TWEET-IE Grand Opening Event

Prof. Alessandro Croce
Department of Aerospace Science and Technology
Politecnico di Milano

Athens, 24-26 January 2023

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

POLITECNICO
MILANO 1863

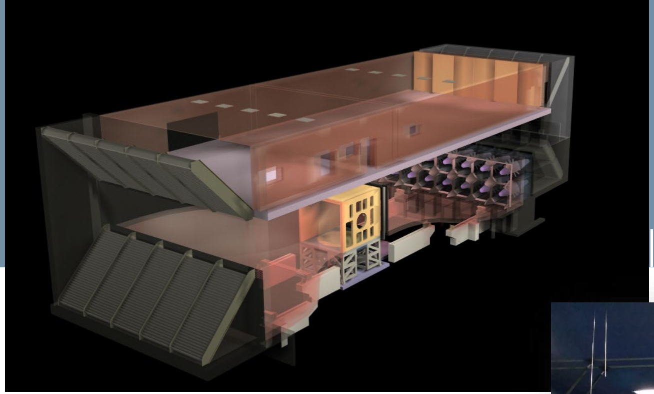
DIPARTIMENTO DI
SCIENZE E TECNOLOGIE AEROSPAZIALI

POLI-Wind

Review of current state of the art on measurement techniques and WT testing: 15 years of experience of the POLI-wind group at POLIMI

Prof. Alessandro Croce
Department of Aerospace Science and Technology
Politecnico di Milano

Outline



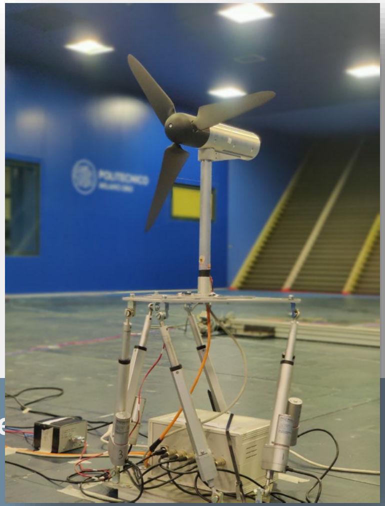
The Politecnico di Milano Wind Tunnel – GVPM

Passive & Passive/Active Load Alleviation in Waked Conditions

Wind Turbine Wake Interactions and Wind Farm Controls

Measurements test

Floating cases



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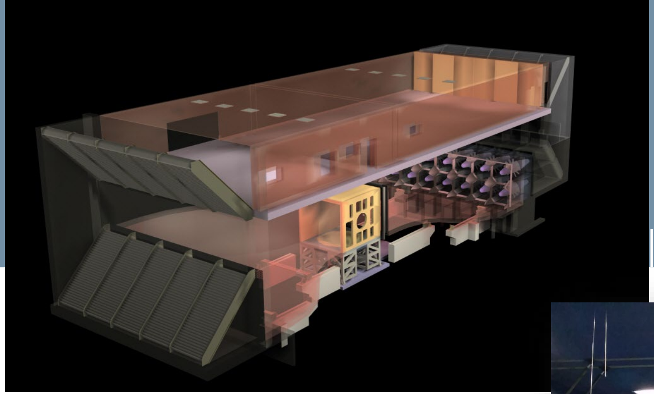
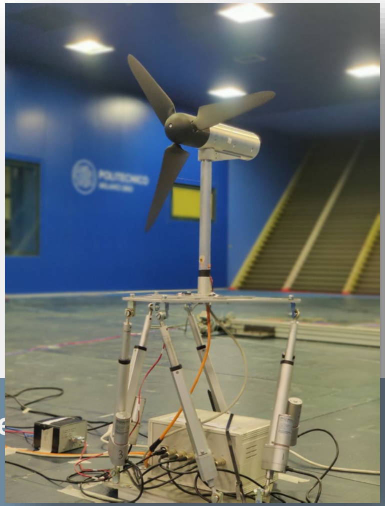
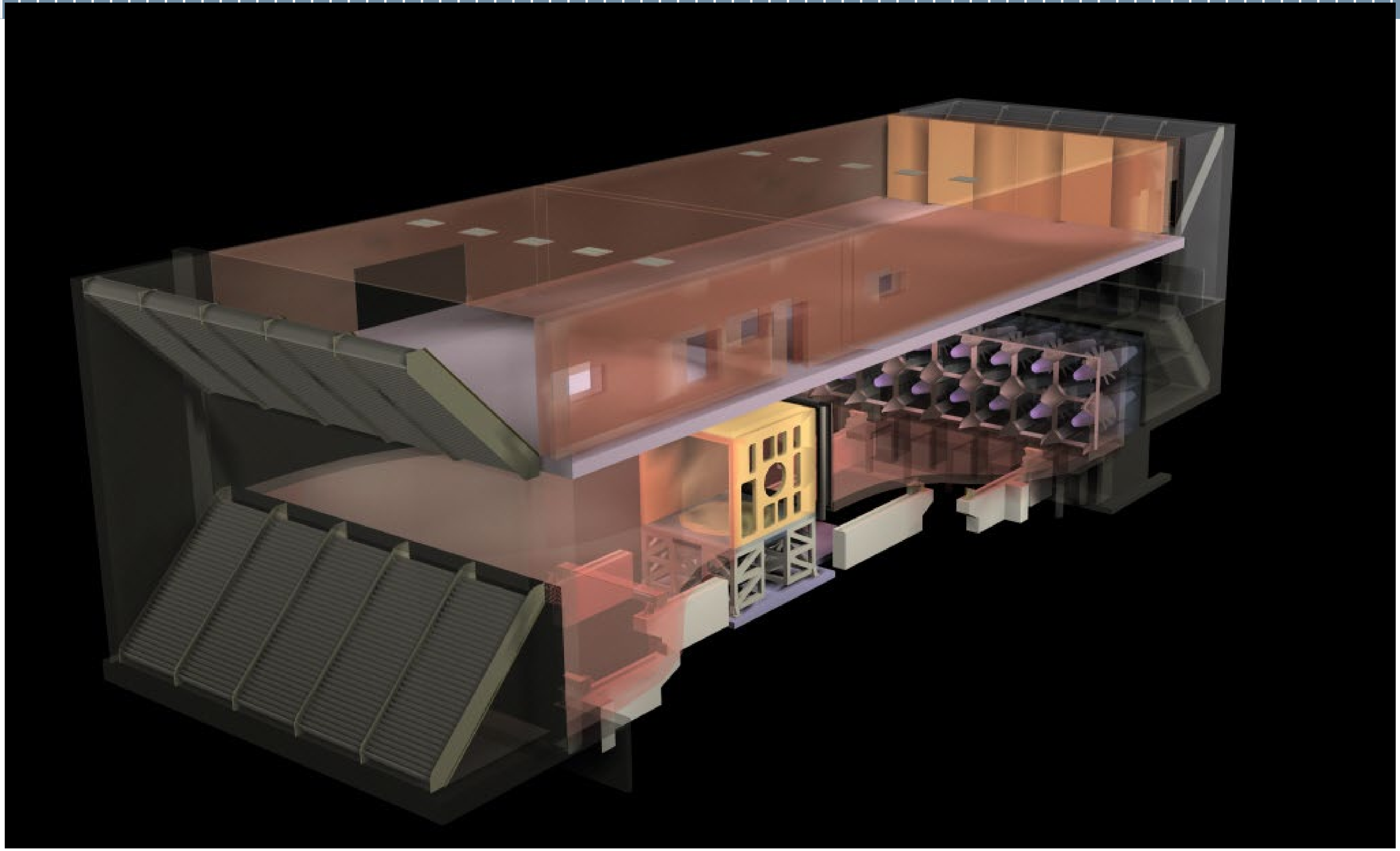



The Politecnico di Milano Wind Tunnel – GVPM



GVPM
POLITECNICO
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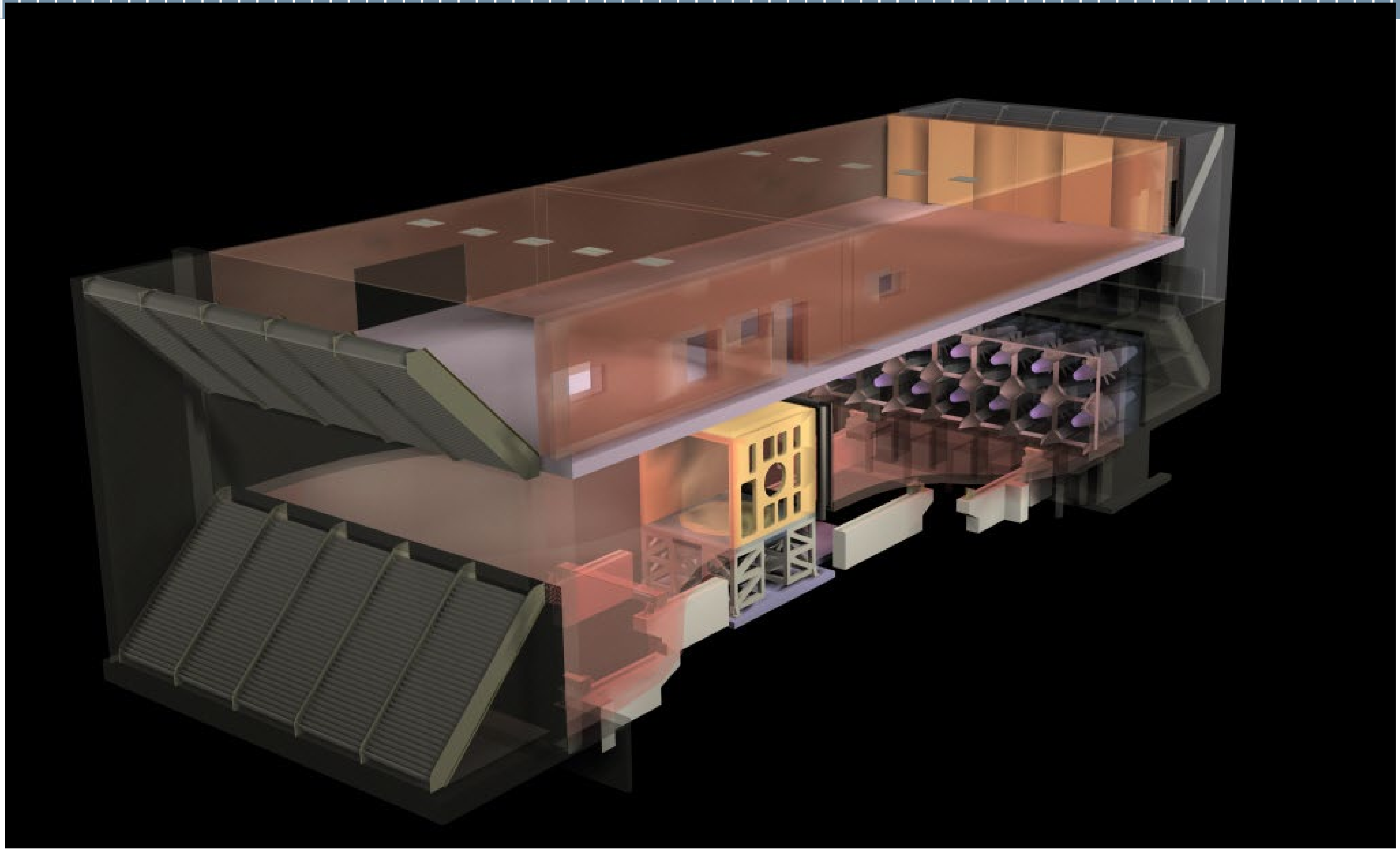
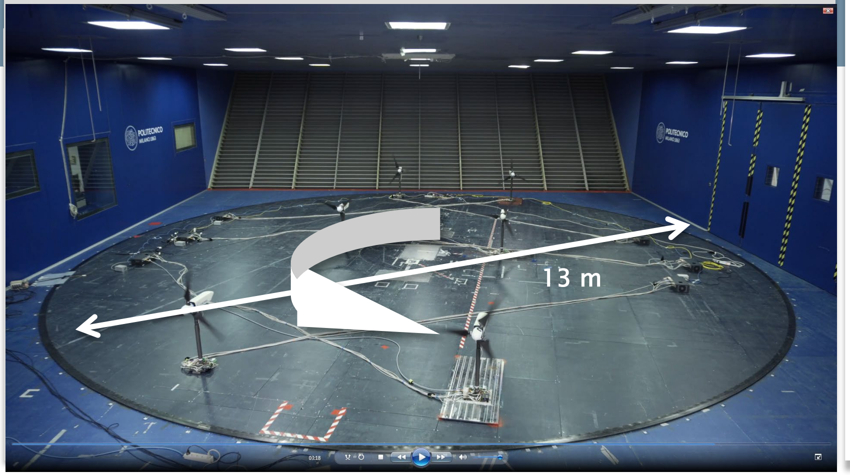
The Politecnico di Milano Wind Tunnel – GVPM

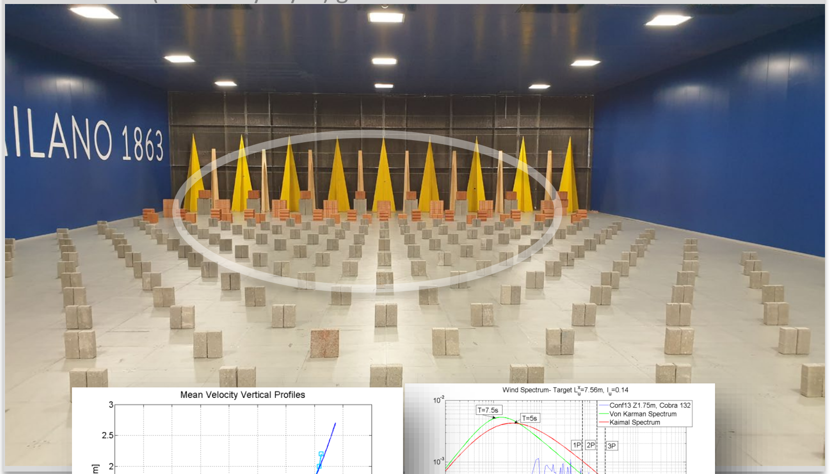


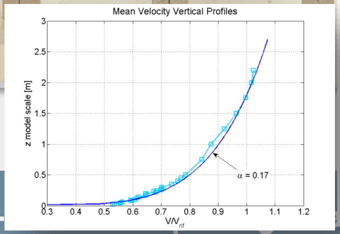
The Politecnico di Milano Wind Tunnel

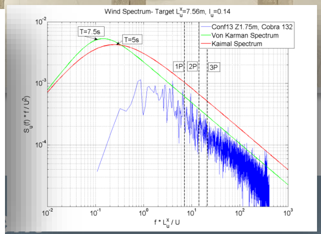
Turn-table

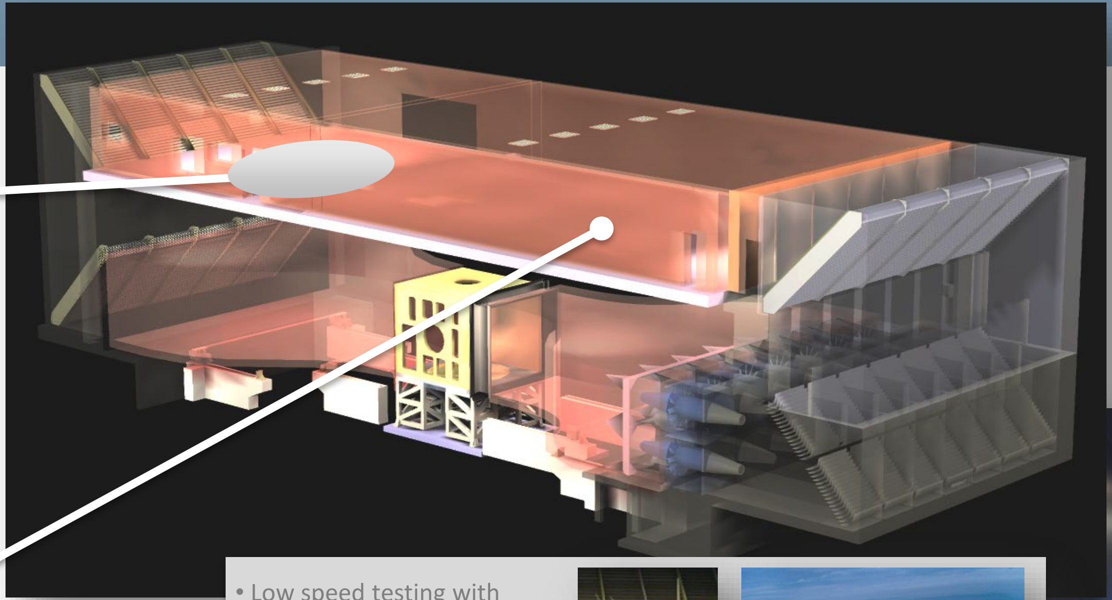


Turbulence (boundary layer) generators







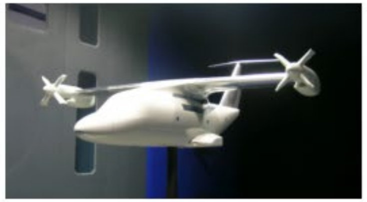


- Low speed testing with vertical wind profile
- Multiple wind turbine testing (wake-machine interaction)

High speed testing
Aerodynamic characterization (C_p-TSR-β & C_F-TSR-β curves)

