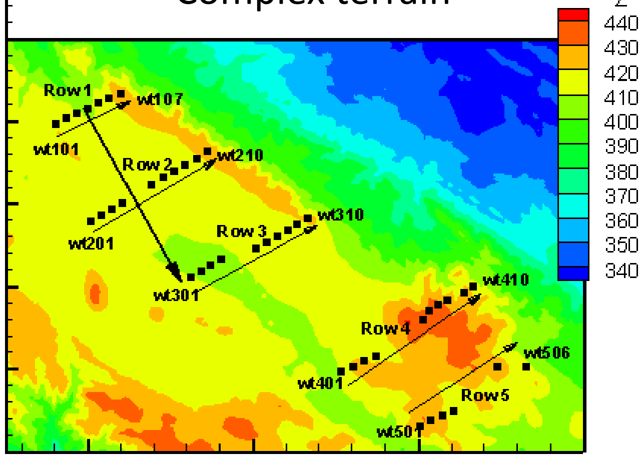
Flat terrain

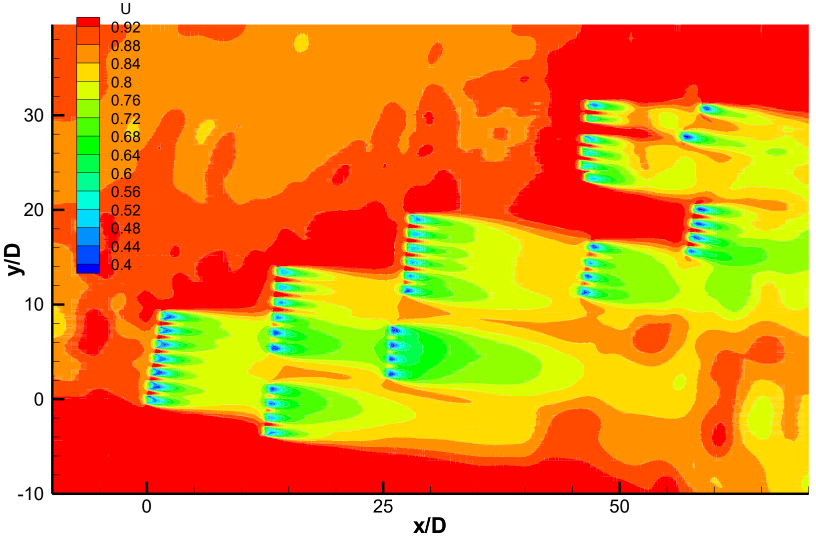


Velocity contours



Complex terrain





WIND TUNNEL

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www.wt.fluid.mech.ntua.gr

windtunnel.ntua

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Environmental Flows and Buildings

Wind Tunnel Testing and CFD

Prof. Demetri Bouris

Technical Info Day, NTUA Wind Tunnel Facility – Capacity and Services

June 25th , NTUA, Athens

TWEET-IE / Twin Wind tunnels for Energy and the EnvironmenT – Innovations and Excellence

HORIZON-WIDERA-2021-ACCESS-03-01 / PR# 101079125

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Environmental Flows at NTUA WT

- Wind engineering studies are performed for numerous applications
  - Wind turbines
  - Wind farms
  - Buildings
  - Building complexes
  - Pollutant dispersion etc

Environmental Flows at NTUA WT

- Field measurements are difficult to control

- Computer-aided simulation (CFD) is a more recent and powerful tool in modeling the ABL. It provides valuable insight but many unexplained complexities remain

- Testing in a wind tunnel is repeatable, more accessible and accurate. Challenges exist

Examples :

Wind Tunnel Testing – Atmospheric Flows

Computational Fluid Dynamics – Atmospheric Flows

- Modelling the Atmospheric Boundary Layer
- Flows past buildings
- Flows past photovoltaic panel arrays
- Flows past vegetation

Structure of the ABL

for FUR in neutral atm.

(Flat Uniformly Rough Terrain)

PBL Planetary Boundary Layer

ABL Atmospheric Boundary Layer
(surface shear stress negligible)

ASL Atmospheric Surface Layer
(turbulent fluxes vary ±10%)

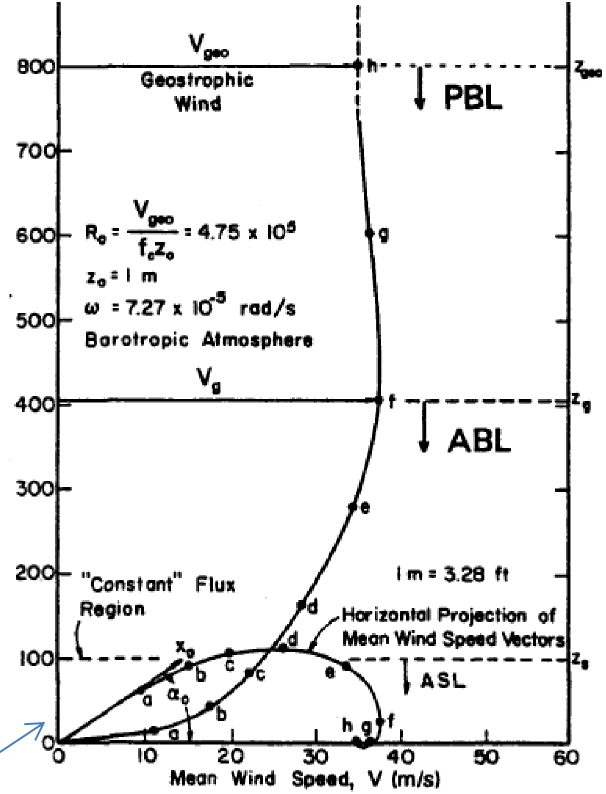
z_{geo} geostrophic height

z_g gradient height

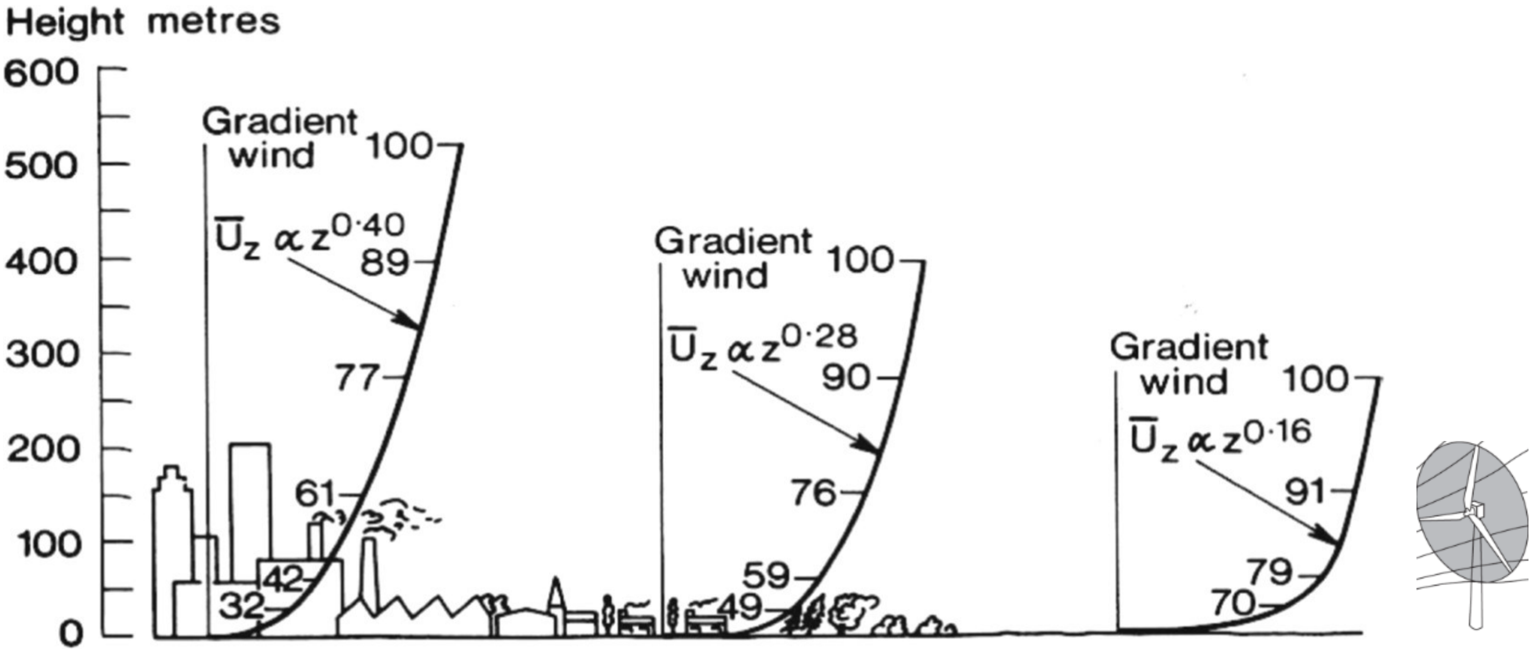
z_s surface layer height

Eckman Layer

~ logarithmic profile

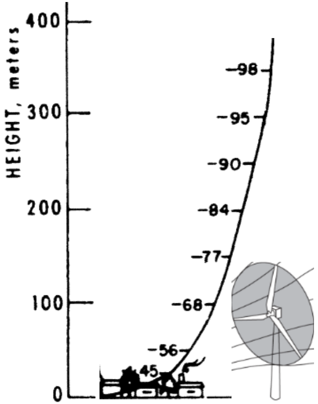


Modeling Criteria - Similarity



Effect of surface roughness (z_o)

Modeling Criteria - Similarity



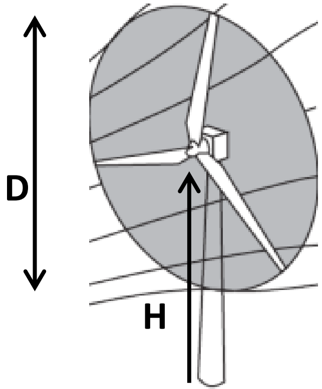
When creating a scale model to study,

the following criteria must be fulfilled

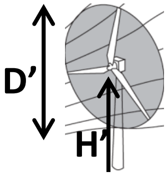
- **Geometric Similarity:** Similarity of dimensions (length)
- **Kinematic Similarity:** Similarity of time and length scales
- **Dynamic Similarity:** Similarity of forces

Modeling Criteria - Similarity

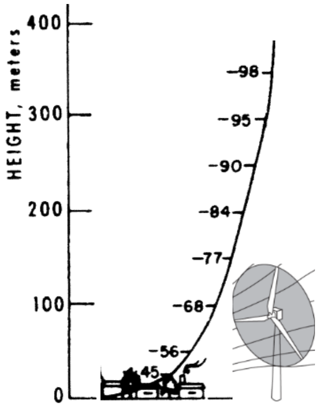
Geometric Similarity: Similarity of dimensions



p: prototype



m: model



$$\left(\frac{D}{H}\right)_p = \left(\frac{D'}{H'}\right)_m$$

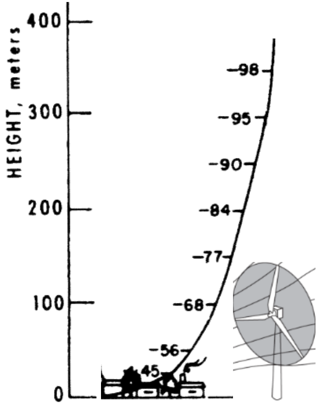
Modeling Criteria - Similarity

Geometric Similarity: Similarity of dimensions

Jensen number

Ratio of structure's length scale to terrain roughness

$$\left(\frac{L_b}{z_0}\right)_m = \left(\frac{L_b}{z_0}\right)_p$$



Ratio of structure's length scale to gradient height

(large scale motion)

$$\left(\frac{L_b}{z_g}\right)_m = \left(\frac{L_b}{z_g}\right)_p$$

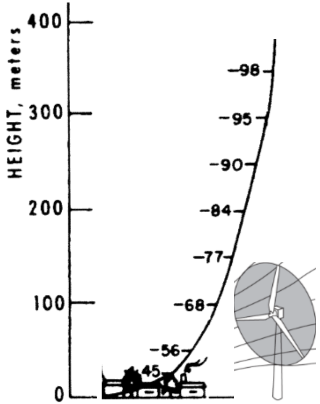
Ratio of structure's length scale to turbulence length scale

(small scale motion)

$$\left(\frac{L_b}{L_t}\right)_m = \left(\frac{L_b}{L_t}\right)_p$$

Modeling Criteria - Similarity

Dynamic Similarity: Similarity of forces



Reynolds number

the ratio of inertial to viscous forces

$$Re = \frac{UL\rho}{\mu}$$

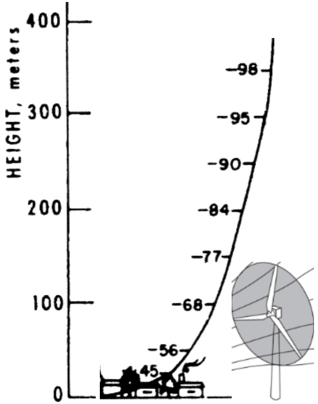
Rosby number

the ratio of inertial to Coriolis forces

$$Ro = \frac{U}{Lf}, \quad f = 2\Omega \sin\varphi$$

- When modeling the ABL (z<300m), Rosby numbers are usually large (i.e. Coriolis insignificant)
- Reynolds effects usually neglected >critical Reynolds number (~10^4 for buildings)
- For geometries with sharp edges (e.g. buildings, wind turbines etc) the flow pattern remains the same >critical Reynolds number

Modeling Criteria - Similarity



Kinematic Similarity:

Similarity of velocity time and length scales

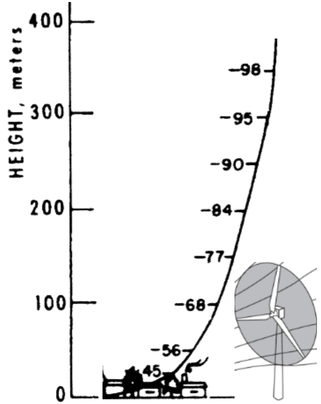
- This mainly refers to incoming flow (upstream boundary layer)
- Difficult to achieve for both mean velocity and turbulence
- Boundary layers can be considered independent of Re number after a critical surface Re number (surface roughness) has been exceeded $u_* z_o / \nu > 2.5$

- Vibrations, fluctuations, unsteady motion : $\left(\frac{TV}{L}\right)_m = \left(\frac{TV}{L}\right)_p \rightarrow \left(\frac{T_m}{T_p}\right) = \left(\frac{L_m}{L_p}\right)\left(\frac{V_p}{V_m}\right)$

e.g. $T_m = T_p(1/300)(1) = T_p/300$

Scaling factor

The most demanding geometric similarity parameter is the ratio of structure's length scale to turbulence length scale since it is a function of height



$$\left(\frac{L_b}{L_t}\right)_m = \left(\frac{L_b}{L_t}\right)_p$$

Cooke (1978), proposed using the ESDU profile for L_{ux} in order to find the scaling factor

$$S = \frac{L_{bp}}{L_{bm}}$$

$$L_{X_u} = 25(z-d)^{0.35} {z_0}^{-0.063}$$

$$SL_{X_{u_M}} = 25[S(z-d)_M]^{0.35}\left[Sz_{0_M}\right]^{-0.063}$$

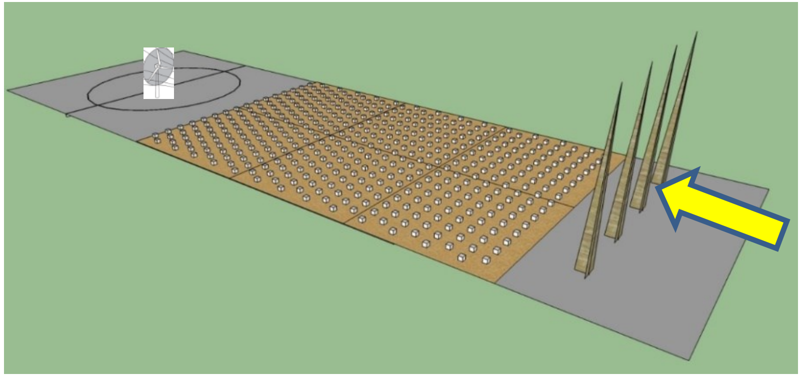
$$S = \frac{91.3{(z-d)_M}^{0.491}}{L_{X_{uM}}^{1.403} z_{0M}^{0.088}}$$

Equipment for Modelling the Wind

Boundary Layer Development (augmentation) Devices

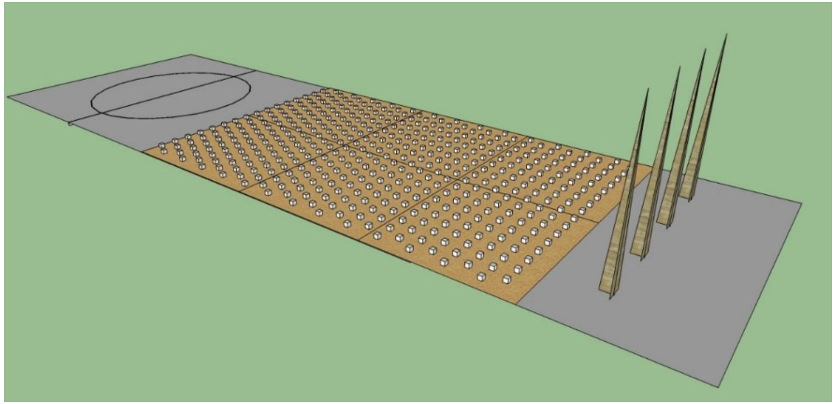
- Even with long wind tunnels, the boundary layer depth may not be sufficient to study models of adequate scale e.g. < 1:200