The Politecnico di Milano Wind Tunnel - Expertise

Aircraft aeroelasticity



Airplane aerodynamics

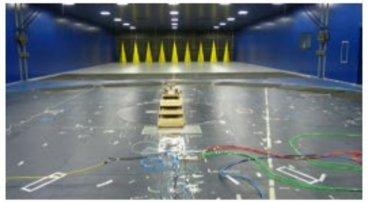
Rotorcraft aerodynamics

Bridge aerodynamics & aeroelasticity

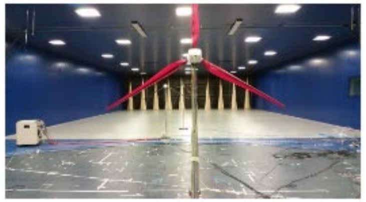
Buildings & roofs

Rail & road vehicles

Sails & marine

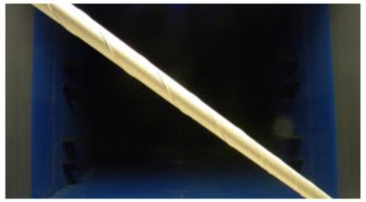


Pollution dispersion & environment

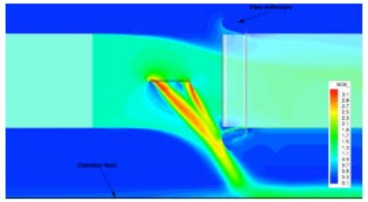


Wind energy

Sport aerodynamics



Cable aerodynamics & aeroelasticity



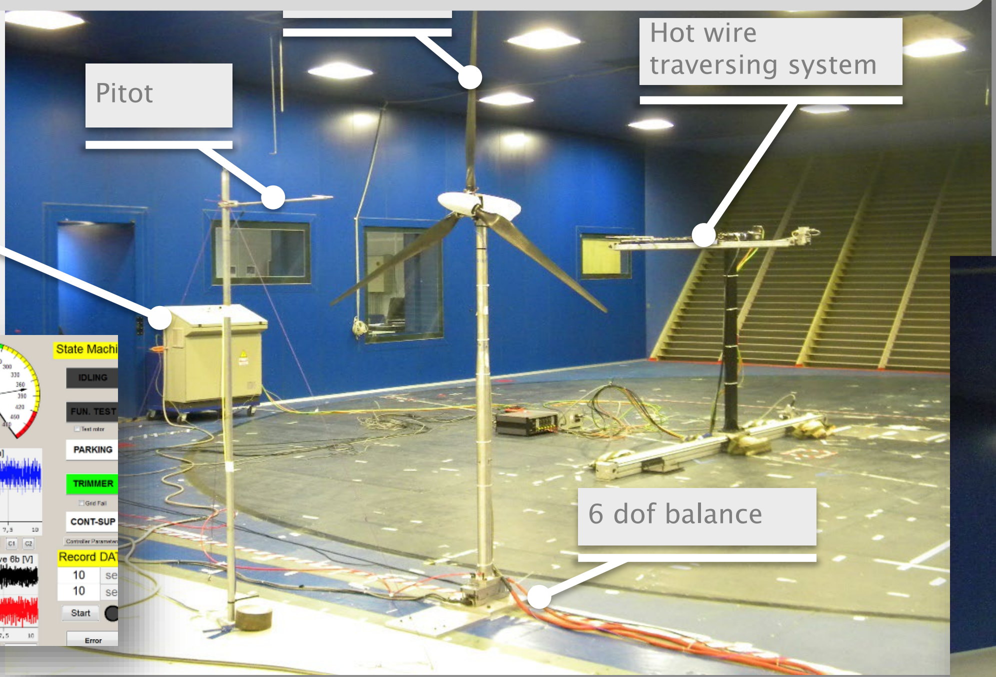
Numerical wind tunnel

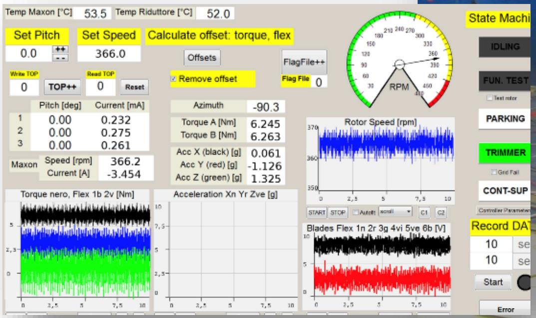
https://www.windtunnel.polimi.it/expertise/

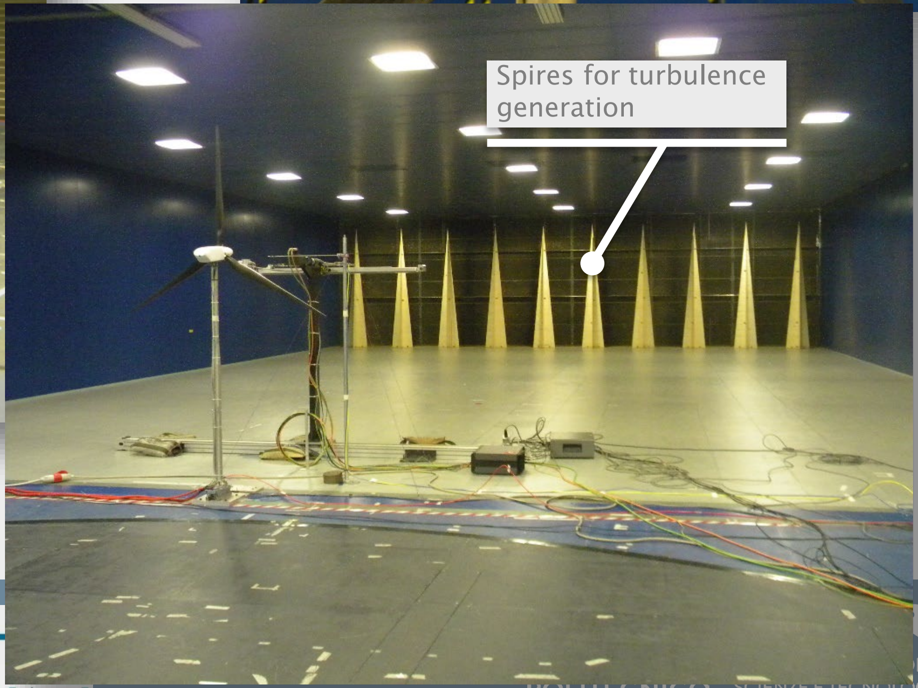
GVPM POLITECNICO MILANO 1863

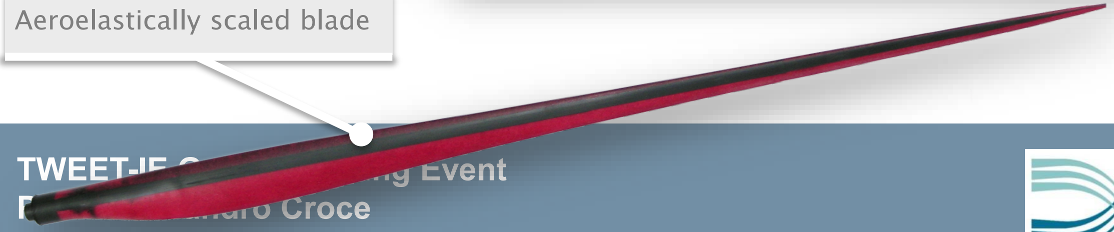
Wind Tunnel Testing for Wind Energy Application: POLI-Wind project 15 years ago

The first scaled wind turbine model with:
- Aeroelastic-scaling
- Real-time individual blade pitch & torque control



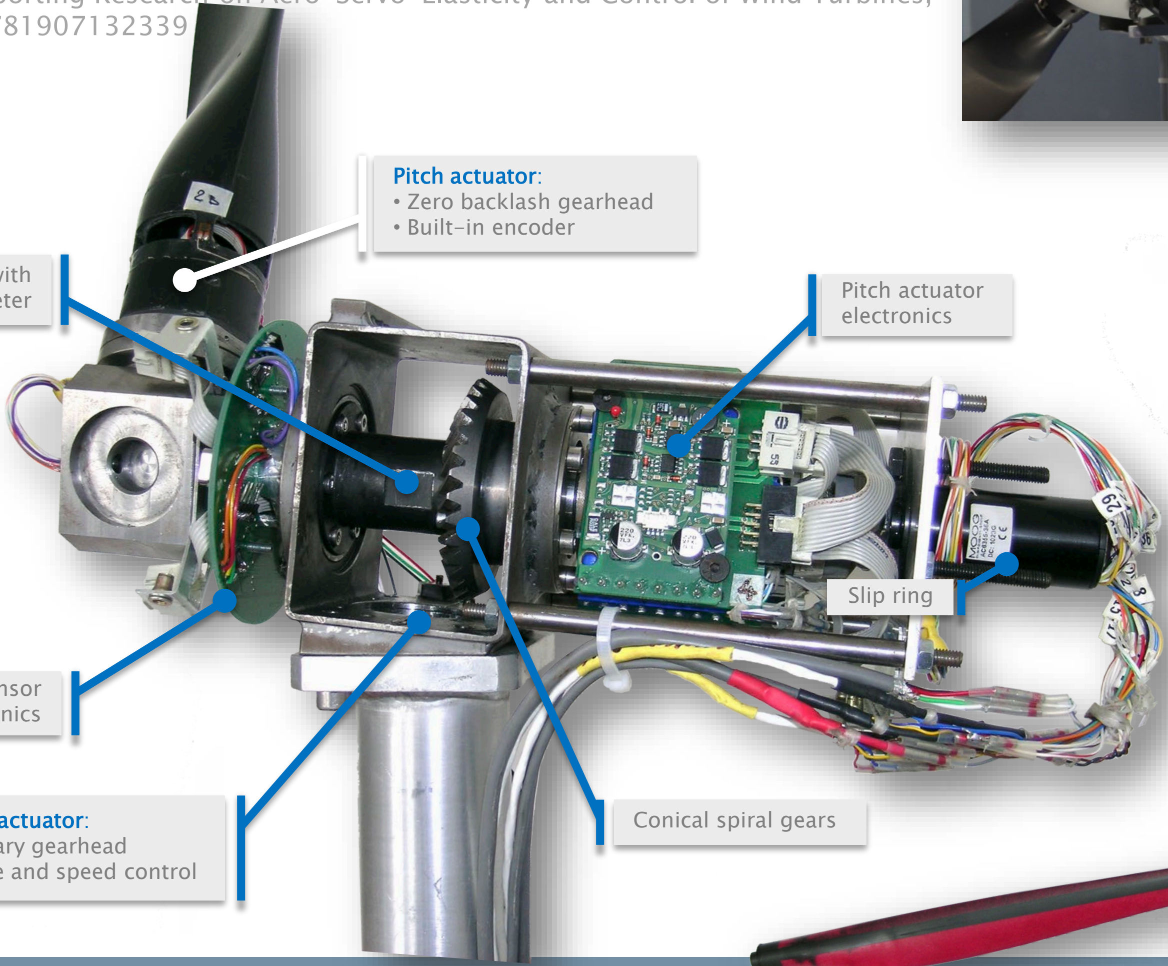


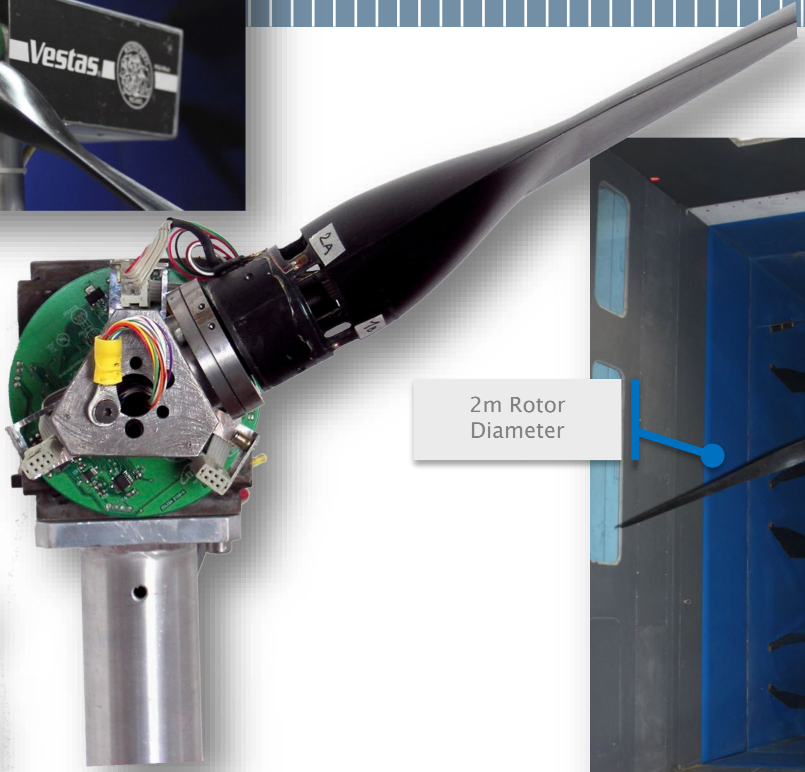


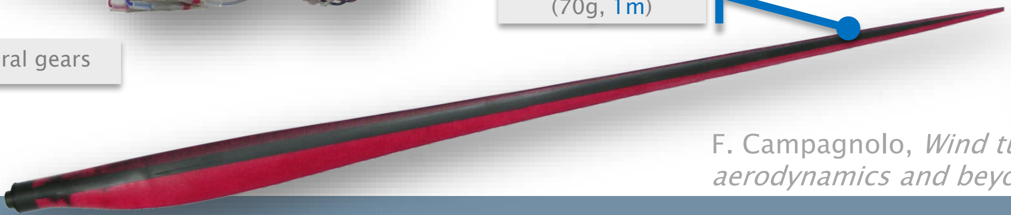


The POLI-Wind Wind Turbine Model V2 – 2010

Bottasso, C.L.; Campagnolo, F.; Croce, A.; Maffenini, L., "Development of a Wind Tunnel Model for Supporting Research on Aero-Servo-Elasticity and Control of Wind Turbines, 2011, ISBN: 9781907132339