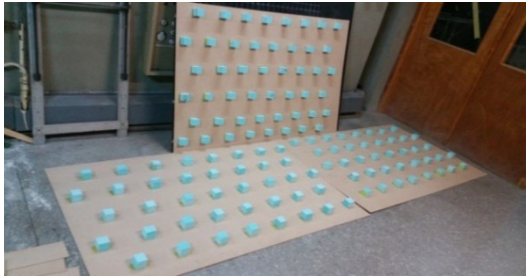
- Augmentation of the boundary layer height or the use of shorter wind tunnels is possible using special devices:
  - Fences
  - Surface roughness elements
  - Spires



ABL Simulation in the NTUA WT

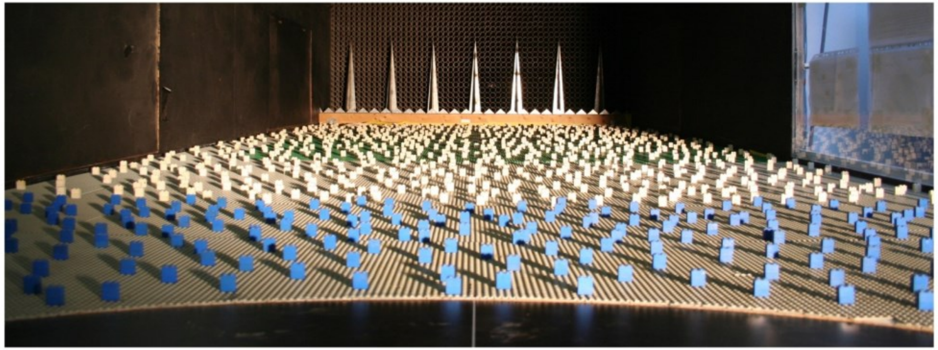
Scale factor 1:300
Spire h=170cm,
b=30cm
Roughness cubes height k=5cm
Roughness cubes spacing D=20cm





NTUA – KIT wind tunnels

Karlsruhe Institute of Technology



(width × height): 2.0 m × 1.0 m

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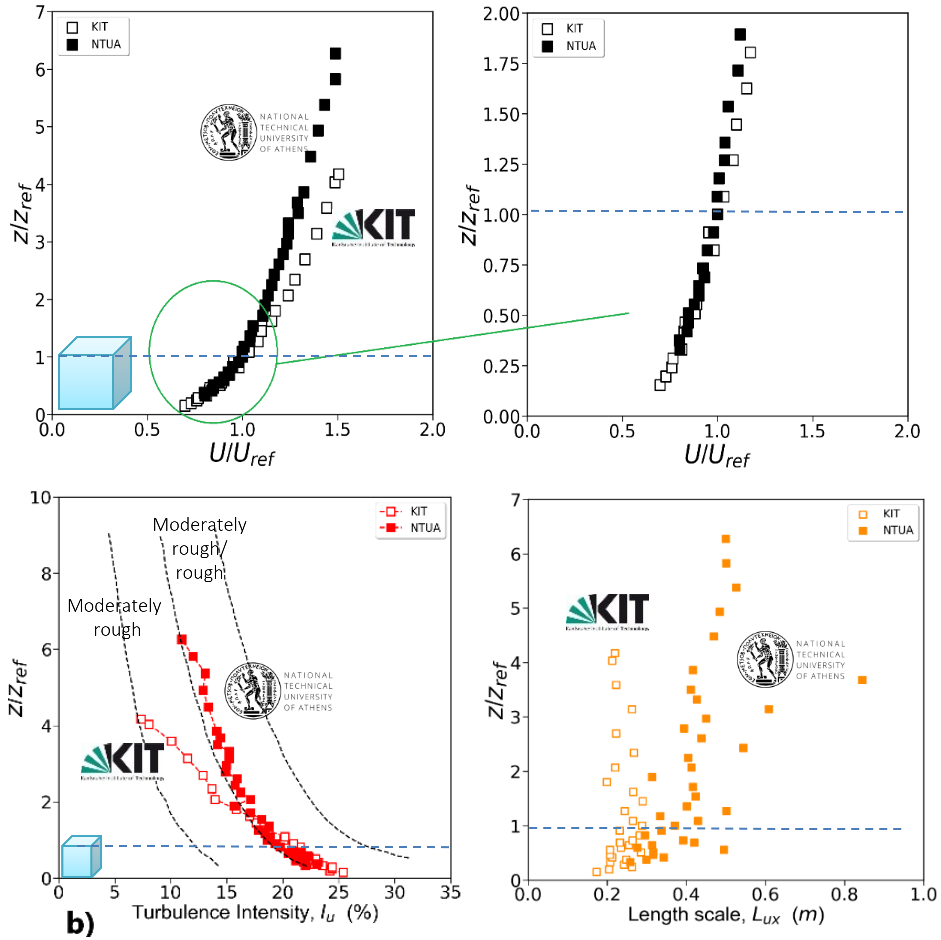
(width × height): 3.5 m × 2.5 m

ABL simulation

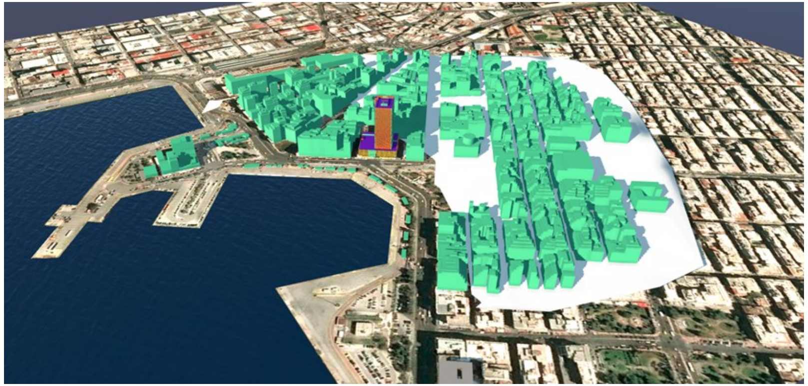


Wind Tunnel Study Examples

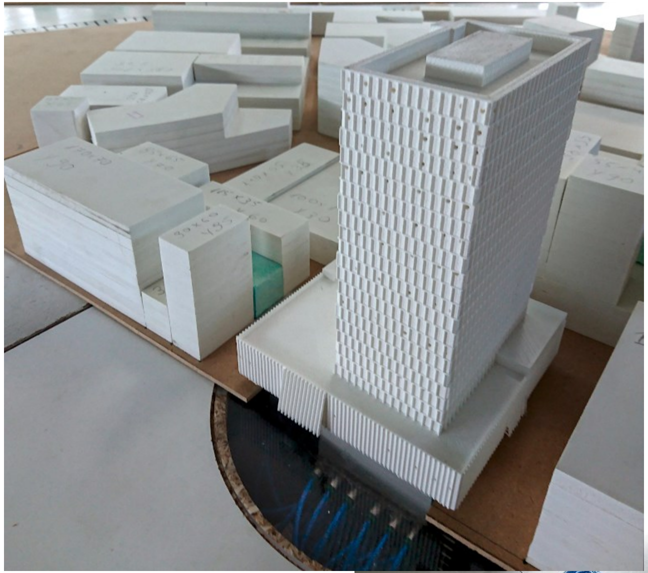
- Piraeus Tower
- PV panels – static
- PV panels – dynamic
- Trees

Piraeus Tower in the Wind Tunnel

An NTUA_WT study contributed to the design of the new façade for the "Piraeus Tower" building in Piraeus, Greece



- 3D printing for the building
- 350 m radius around tower
- 1:300 scale for building and wind
- 350 pressure points
- 8 different wind directions
- Urban terrain ABL conditions