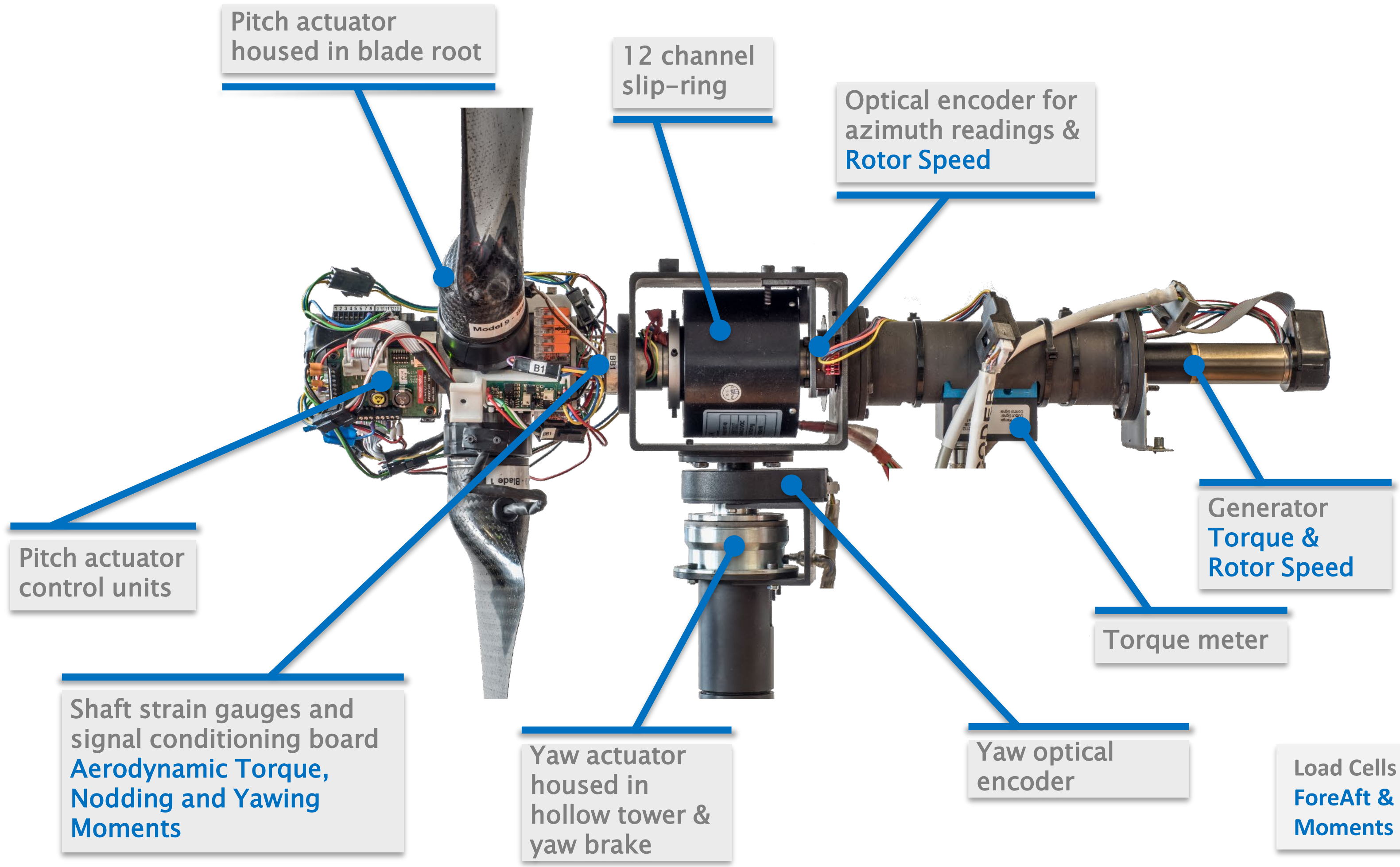


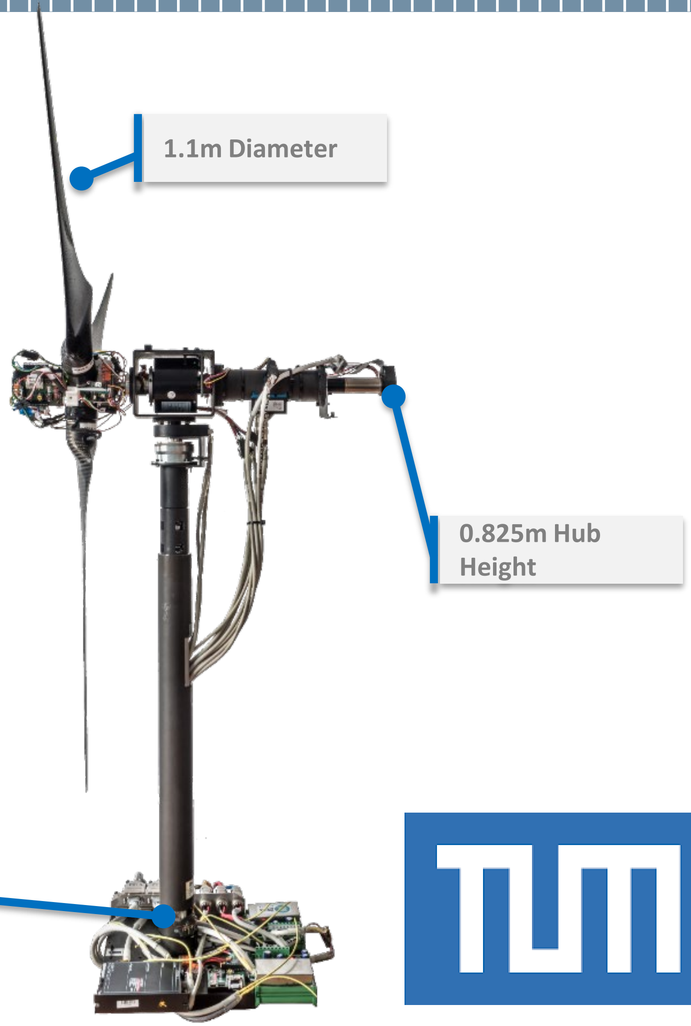




F. Campagnolo, *Wind tunnel testing of scaled wind turbine models: aerodynamics and beyond, PhD Thesis, 2013*

The TUM Wind Turbine Model G1 - 2023

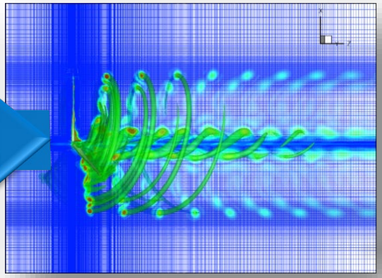


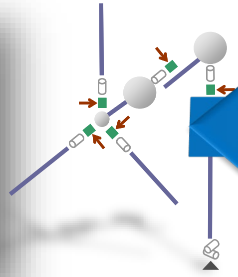


Validation/Calibration of Modeling Tools by Wind Tunnel Testing

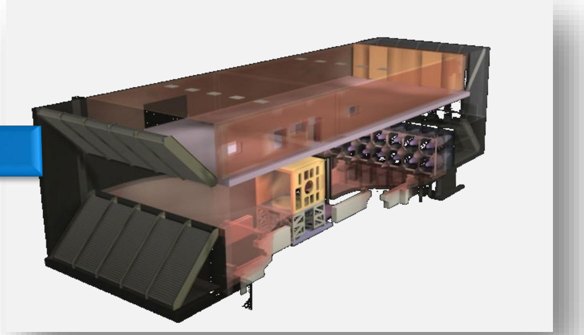
Field (full-scale) testing

Validated mathematical models





Wind tunnel (scaled) testing



Wind tunnel testing:

– Cons:

Usually impossible to exactly match all relevant physics due to scaling

+ Pros:

Better control/knowledge of conditions/errors/disturbances

Much lower costs

Does not replace simulation nor field testing, but works in **synergy** with them

Wind tunnel role is not limited to aerodynamics!

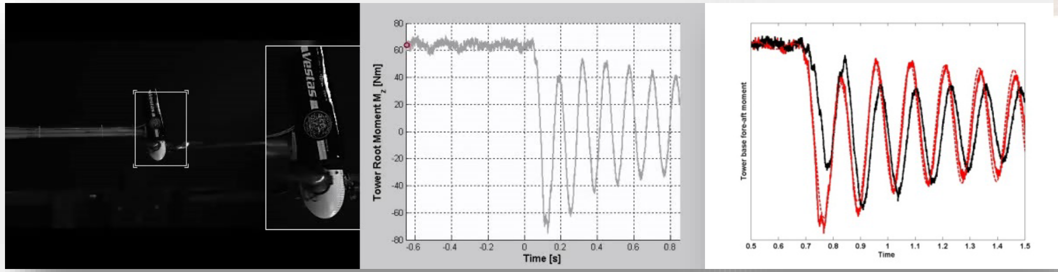
Towards Aerodynamics and Beyond!

Wind Farm Control ▼

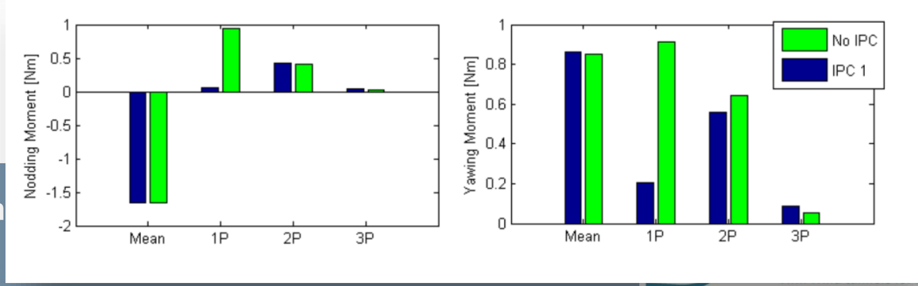
Wake interference conditions ▼

Bend-twist coupling ▼

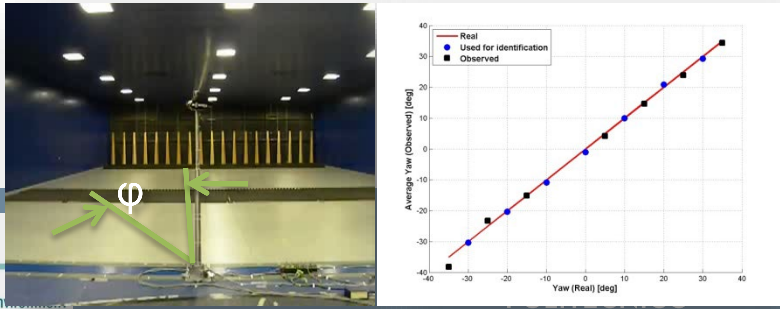
Emergency shutdown▼



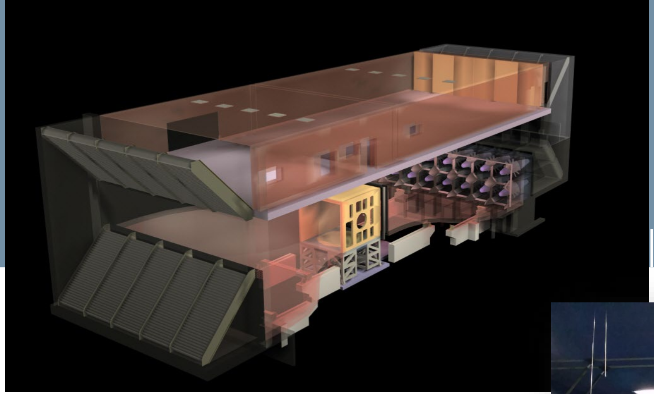
Load alleviation by IPC ▼



Wind direction observer ▼



Outline



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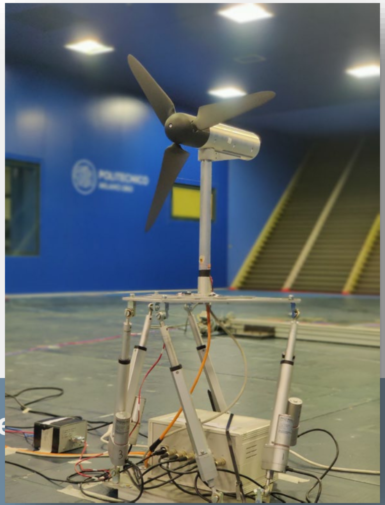


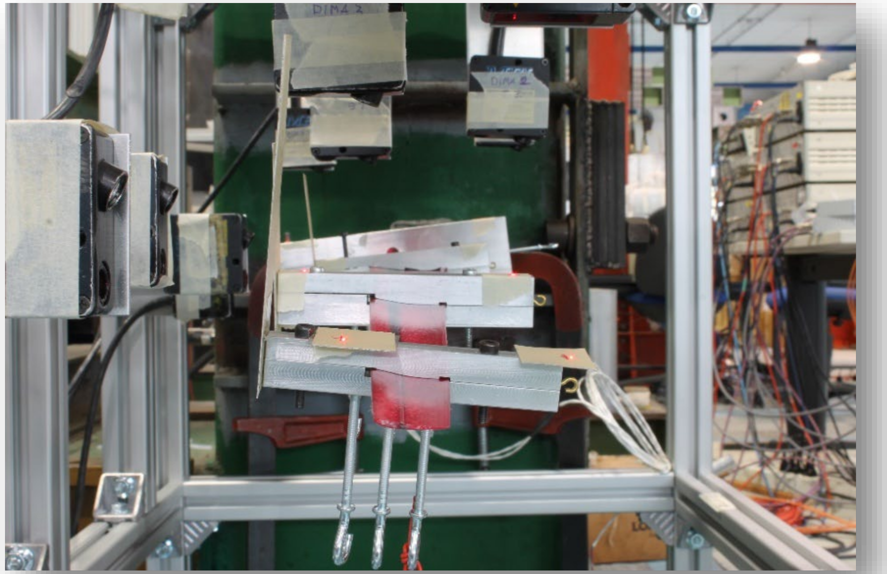
Passive & Passive/Active Load Alleviation in Waked Conditions

Passive & Passive/Active Load Alleviation in Waked Conditions

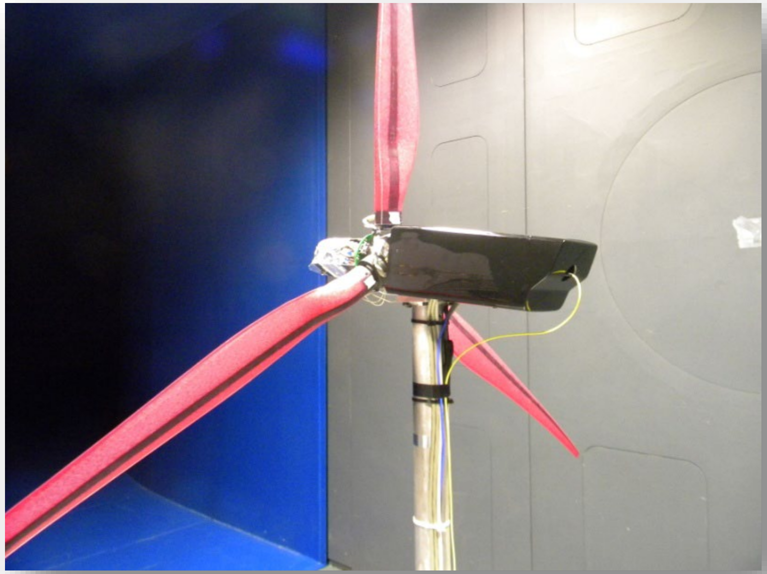
Testing of scaled blade with built-in structural coupling

Fibers rotated in the carbon spar ▼

Structural characterization ▼



Aerodynamic characterization ▼



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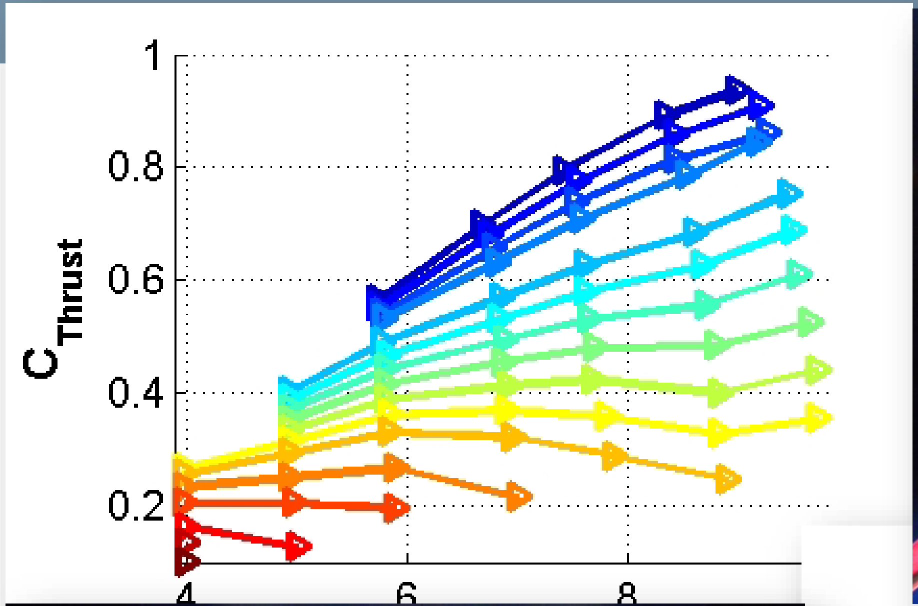
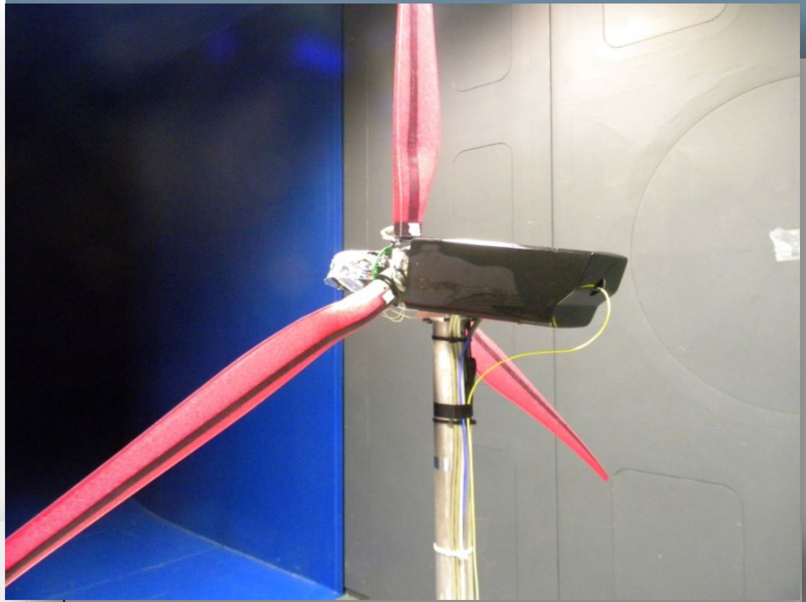
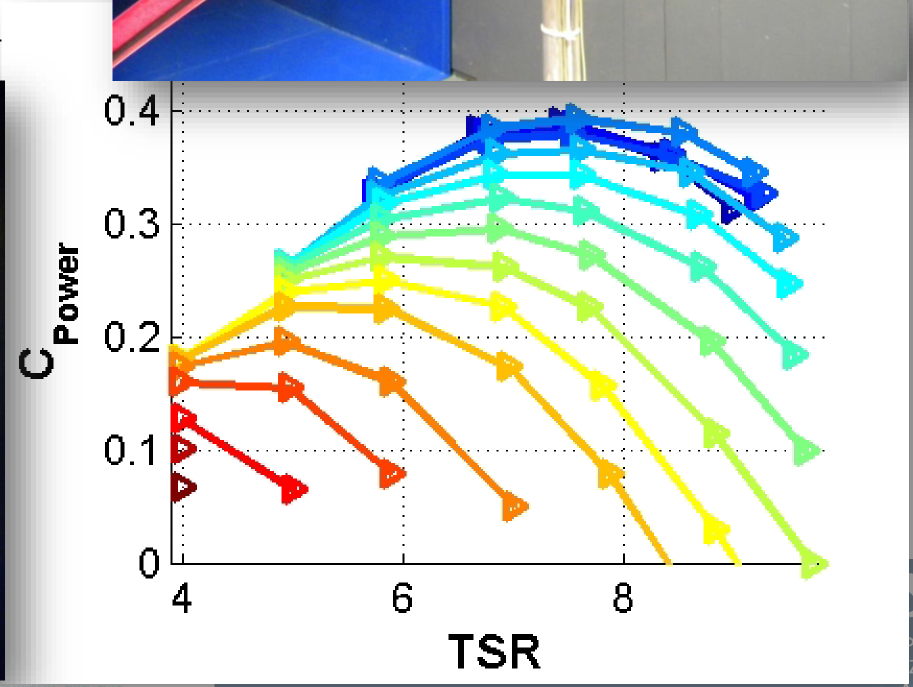
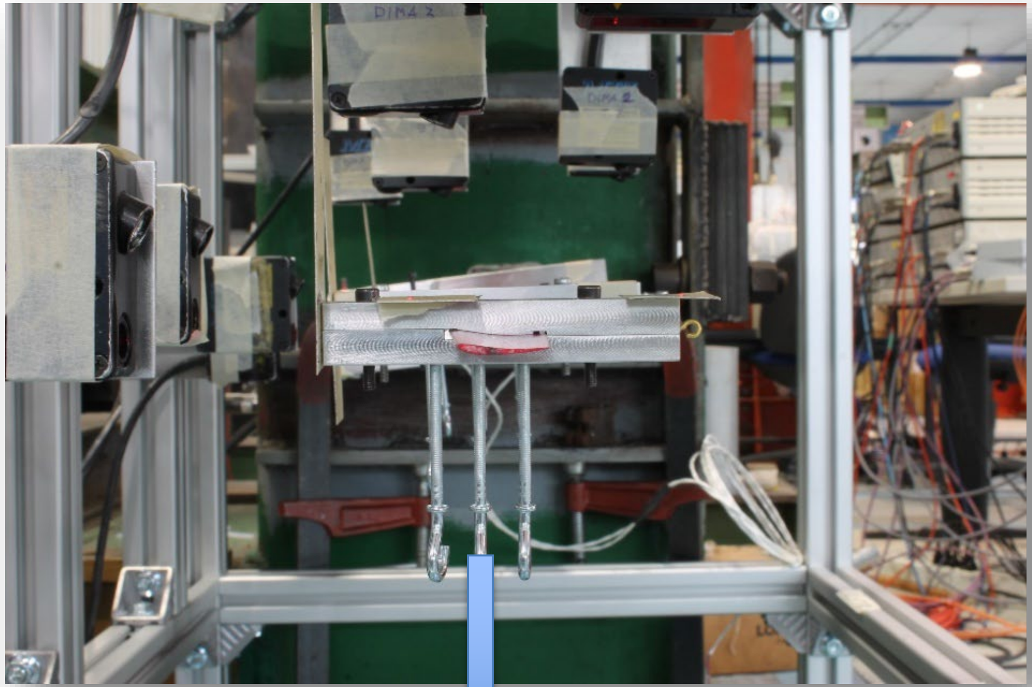
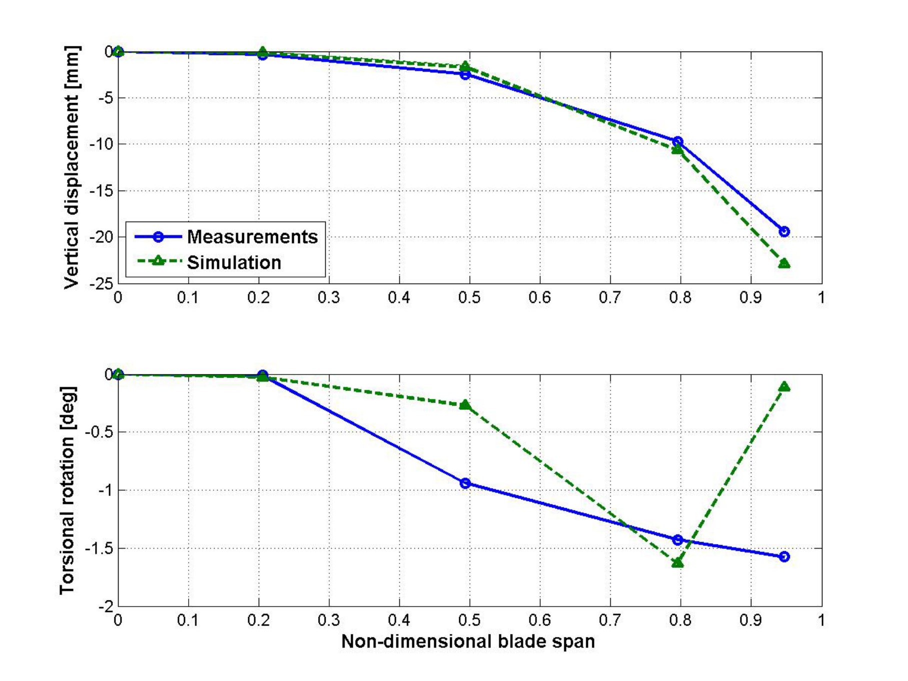