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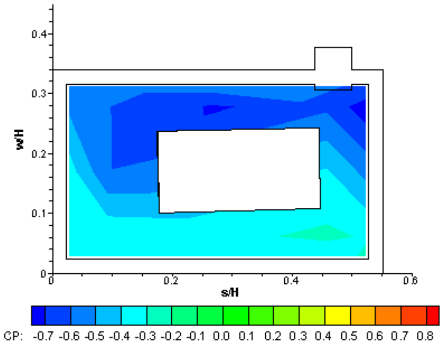
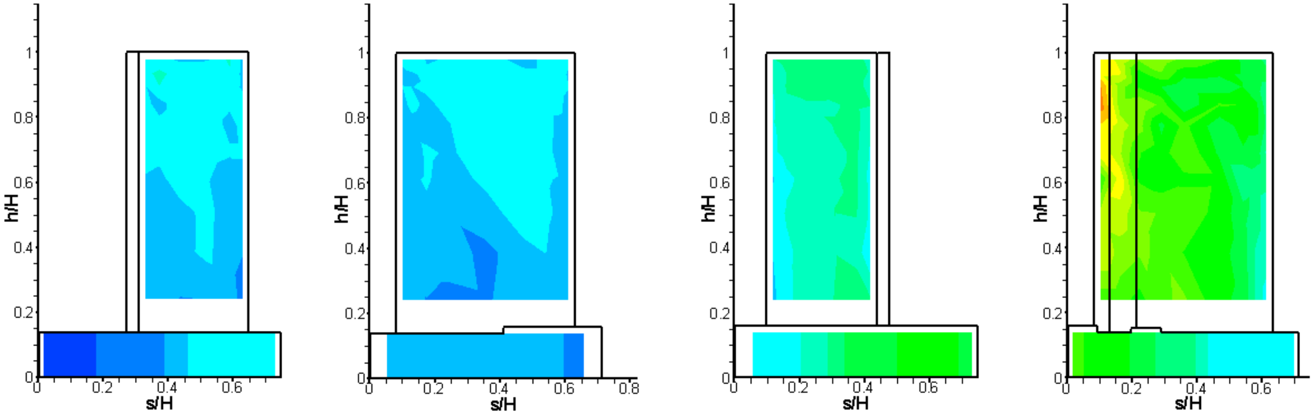
Piraeus Tower in the Wind Tunnel

North NW





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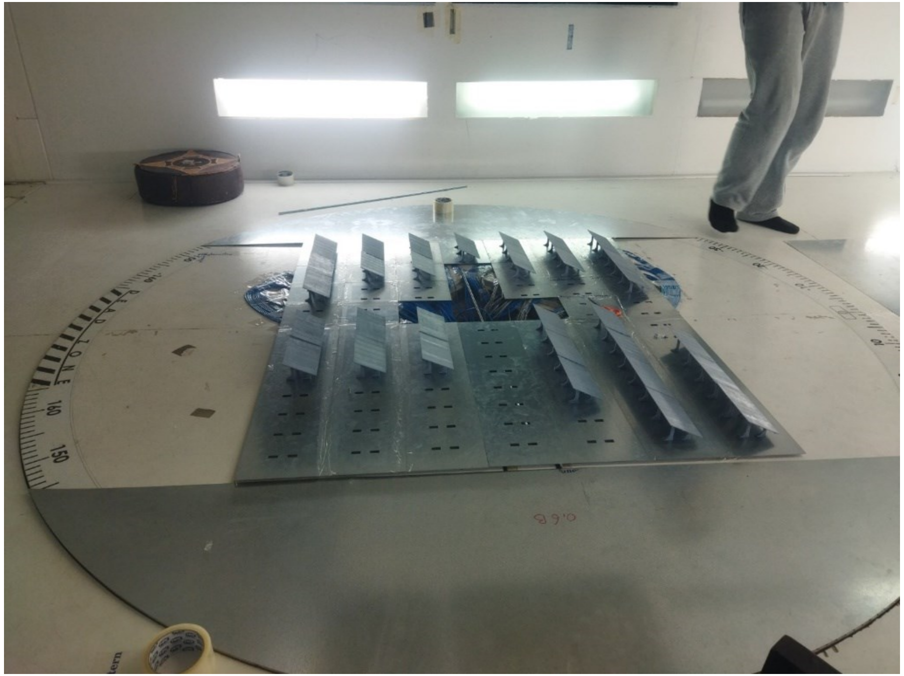
Piraeus Tower in the Wind Tunnel

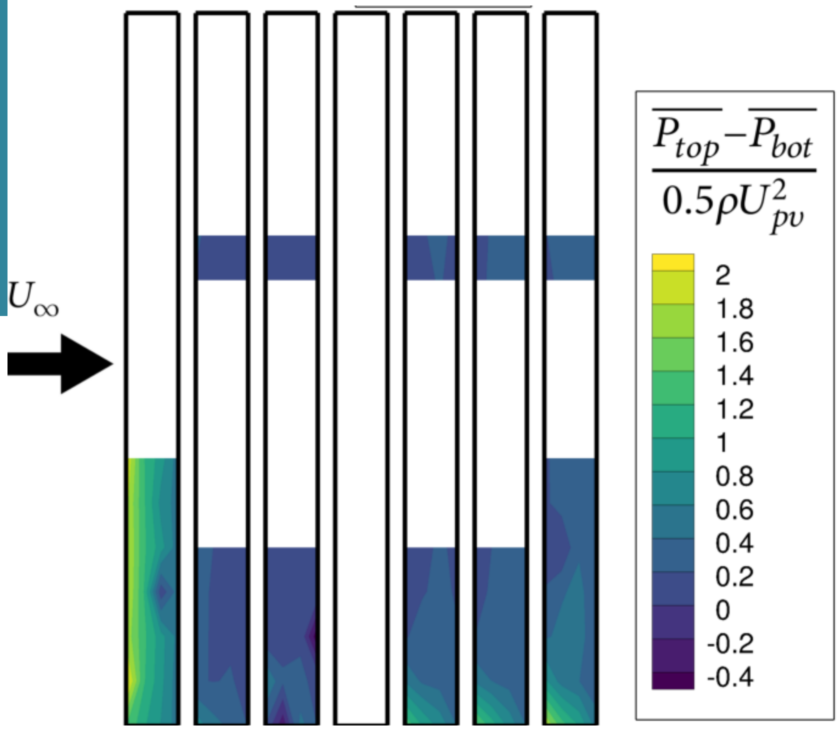
PV panels – static loads

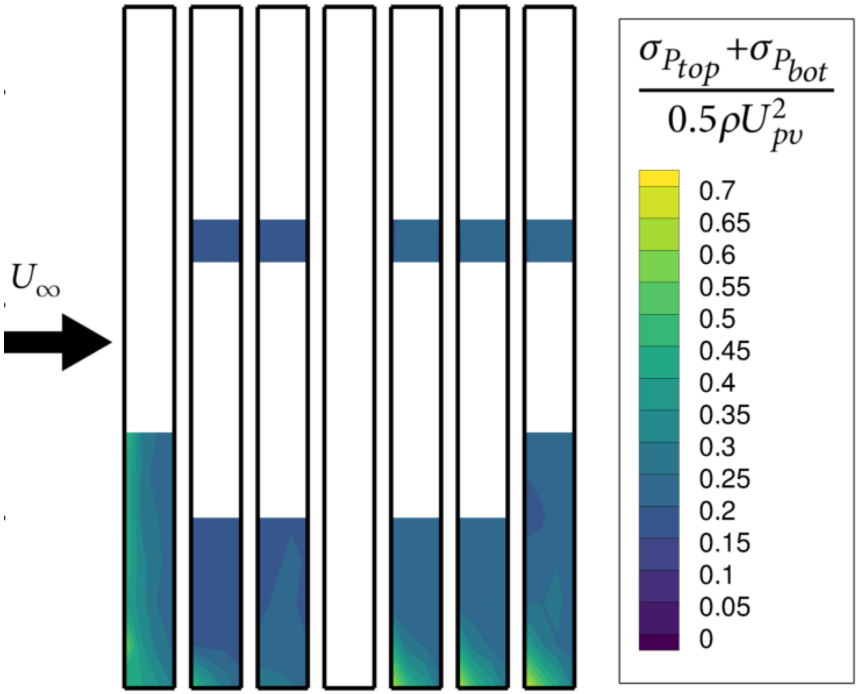


PV panels – static loads

Open terrain ABL conditions

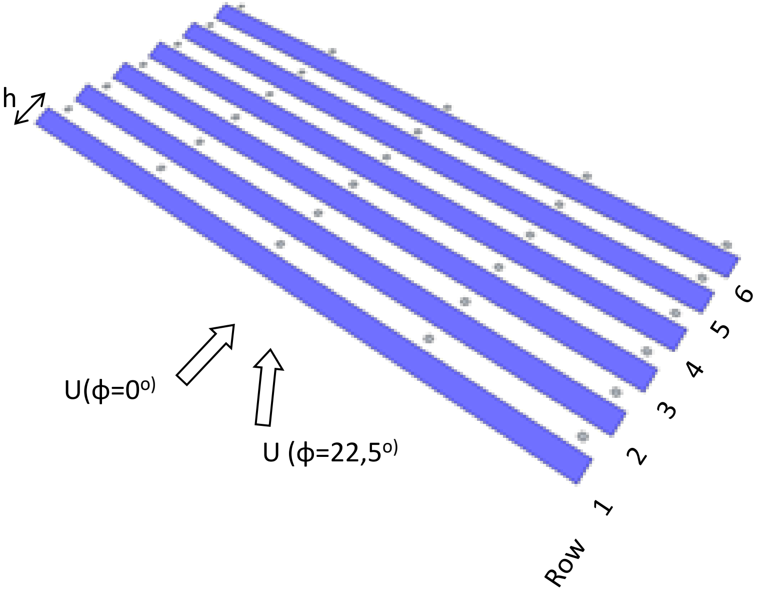
PV panels – static loads

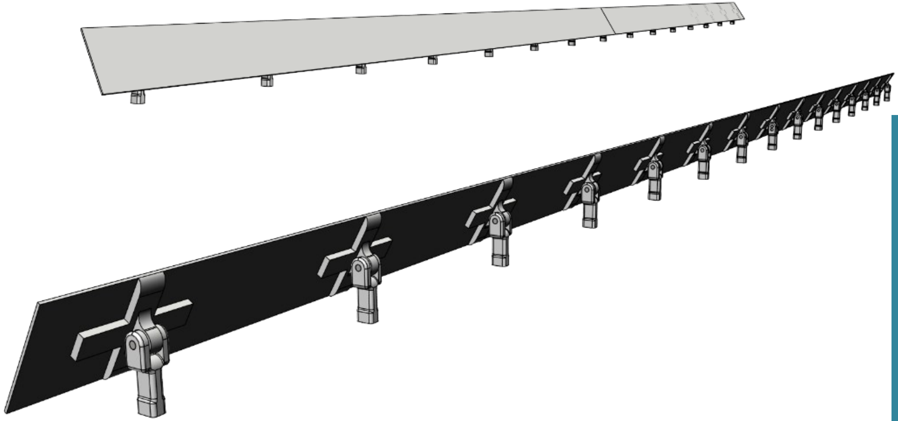


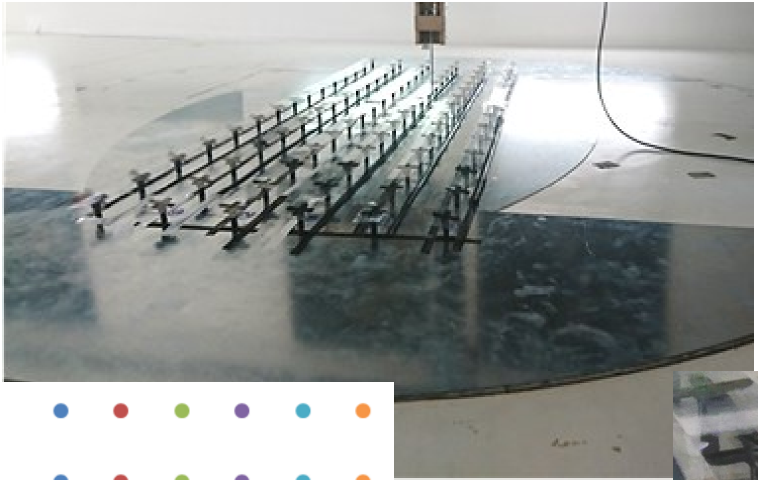


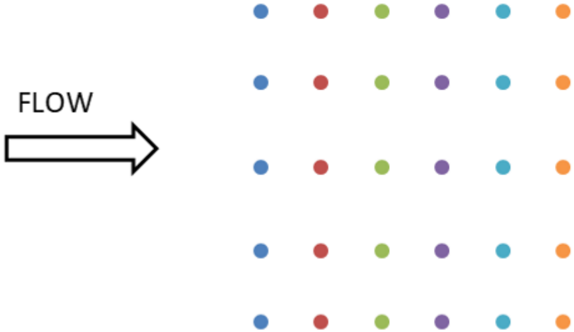
PV panels – static loads

PV panels – dynamic study

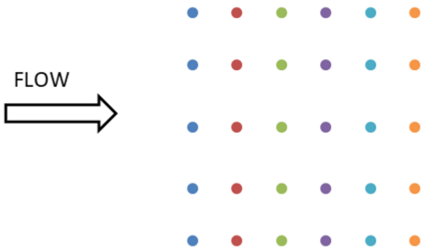


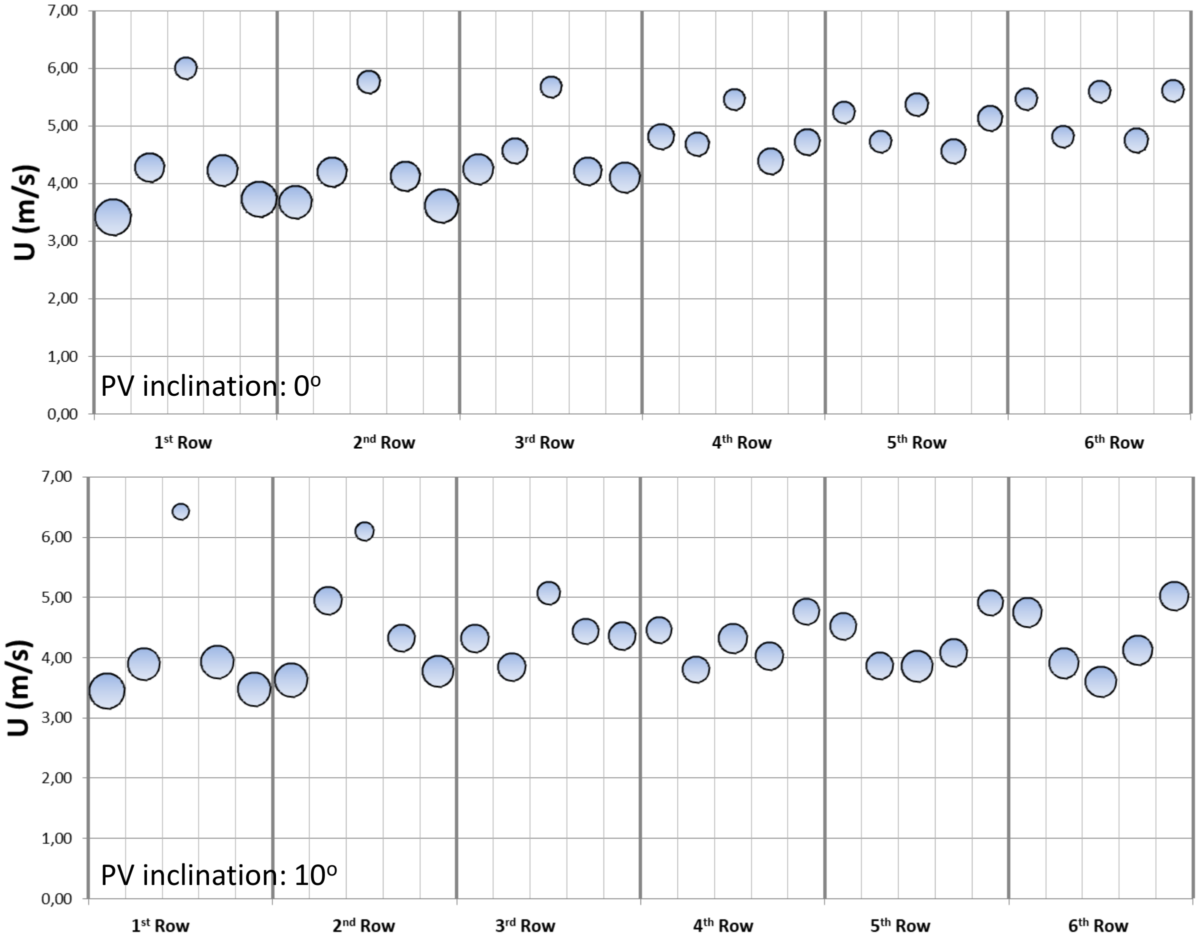






PV panels – dynamic study





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PV panels – dynamic study

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Vegetation

Vegetation-air-buildings interactions,
affect thermal comfort and indoor natural ventilation.

Heat and mass exchange between
vegetation elements and the environment,
depends on trees’ aerodynamical, geometrical and thermal properties.