Design of the Aero-elastically Scaled BTC Composite Blade

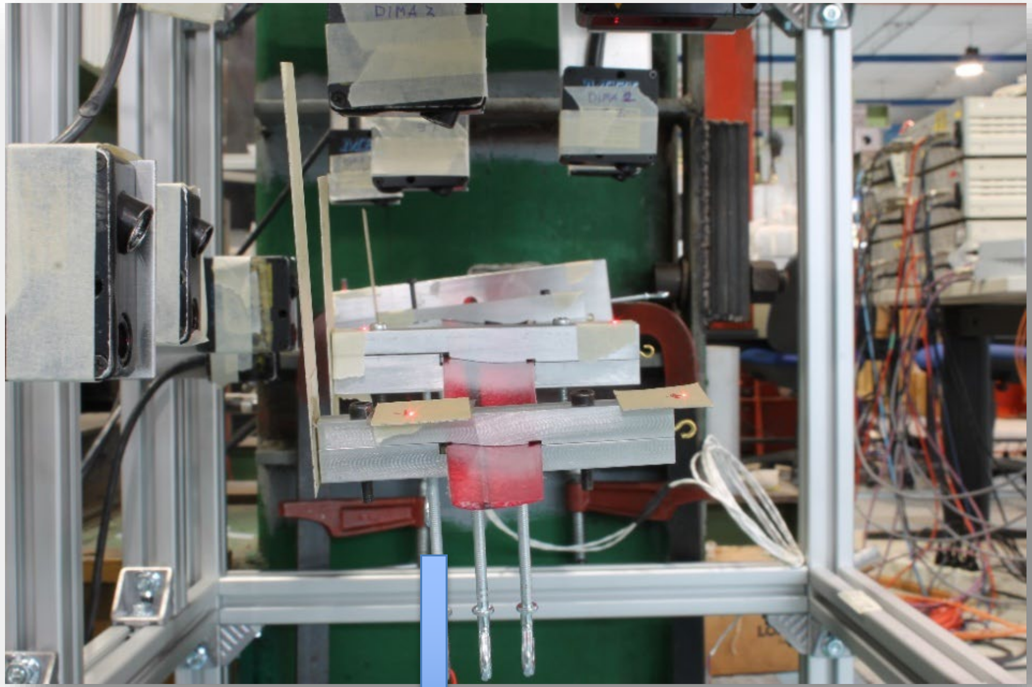




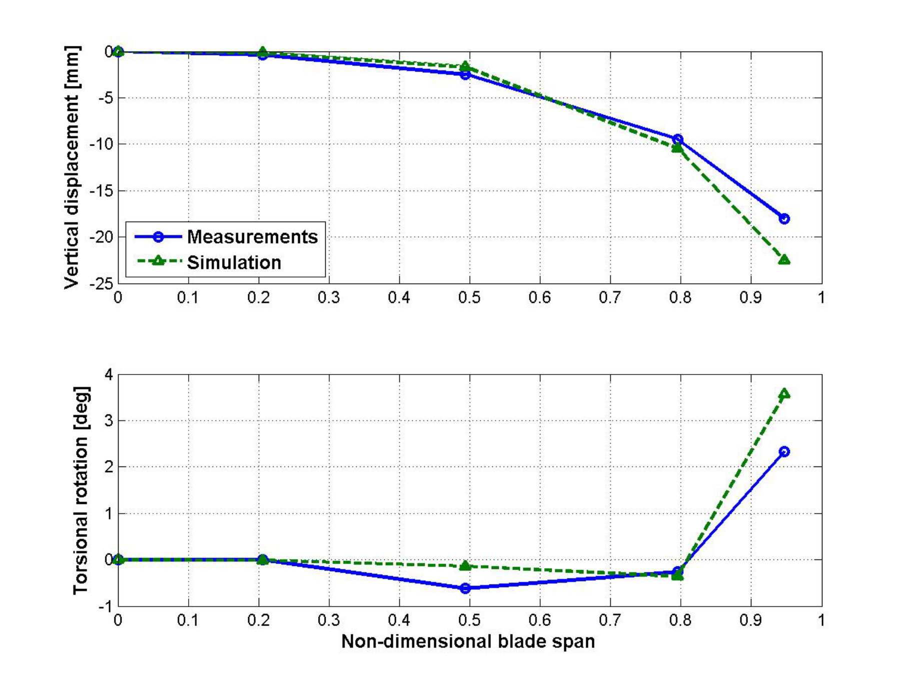
Blade axis pull

Twist to feather

Design of the Aero-elastically Scaled BTC Composite Blade



Leading edge pull



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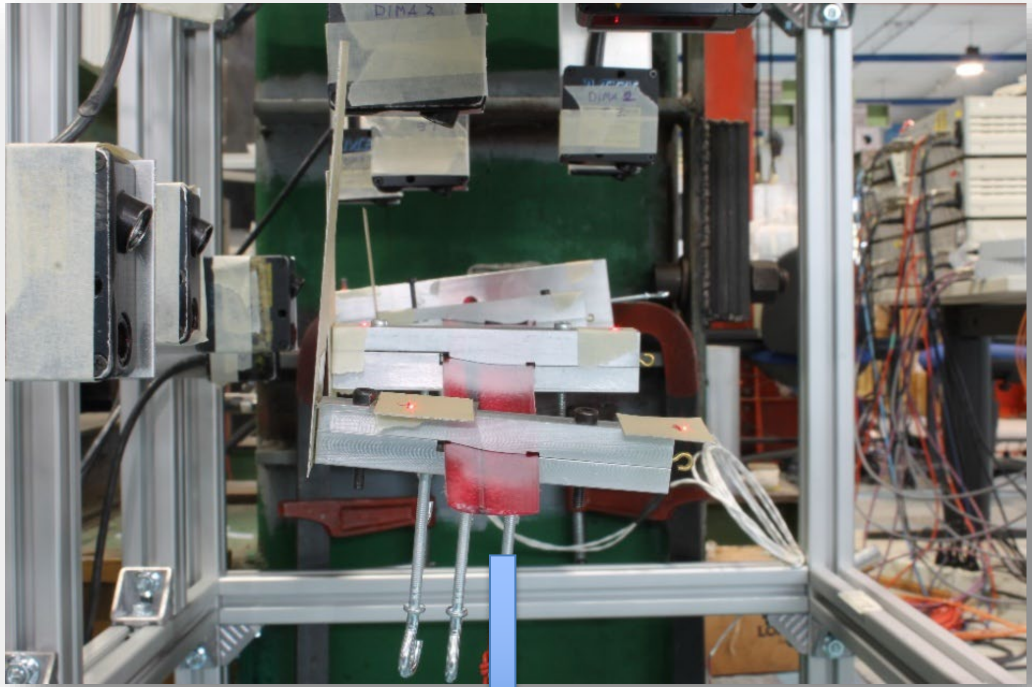
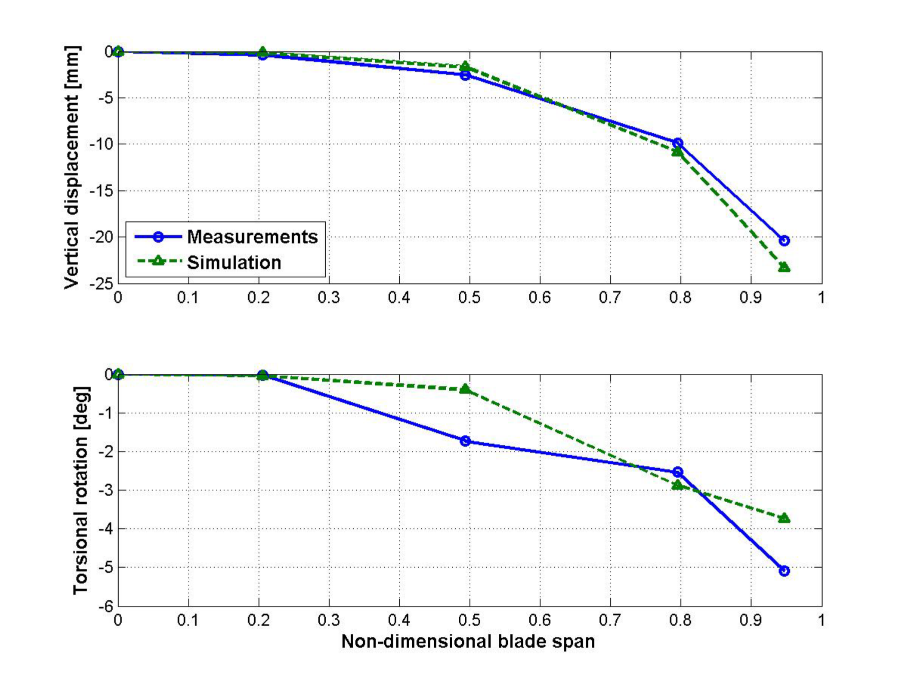


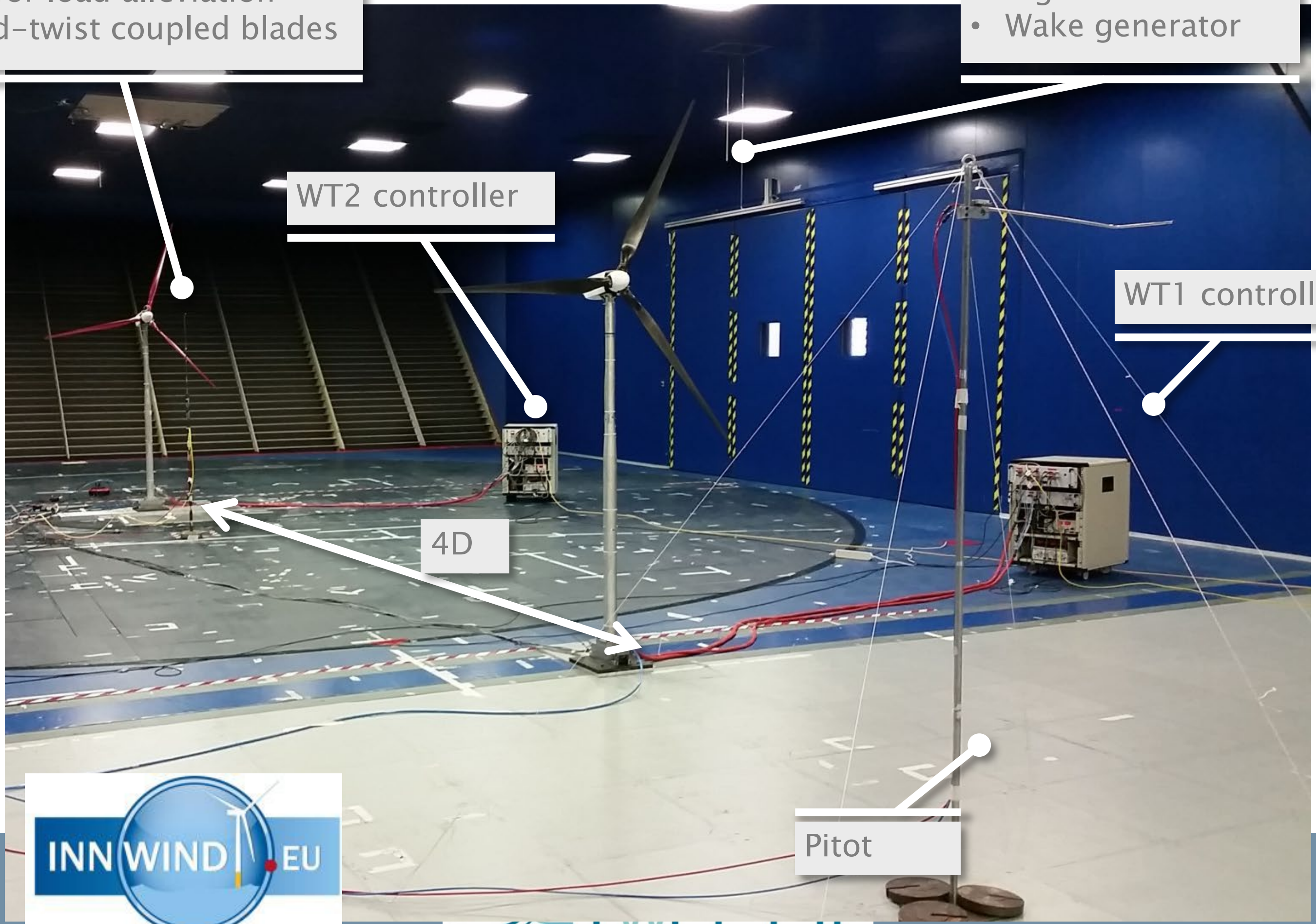


Trailing edge pull

Twist to feather

Passive & Passive/Active Load Alleviation in Waked Conditions

Configuration: 2 machines in partial or full wake interaction



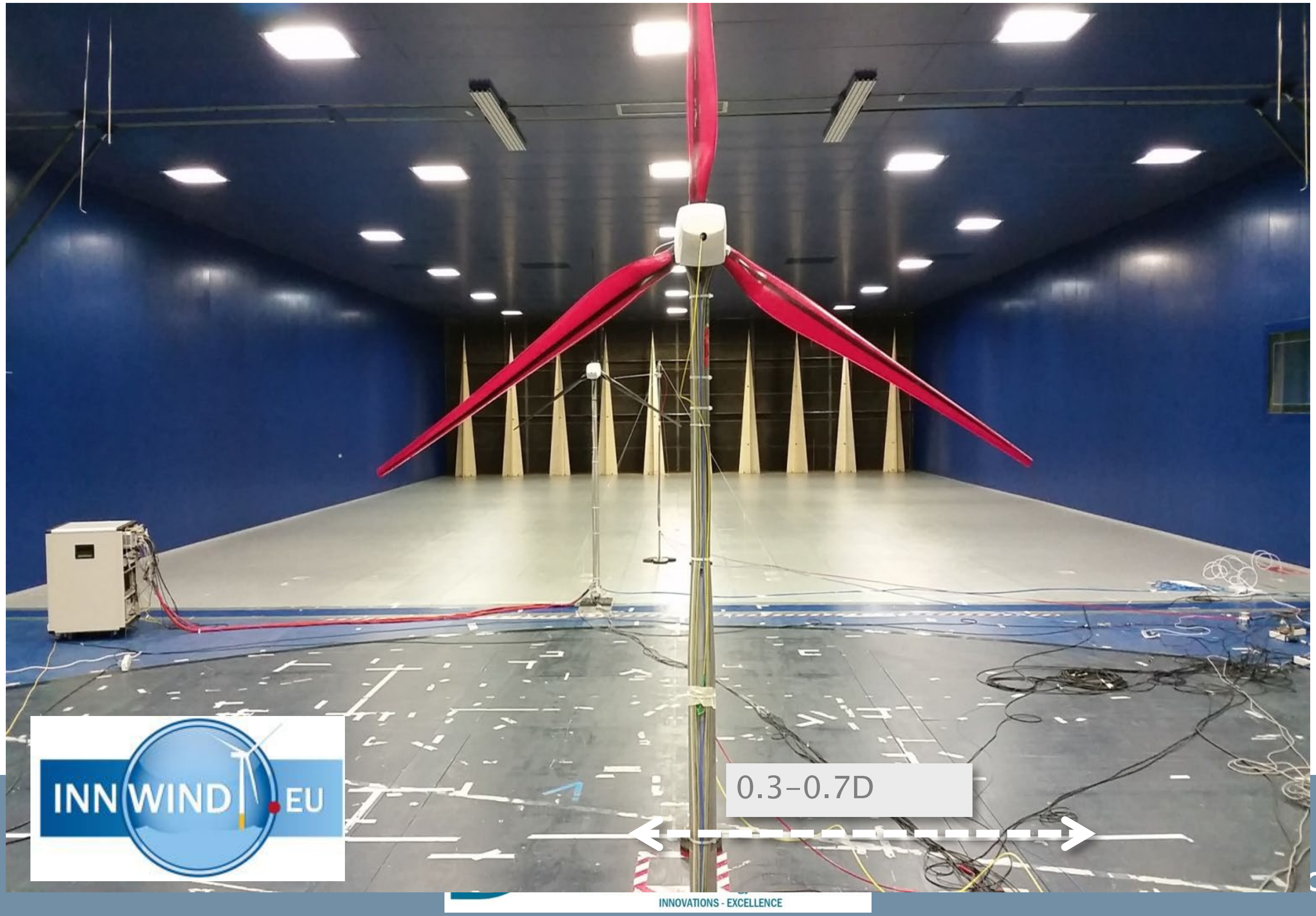
Passive & Passive/Active Load Alleviation in Waked Conditions