Methodology - Definition of trees' aerodynamic parameters

Wind tunnel measurements in the NTUA Test section (2.5m x 3.5m)

- Influence of wind speed on drag coefficient, measured for **6 U_{ref} : 1.5m/s- 10m/s**
- For each reference wind speed, **measurement of the drag force** in the direction of wind speed (F)
- For all trees, **definition of the frontal area (A)** through image processing

- Drag coefficient Cd of the trees for a given reference wind speed U_{ref} (m/s)

$$C_d = \frac{2F}{\rho U_{ref}^2 A}$$

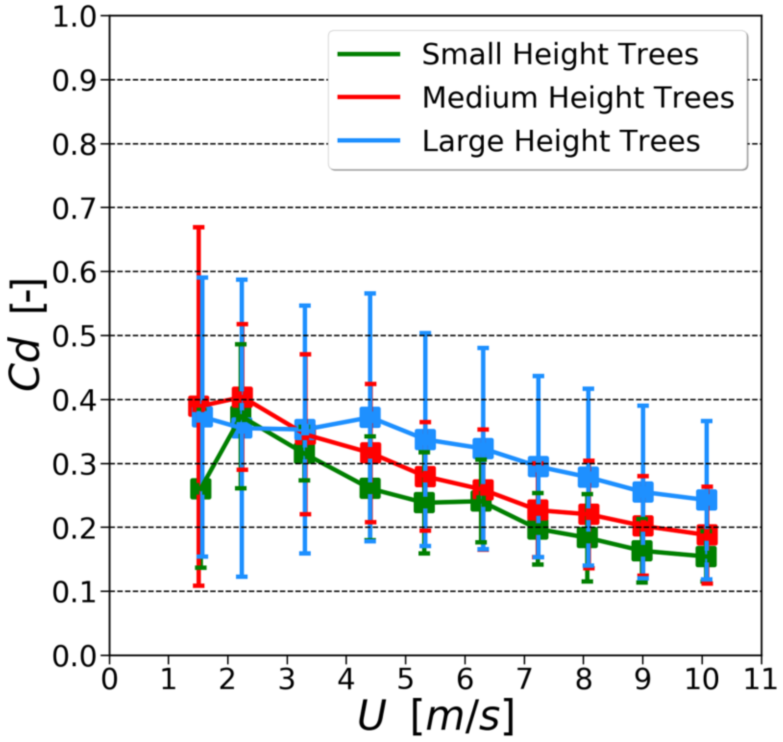
Methodology – Definition of trees' aerodynamic parameters

Citrus sample trees – common tree type in Greek cities, increased drought tolerance, low irrigation needs - Young trees of different heights, tested: **1.3m, 1.5m, 1.8m**

Wind tunnel measurements in the NTUA Test section (2.5m x 3.5m)

Kistler
Multicomponent Force

Results – Drag coefficient (Cd)



- ***Small height test trees***
  Mean Cd=0.15-0.37
  St.Dev =0.039-0.12

- ***Medium height trees***
  Mean Cd=0.18-0.40
  St.Dev =0.073-0.28

- ***Large height trees***
  Mean Cd=0.24-0.37
  St.Dev =0.12-0.22

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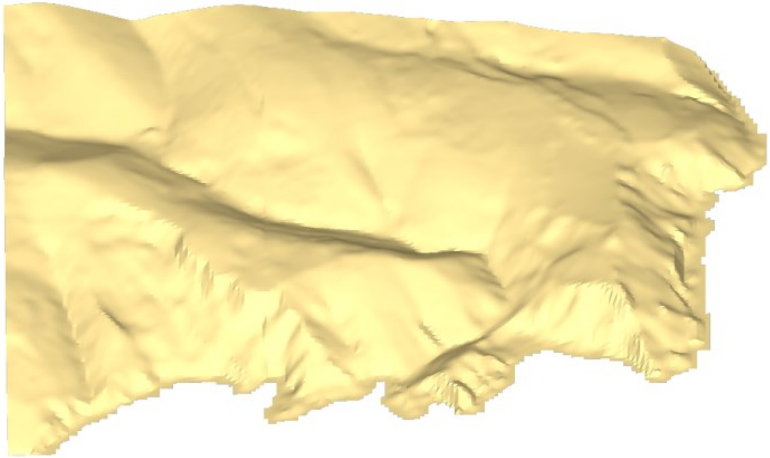
CFD Study Examples

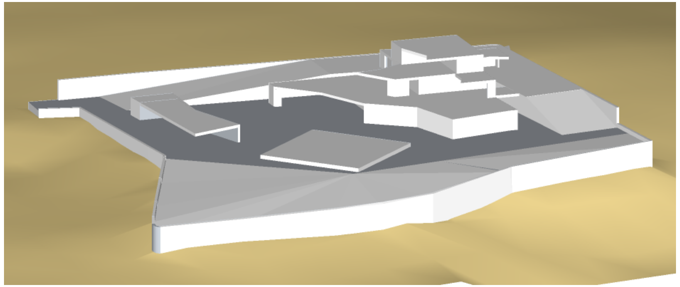
- Wind flow past buildings
  - In complex terrain
  - With vegetation and wind barriers

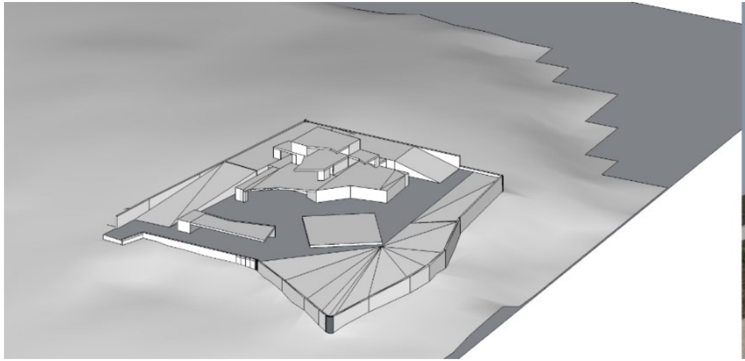
Wind flow past buildings in complex terrain

Challenges

- Representative computational model
- Adequate spatial resolution
- Flexibility in wind direction calculation
- Application of appropriate ABL BCs
- Determine areas of discomfort
- Provide protection from wind







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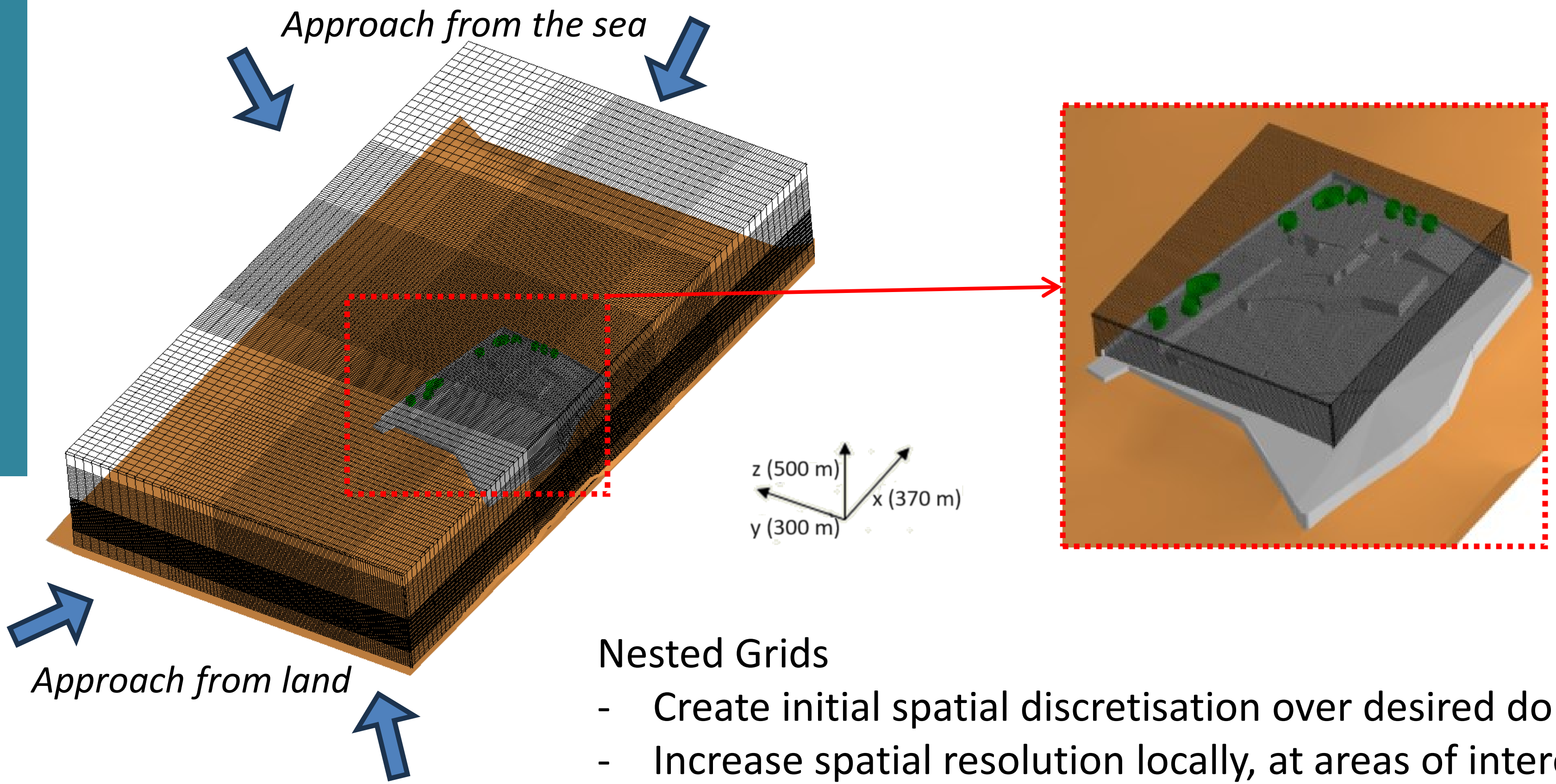
Computational model