Partial waked conditions:

- Offset: 0.30-0.45-0.60-0.75 D
- Distance: 4D

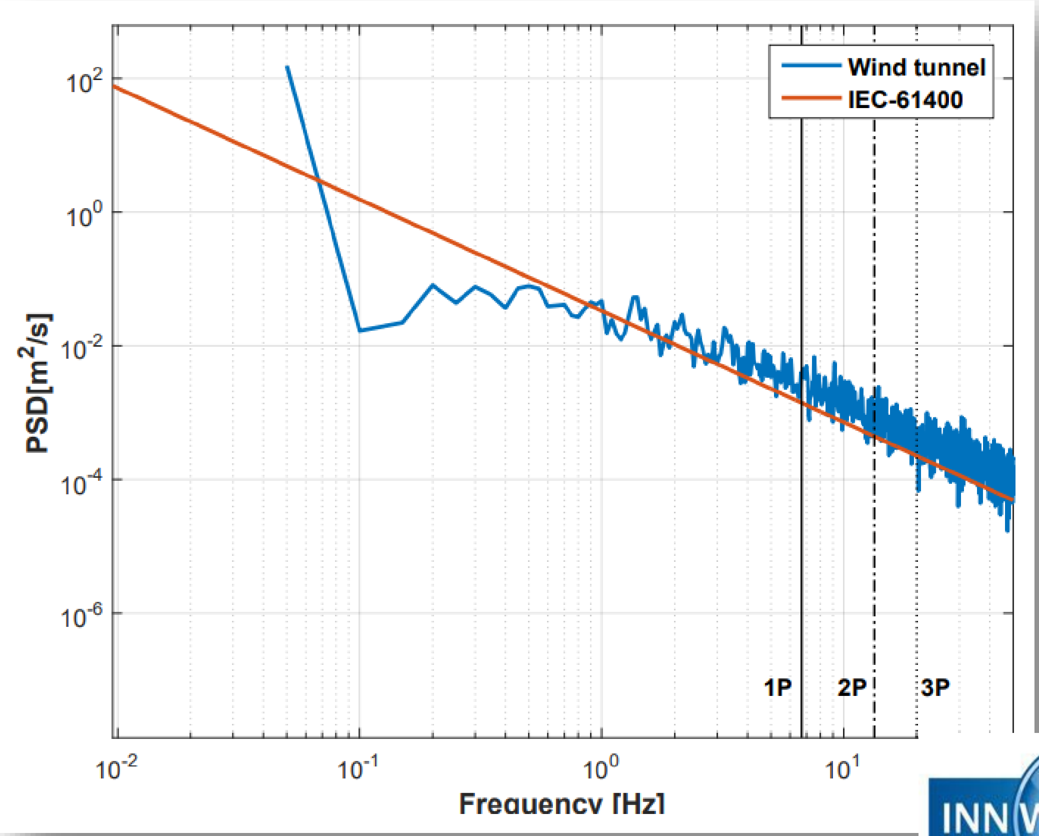
Wind conditions:

- 5.0m/s, pitch = -1.75deg (region II)
- 6.5m/s, pitch = 6deg (region III)

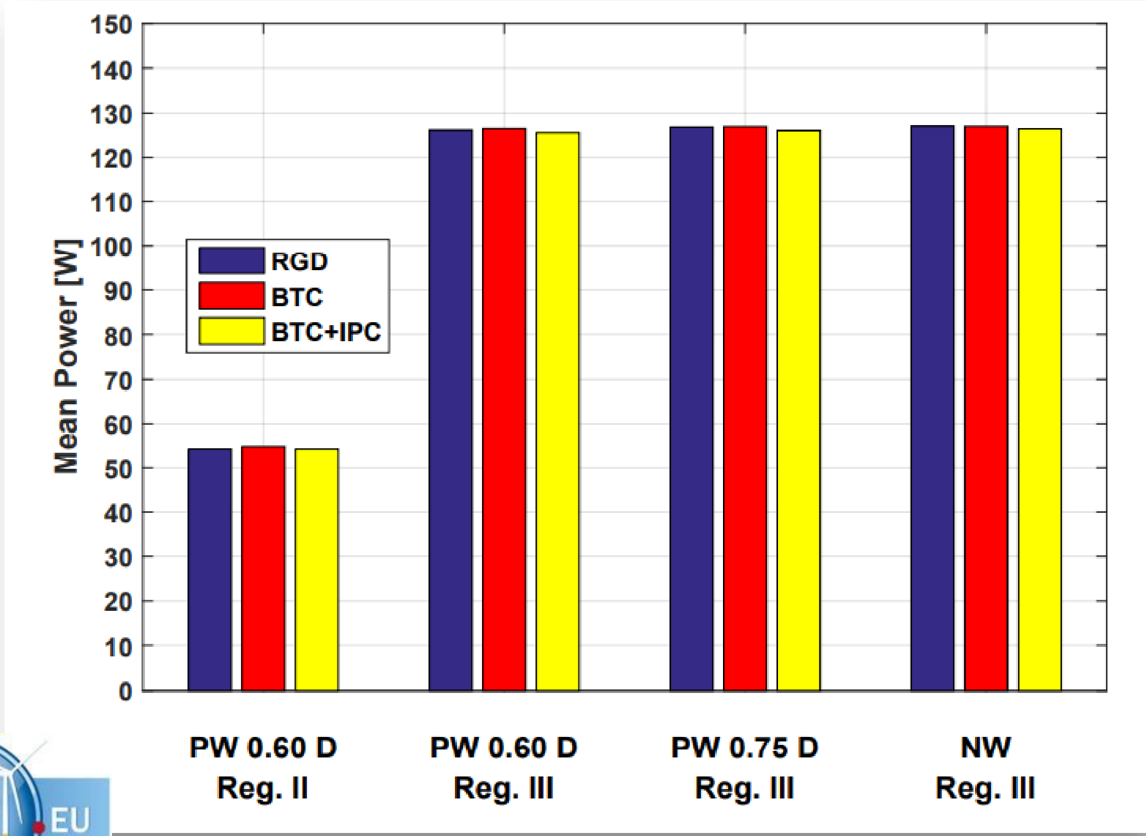


Passive & Passive/Active Load Alleviation in Waked Conditions

Hub height wind speed PSD (6 m/s) VS IEC61400



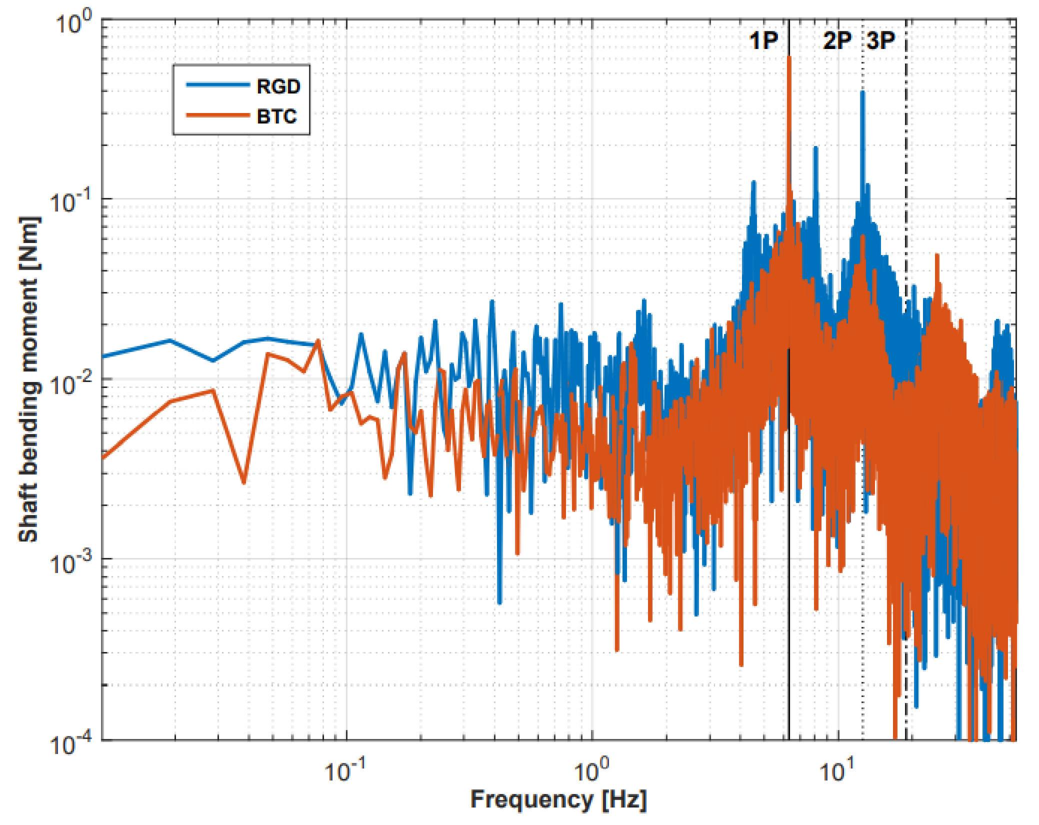
Downwind WT model mean power



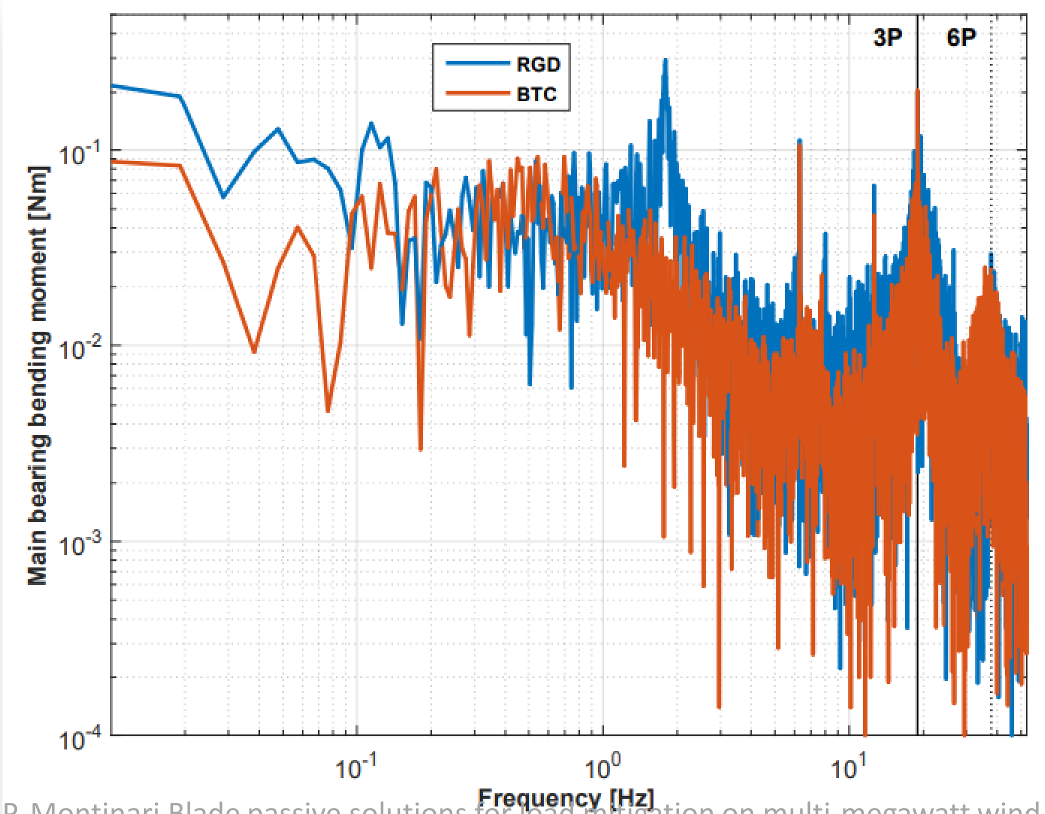
Passive & Passive/Active Load Alleviation in Waked Conditions

No wake – region III

- Rotating system: shaft bending moment



- Fixed system: main bearing bending moment

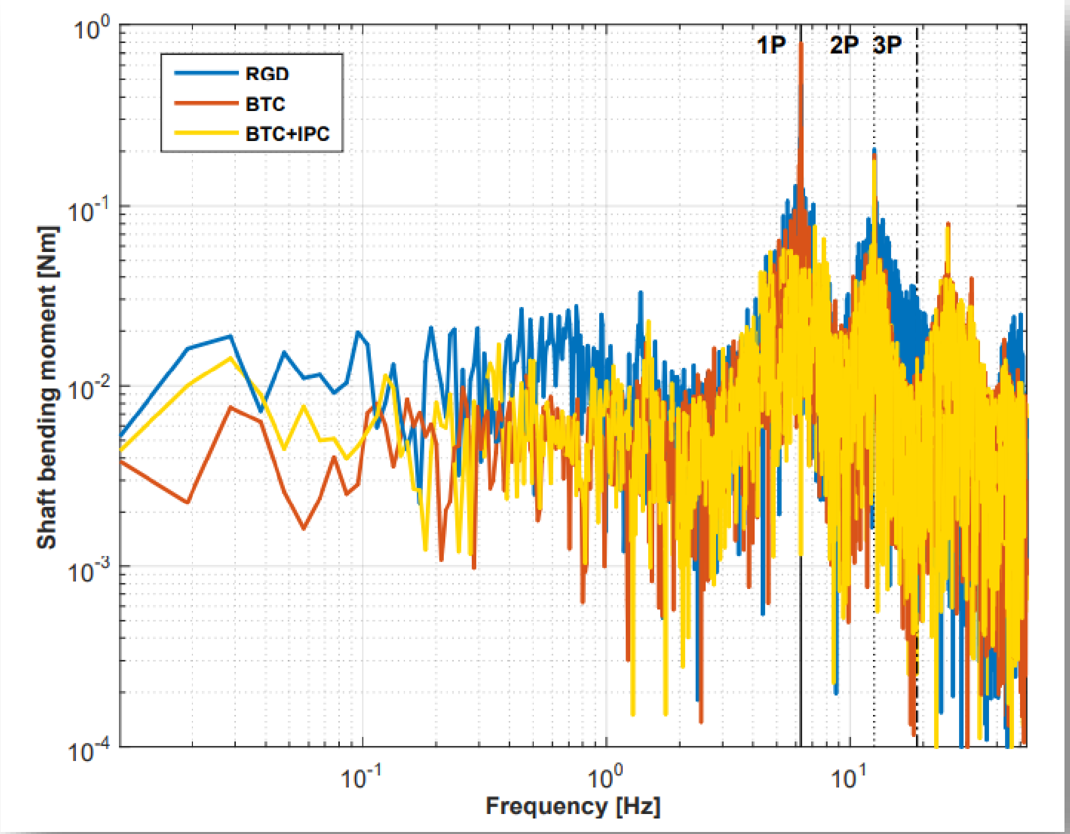


P. Montinari,Blade passive solutions for load mitigation on multi-megawatt wind turbine

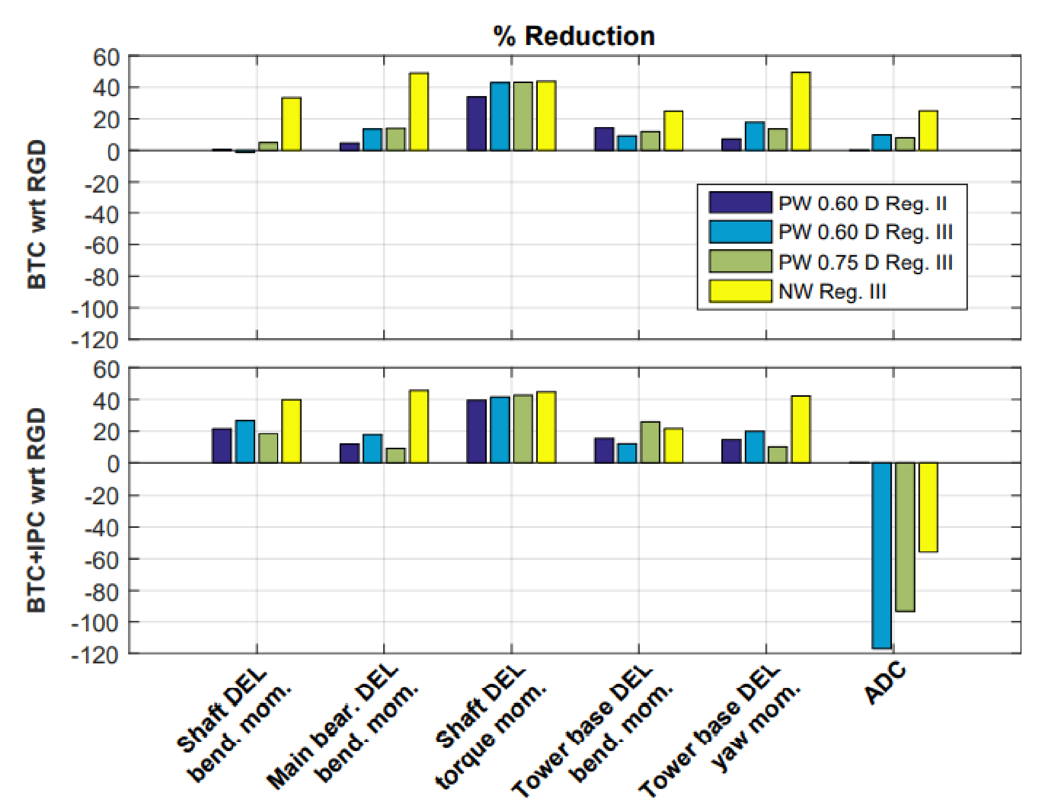
Passive & Passive/Active Load Alleviation in Waked Conditions

Partial wake 0.6D – region III

- Rotating system: shaft bending moment



- Rotating system: shaft bending moment

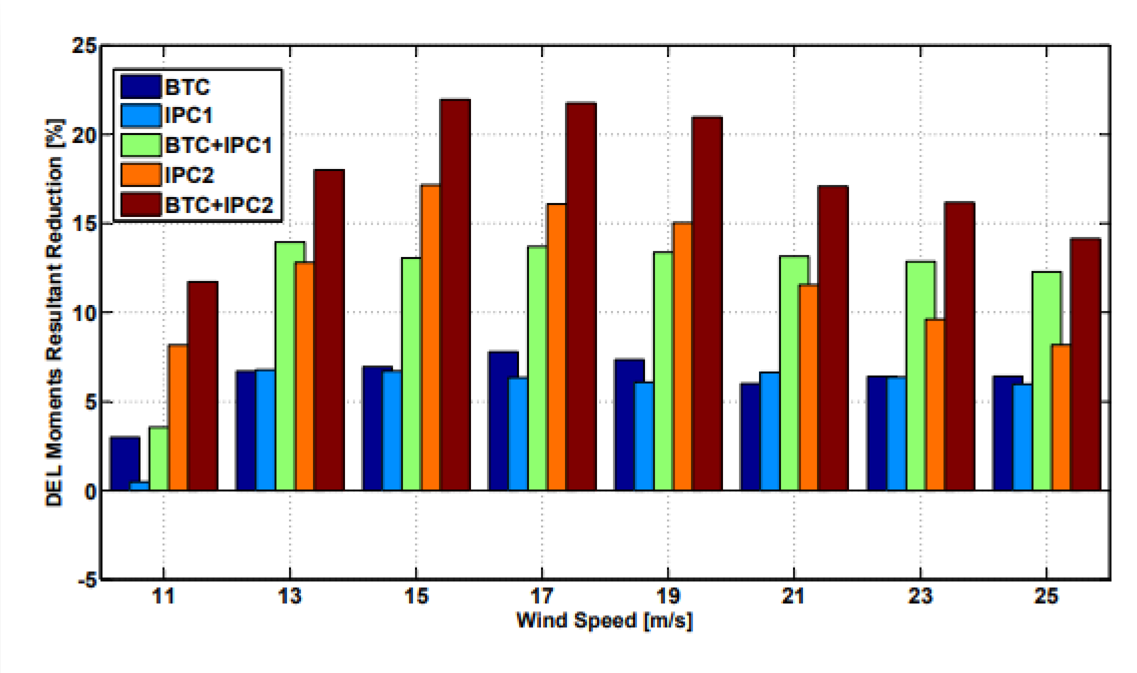


P. Montinari,Blade passive solutions for load mitigation on multi-megawatt wind turbine

Passive & Passive/Active Load Alleviation in Waked Conditions

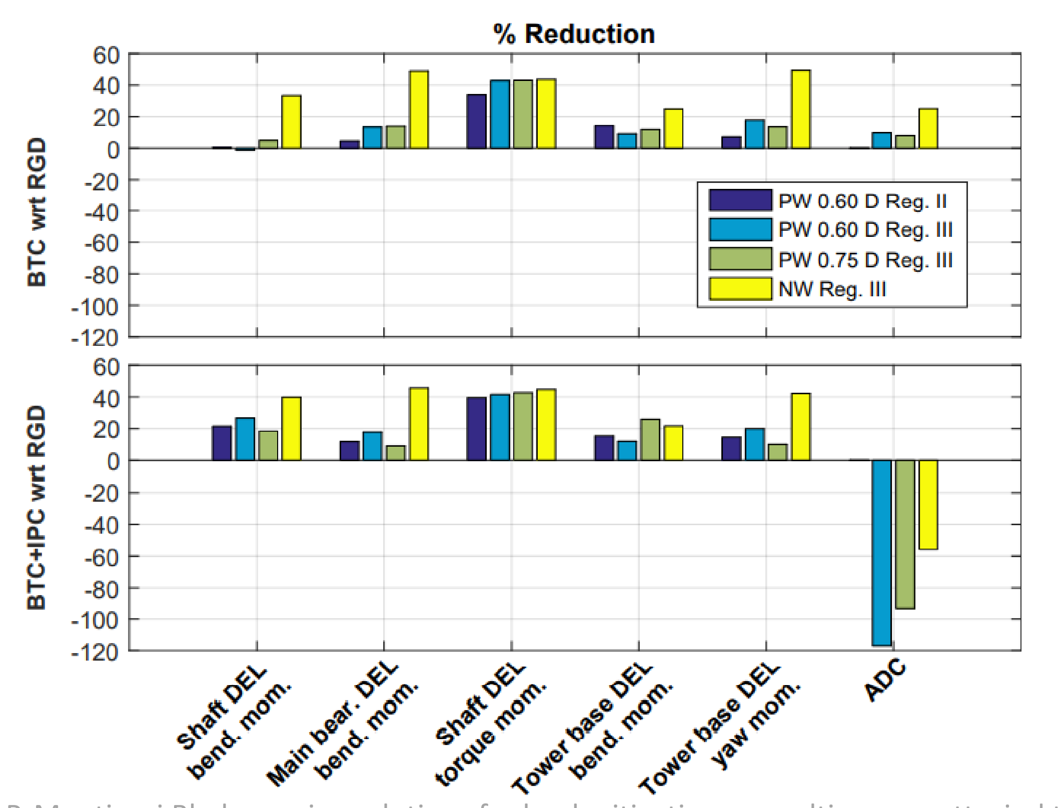
Comparison with aeroelastic simulation of a MW wind turbine

- Rotating system: shaft bending moment



C.L. Bottasso, F. Campagnolo, A. Croce, C. Tibaldi, *Optimization-based study of bend–twist coupled rotor blades for passive and integrated passive/active load alleviation,* https://doi.org/10.1002/we.1543

- Rotating system: shaft bending moment



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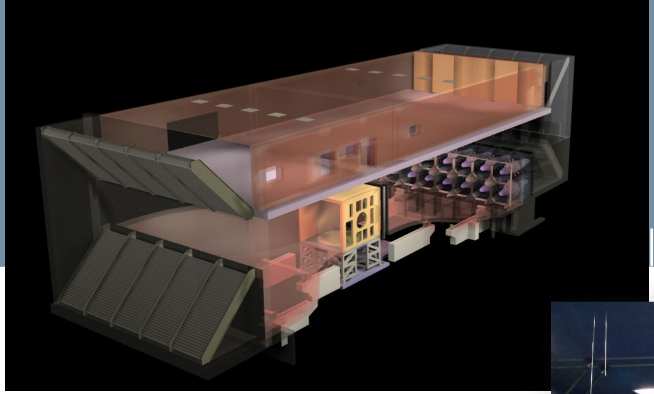

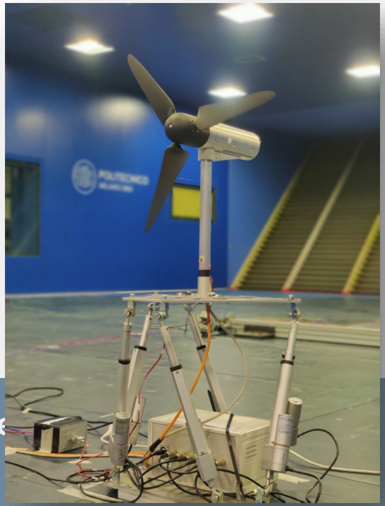

Application: Wake Measurements

Configuration: Mini Scaled Wind Farm from 2 to 6 machines in partial or full wake interaction

CL-Windcon

CL-WINDCON 'Closed Loop Wind Farm Control' (H2020-LCE-2016-2017, 2016-2019).

G1 scaled wind turbines and wind farm controller provided by Technische Universität München

Application: Wake Measurements

Configuration: Mini Scaled Wind Farm from 2 to 6 machines in partial or full wake interaction

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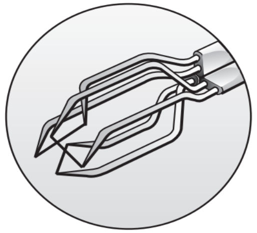
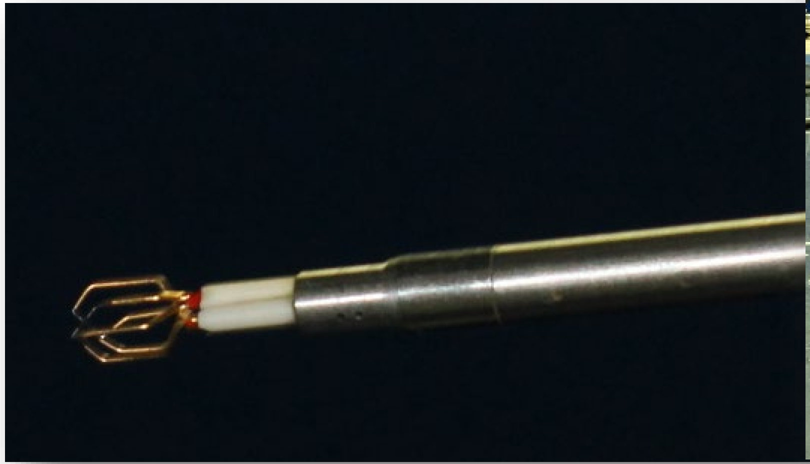
G1 scaled wind turbines and wind farm controller provided by Technische Universität München

Application: Wake Measurements

- Flow measurements were conducted using two hot-wire anemometers installed on a 2D traversing system.
- Working area (depending on the traverse system) is 3-4m x 3m
- 3D flow components are measured.





CL-Windcon

DANTEC DYNAMICS

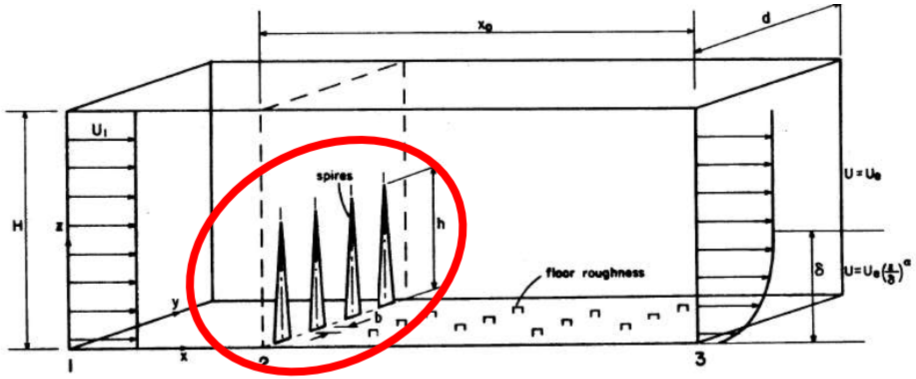
Facility Overview

Several neutrally stable ABLs can be simulated within the wind tunnel.

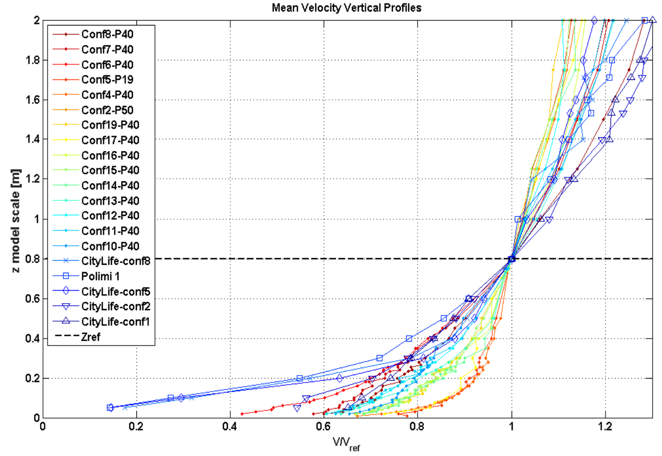
The catalogue regards mainly streamwise velocity and turbulence intensity profile.

For the wind farm tests two wind profiles are used:

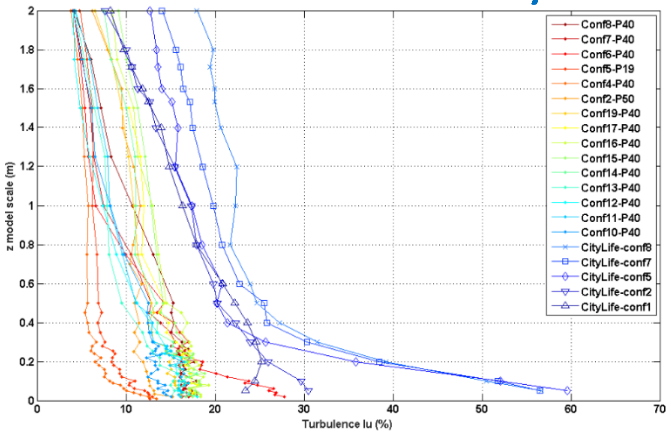
- Onhore: α = 0.2
- Offshore: α = 0.079



Mean wind speed



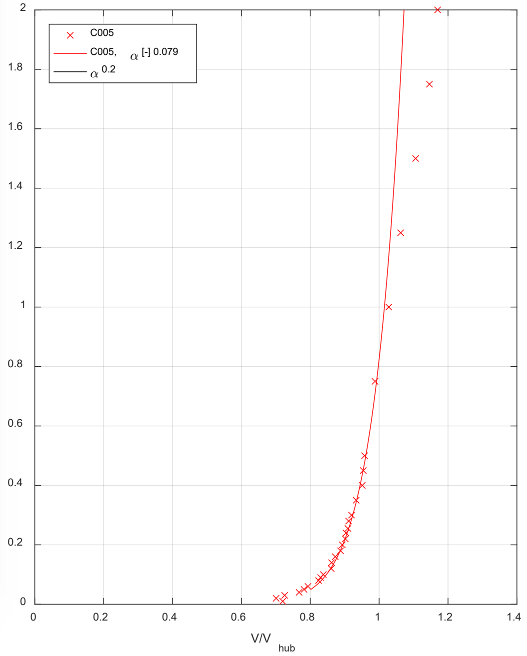
Turbulence Intensity



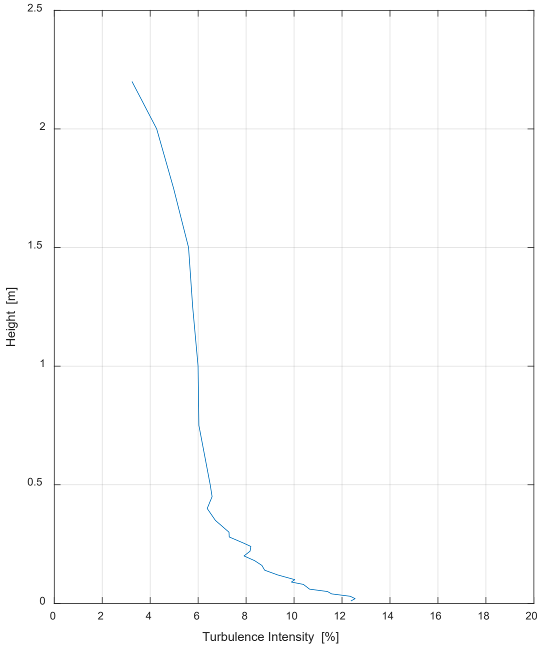
CL-Windcon

Off-shore wind condition

Mean wind speed



Turbulence Intensity



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

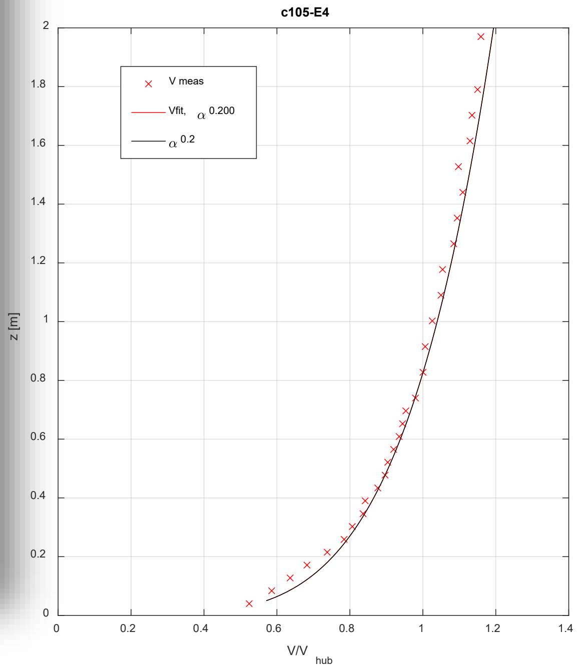
POLITECNICO MILANO 1863

DIPARTIMENTO DI SCIENZE E TECNOLOGIE AEROSPAZIALI

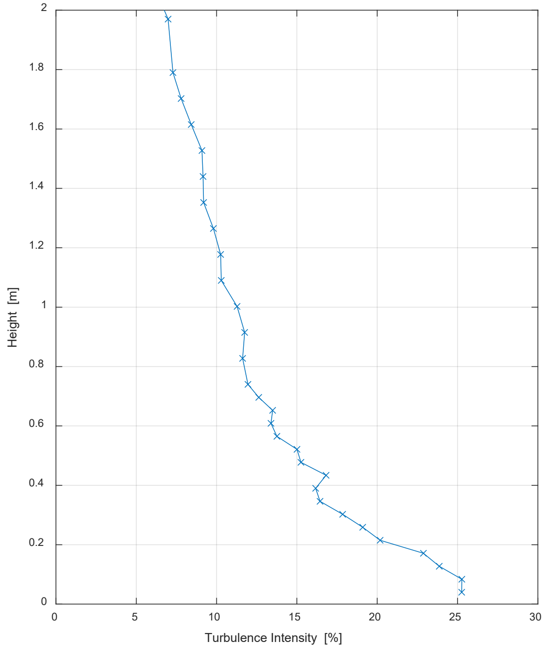
POLI-Wind

On-shore wind condition

Mean wind speed

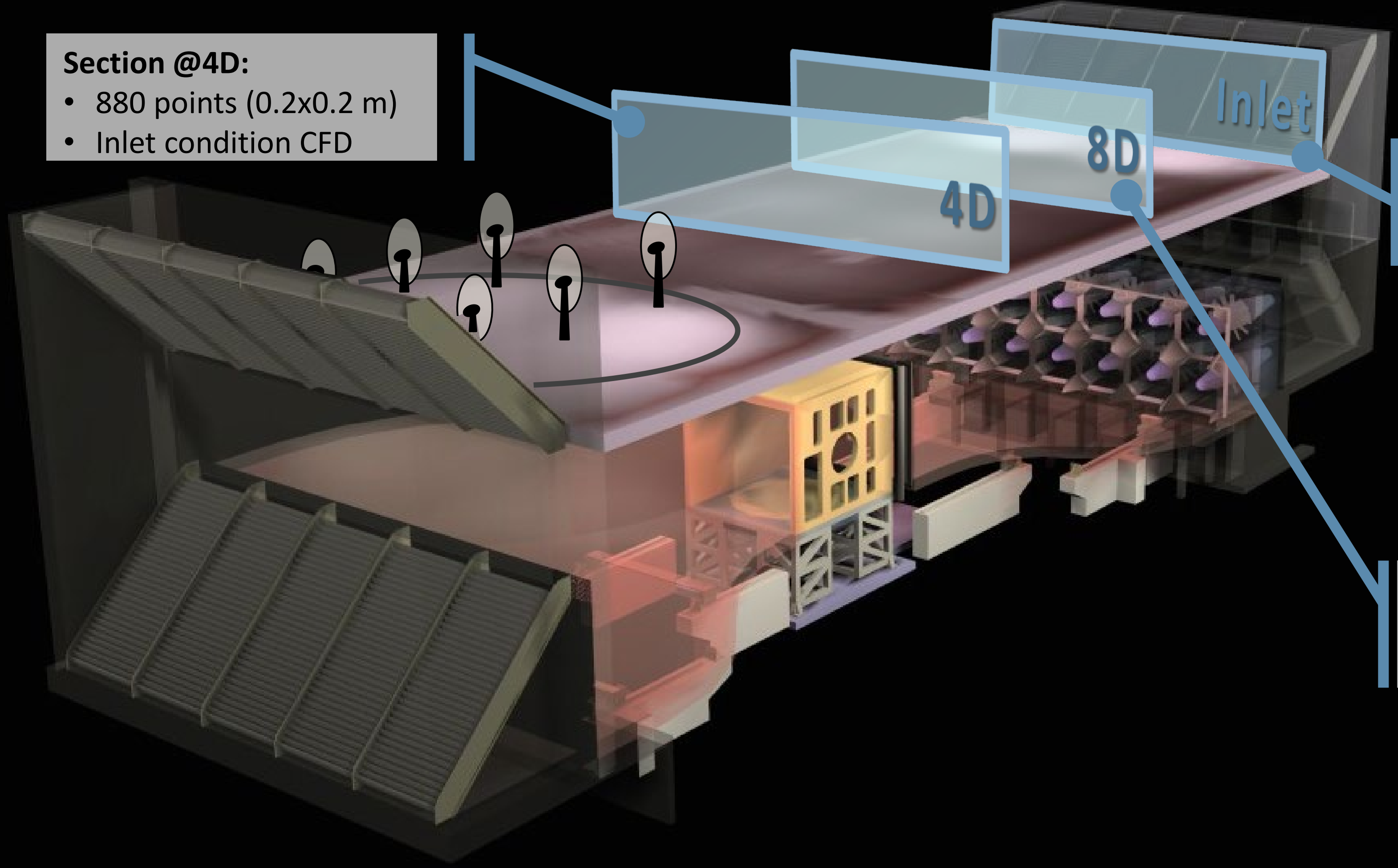


Turbulence Intensity



CL-Windcon

Flow measurement



Section @4D:
- 880 points (0.2x0.2 m)
- Inlet condition CFD

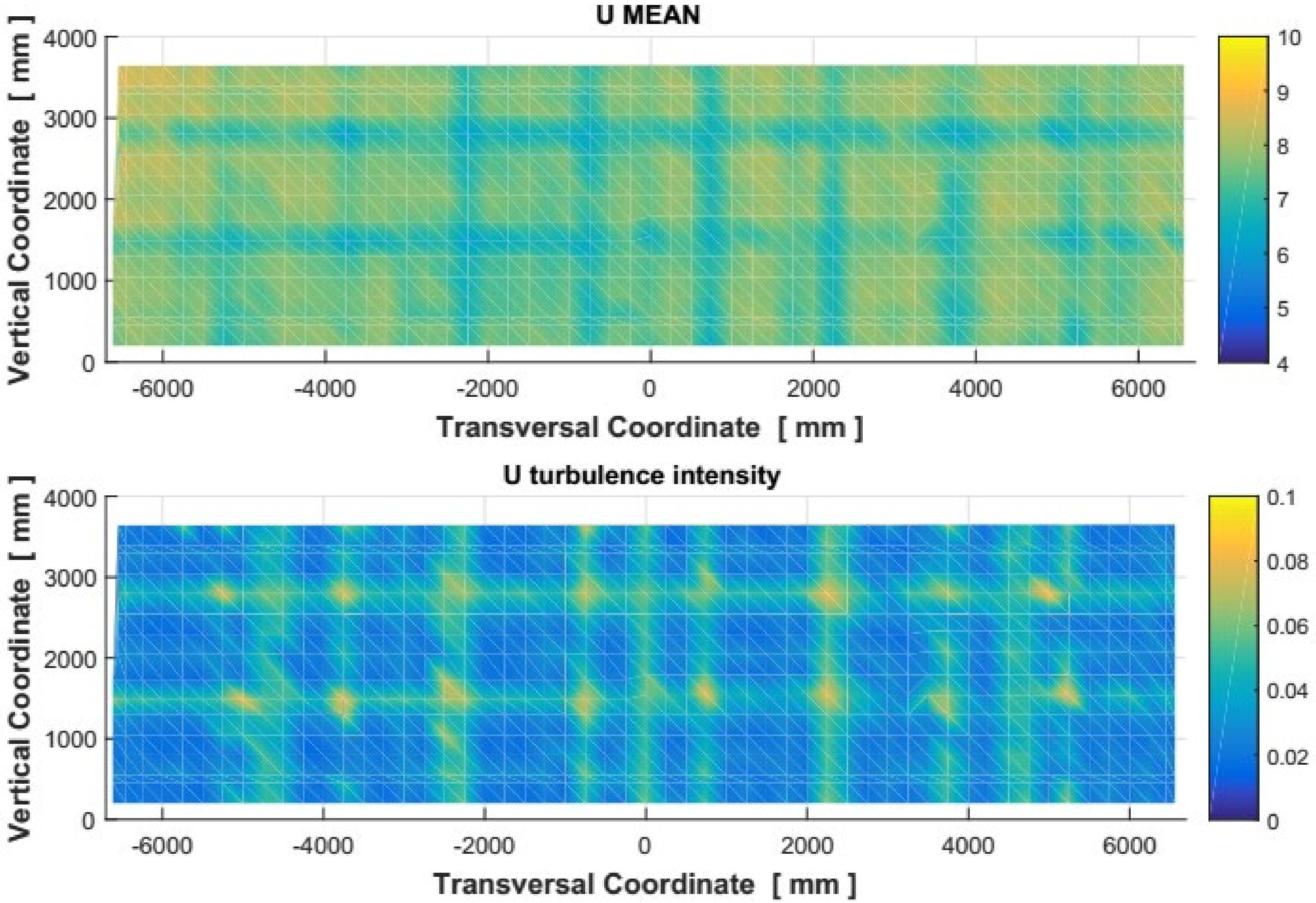
Inlet section:
- 880 points (0.2x0.2 m)
- w/o spires

Section @8D:
- 880 points (0.2x0.2 m)
- ABL development

Flow measurement

INLET PLANE

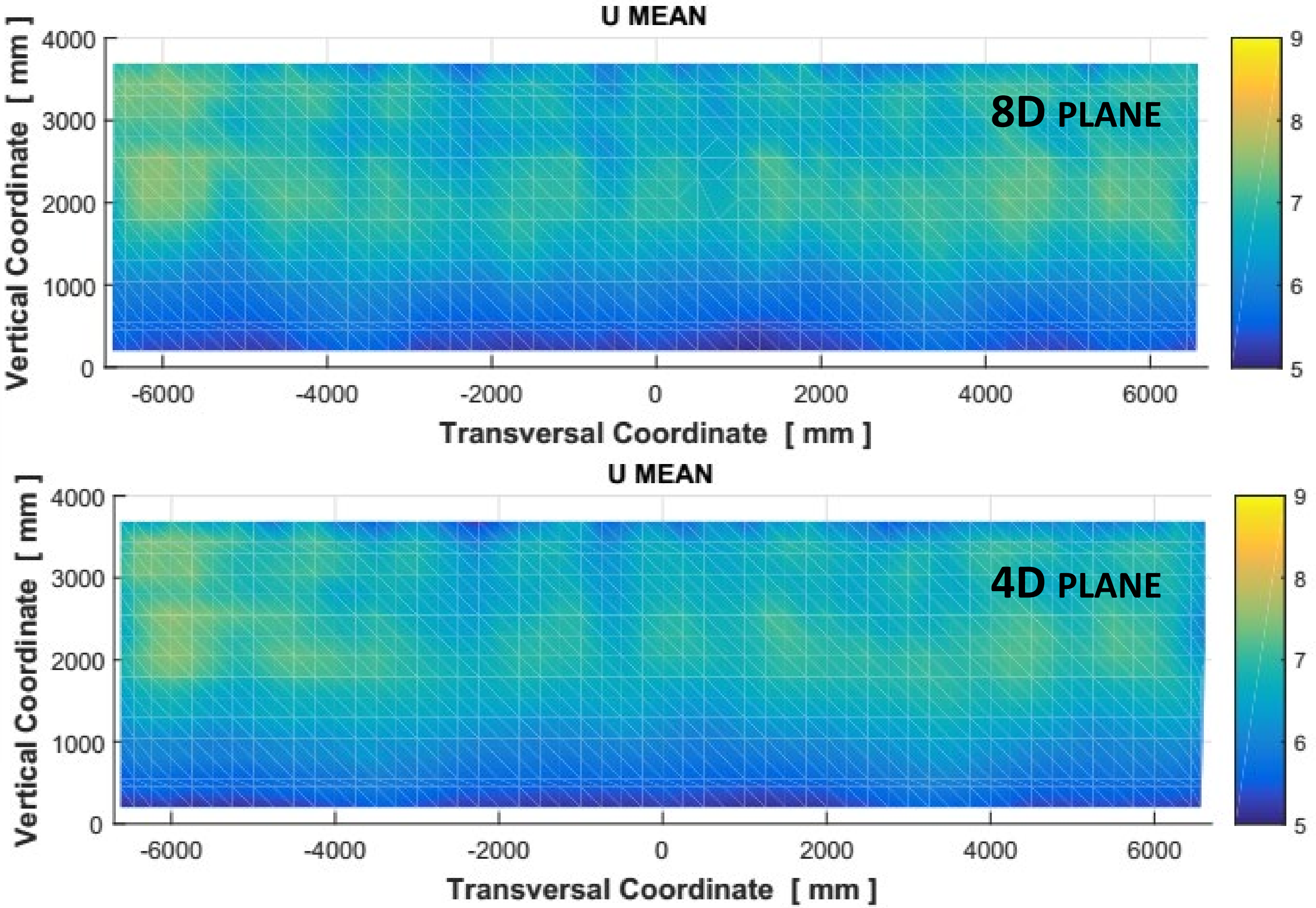
Flow measurement at the inlet shows uniform velocity and turbulence intensity. Wind tunnel structural elements effects are visible on the measured flow characteristics.