Nested Grids

- Create initial spatial discretisation over desired domain
- Increase spatial resolution locally, at areas of interest.
- Apply ABL BC according to land type. Mesoscale theory

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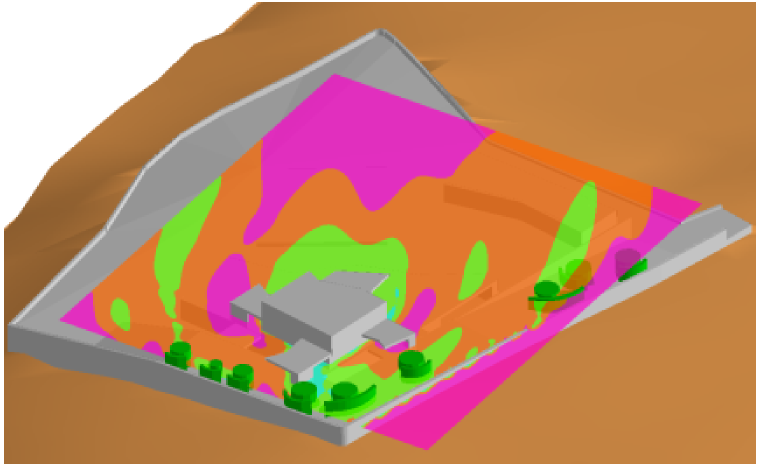
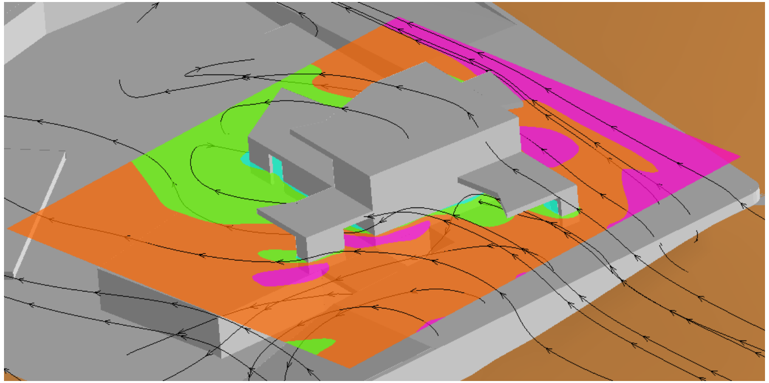
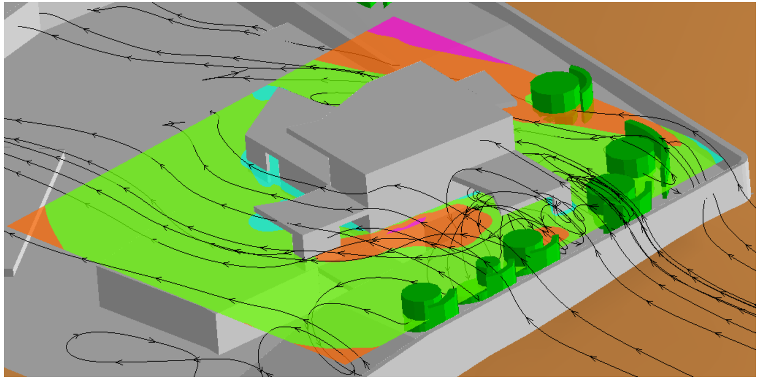
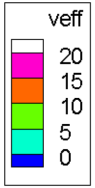
Spatial Resolution (gridding)









$$v_{eff} = V \times (1 + C \times \frac{V_{rms}}{V})$$

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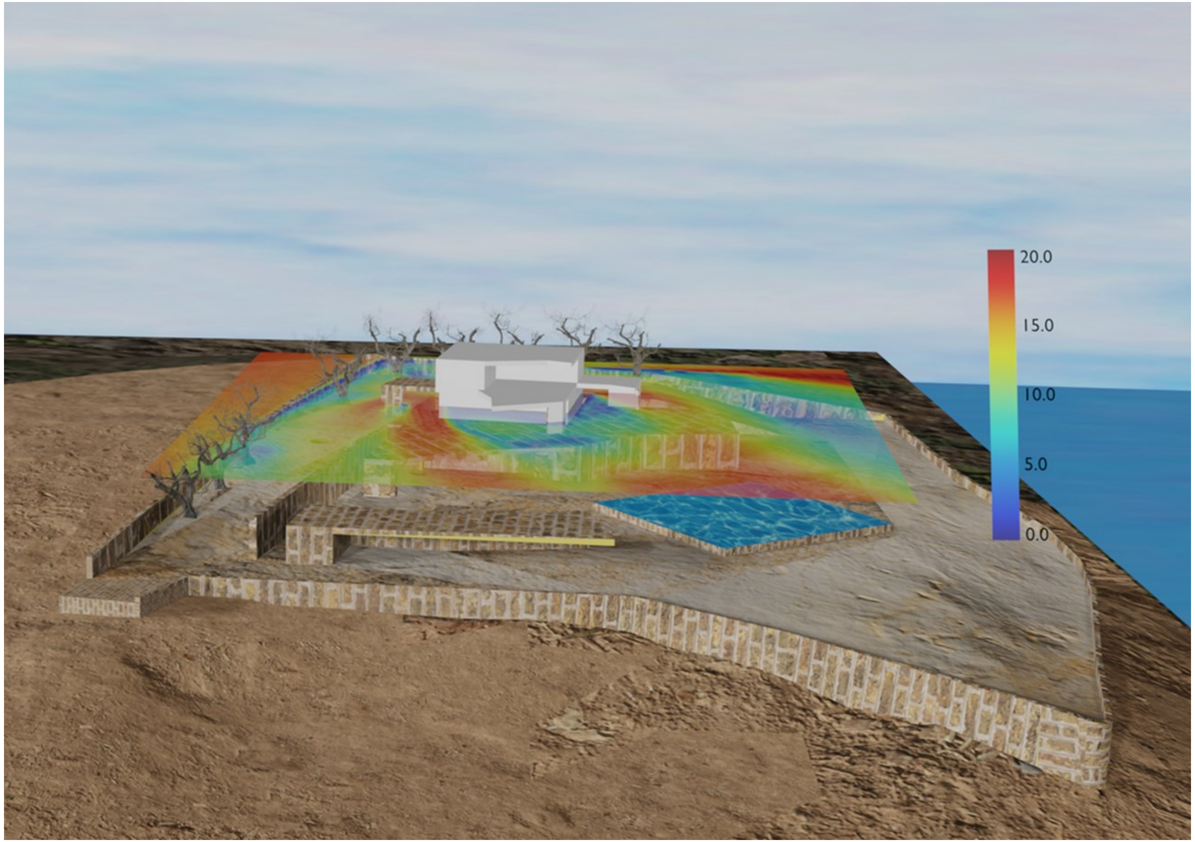
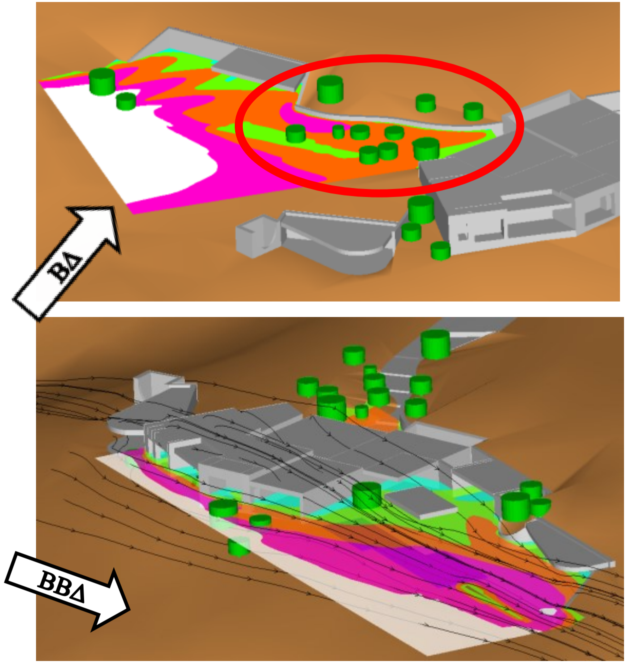
Solve N-S equations on grid

Final presentation

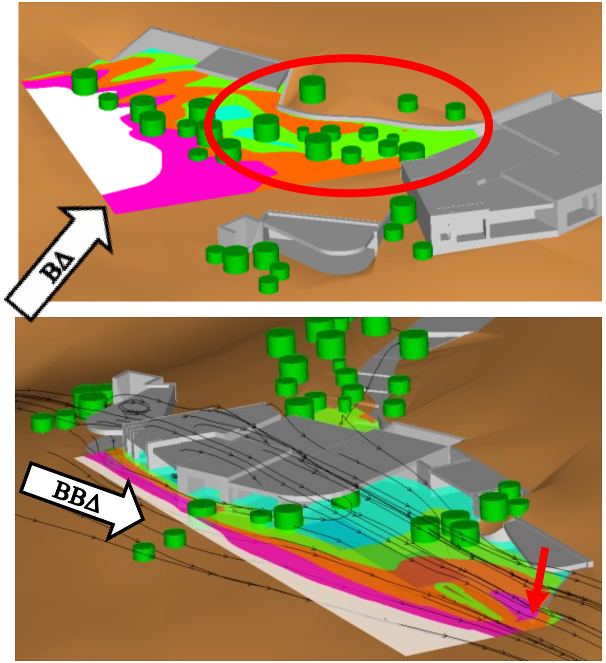


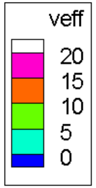
Vegetation and wind barrier design

Initial Design

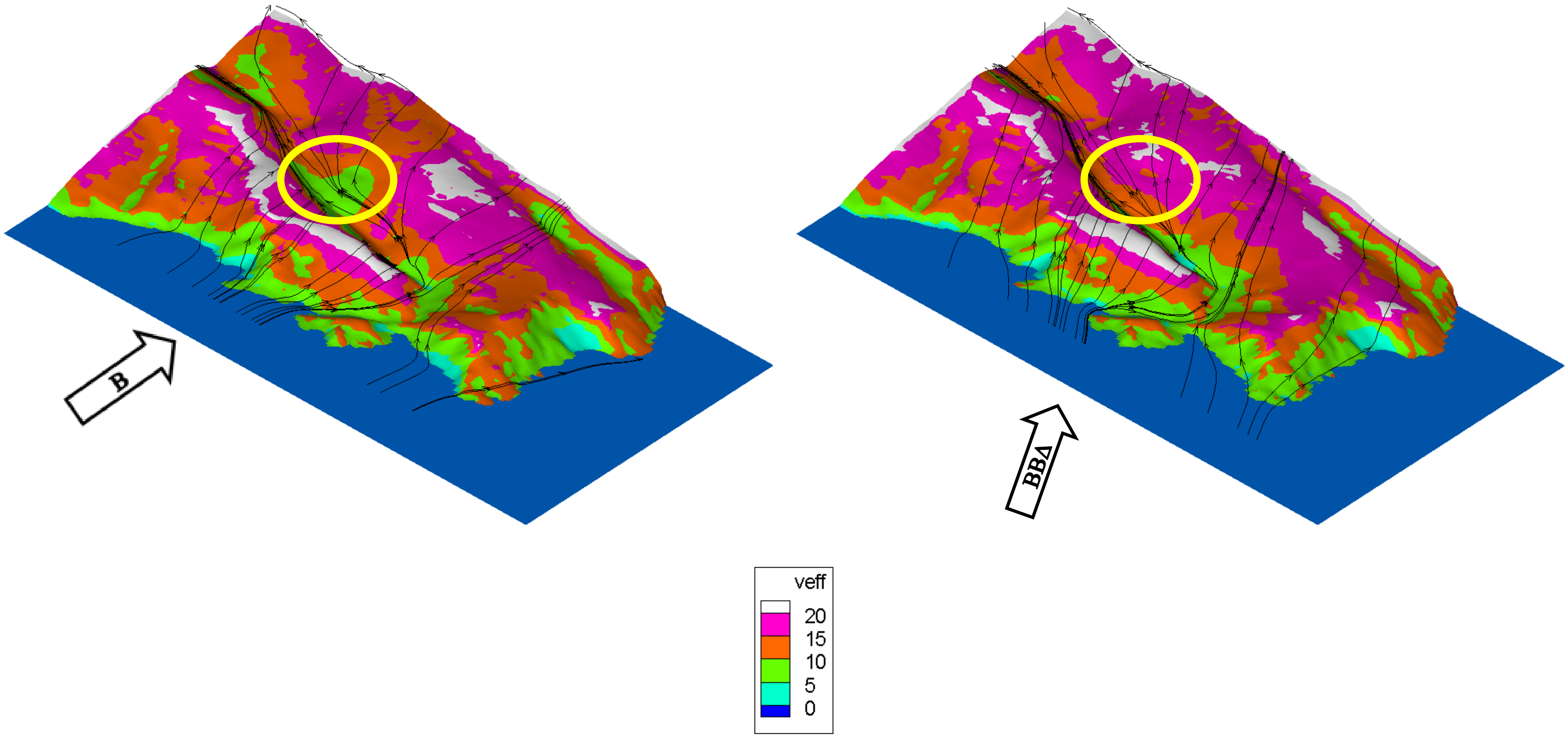


Final Design

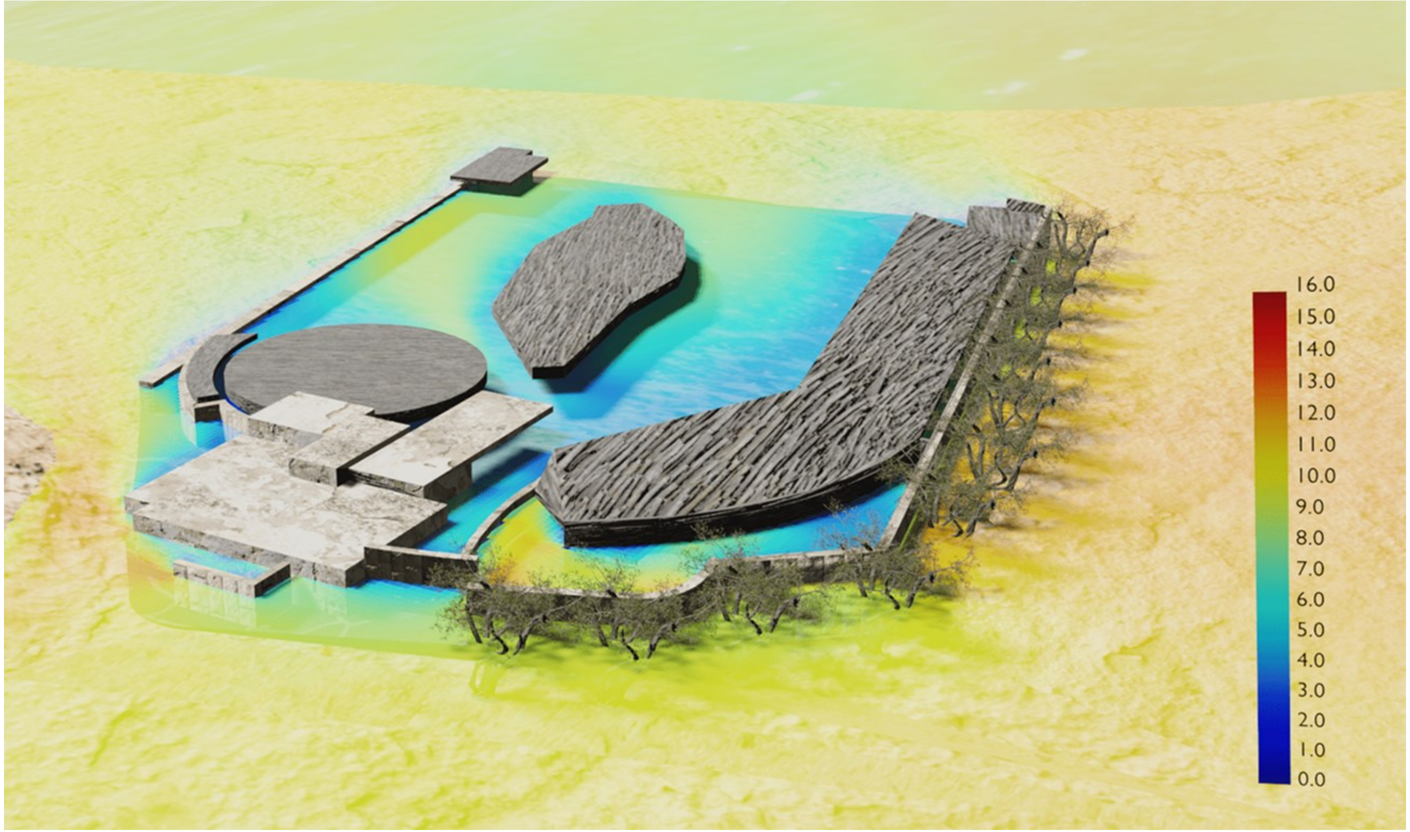




Effect of wind direction



Wind and vegetation barriers for commercial use



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