CL-Windcon

Flow measurement

OFF-SHORE CASE



CL-Windcon

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

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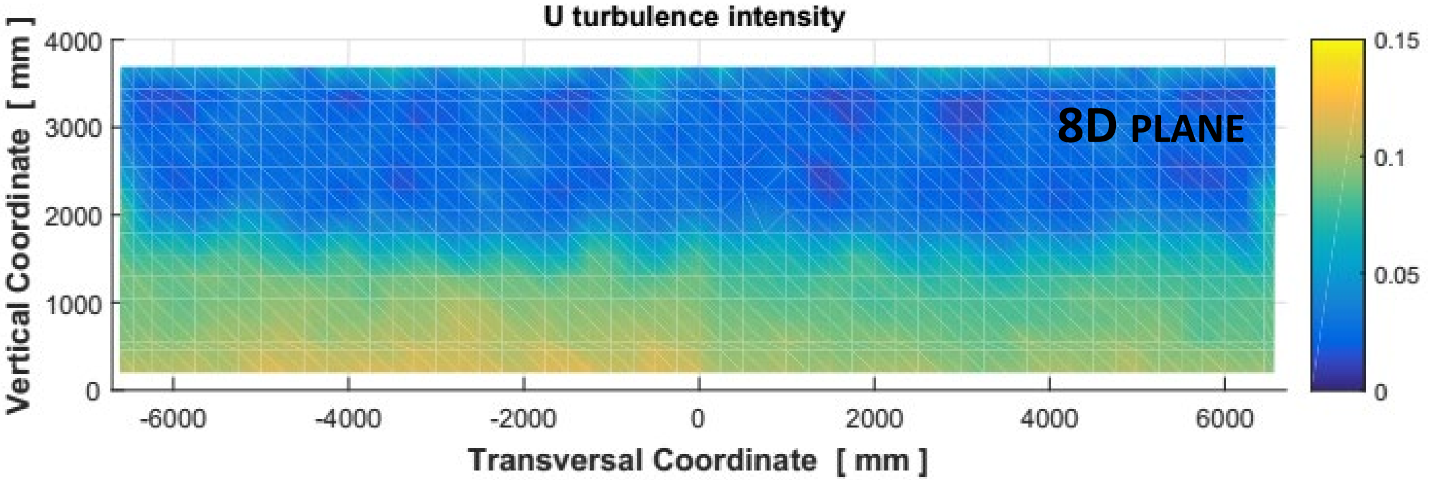
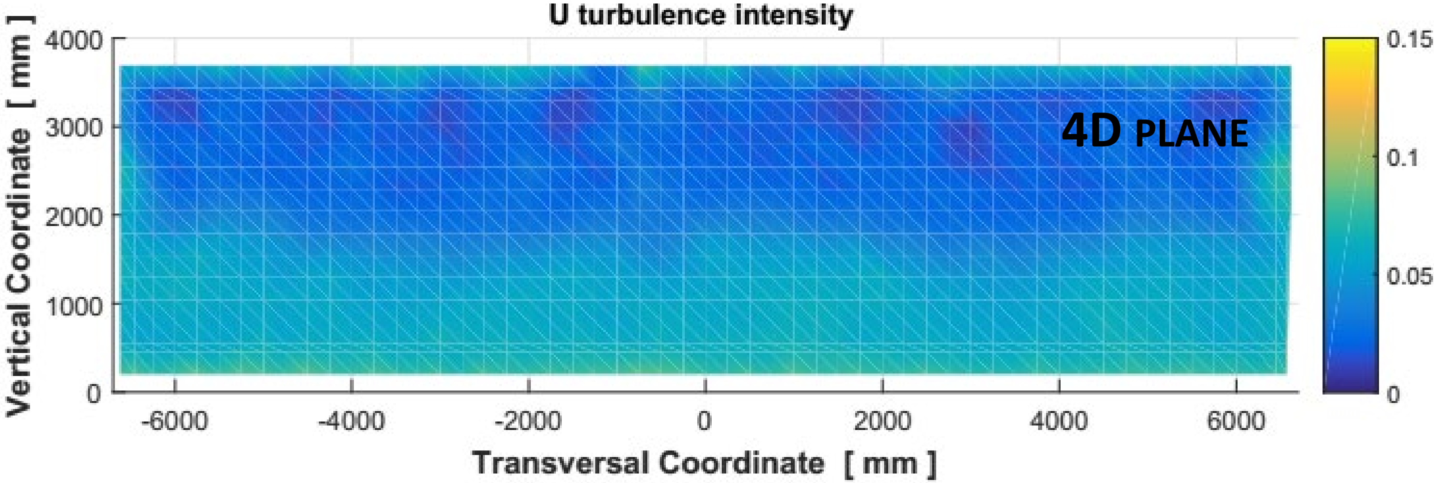
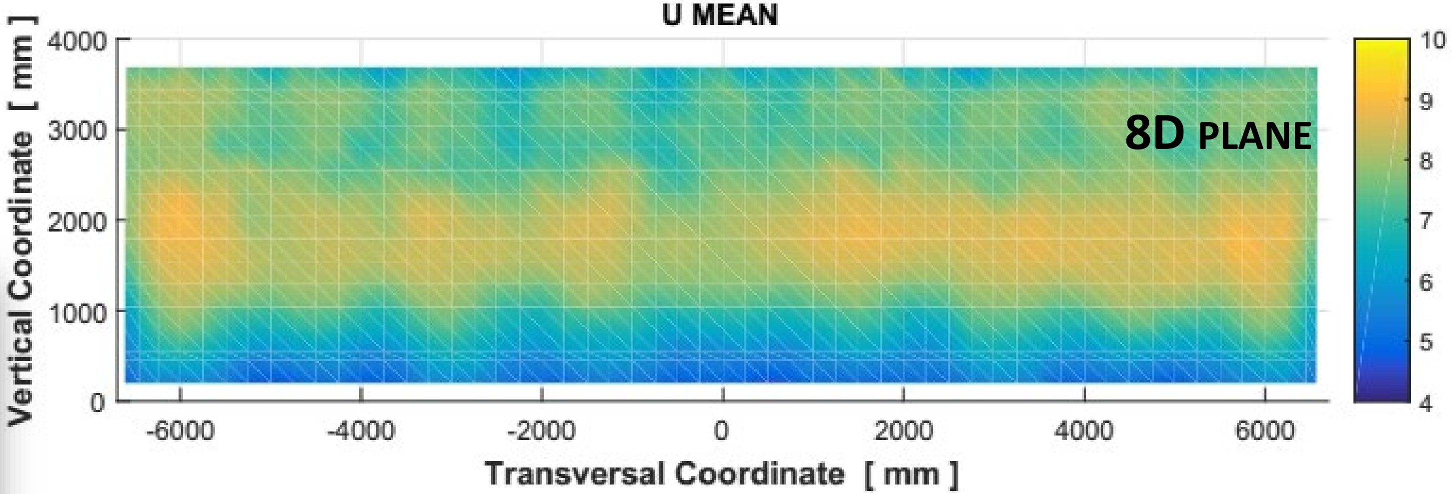


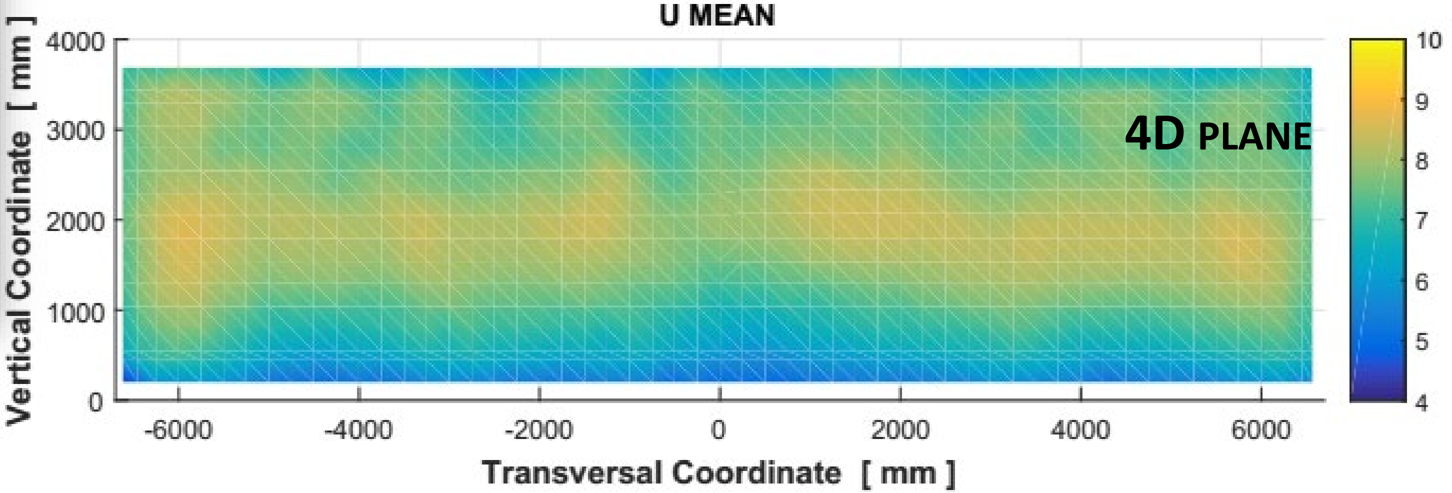


CL-Windcon

Flow measurement

ON-SHORE CASE

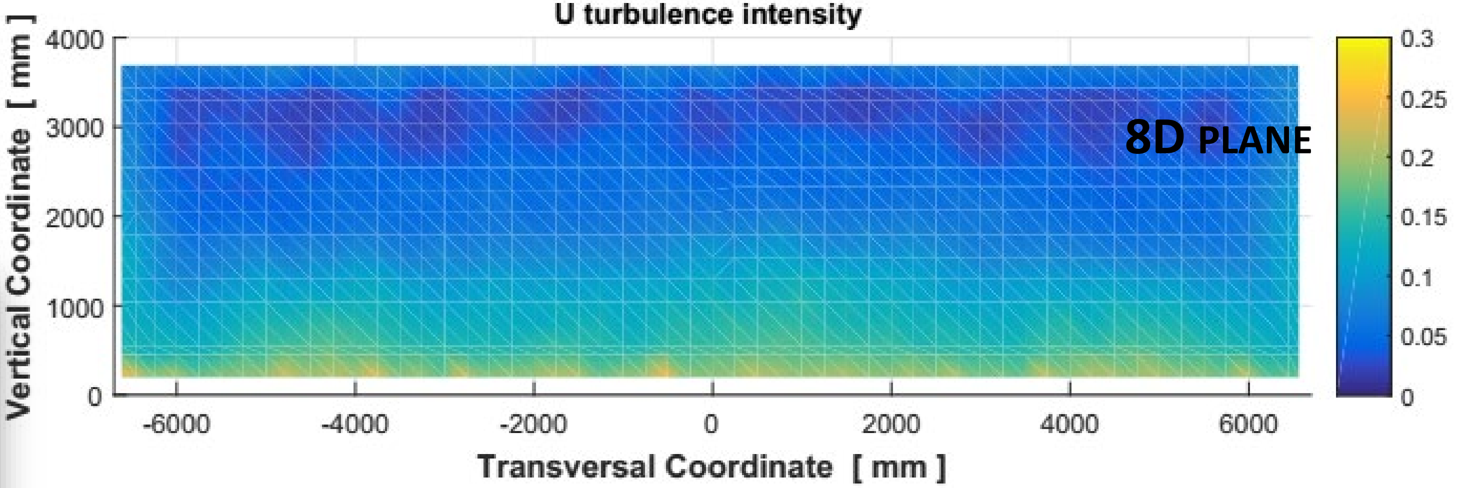


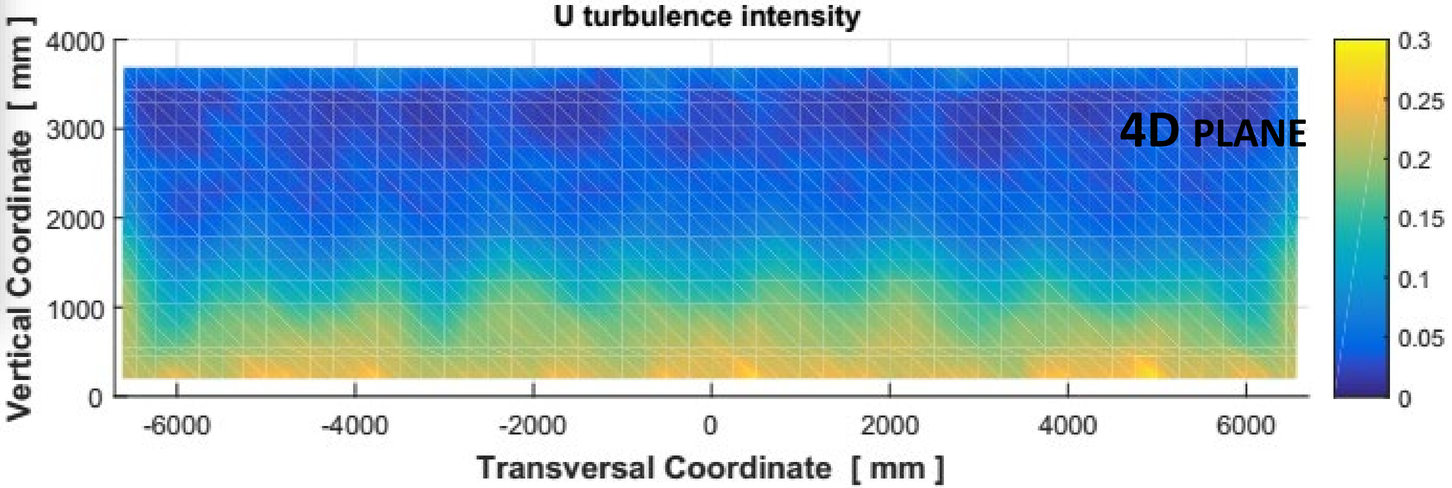


CL-Windcon

Flow measurement

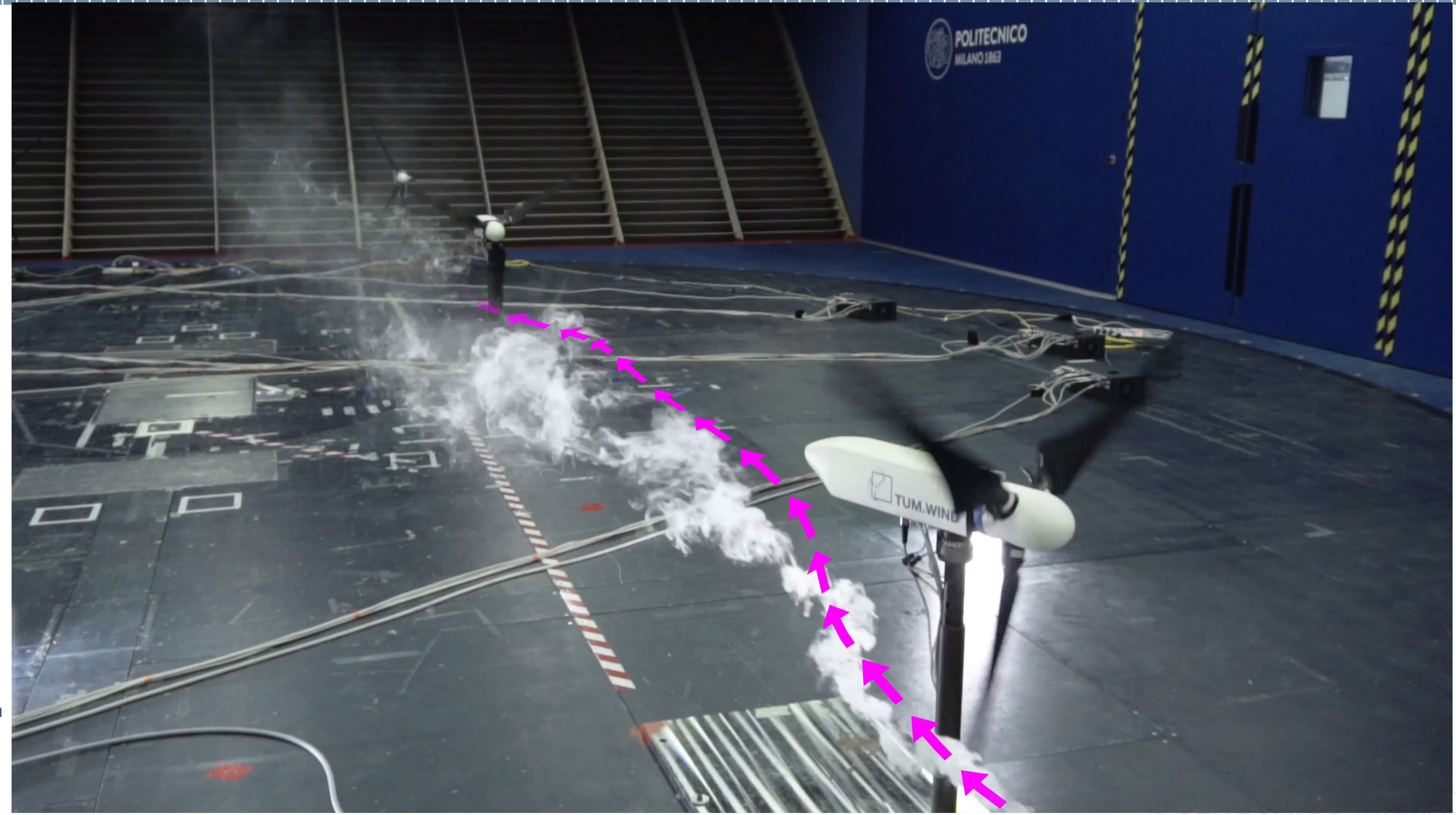
ON-SHORE CASE





CL-Windcon

Wind Tunnel - Wind Turbines Innovative Applications



CL-Windcon

Wind Turbine Wake Interactions and Wind Farm Controls

Configuration: 6 machines on the rotating table

w/o wind farm control

w wind farm control (wake steering)

CL-Windcon

CL-WINDCON ‘Closed Loop Wind Farm Control’ (H2020-LCE-2016-2017, 2016-2019).

G1 scaled wind turbines and wind farm controller provided by Technische Universität München

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CL-Windcon

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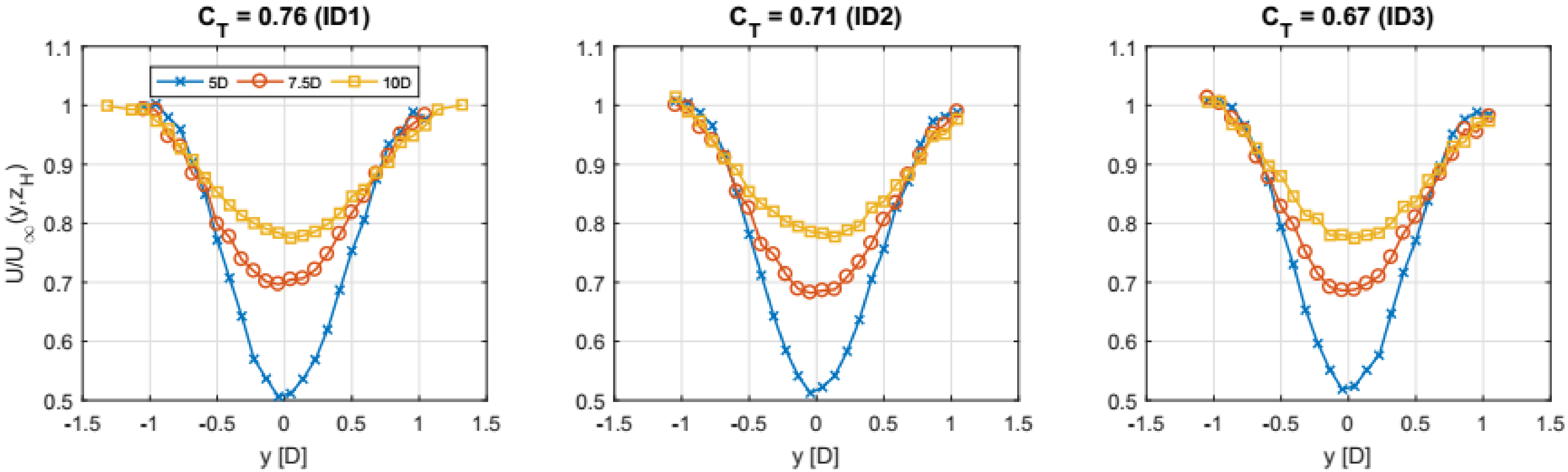
G1 scaled wind turbines and wind farm controller provided by Technische Universität München

Flow measurement

Wake measurement for different wind turbine conditions:

- De-rating (C_T)

HORIZONTAL PROFILE - OFFSHORE WIND @WT1

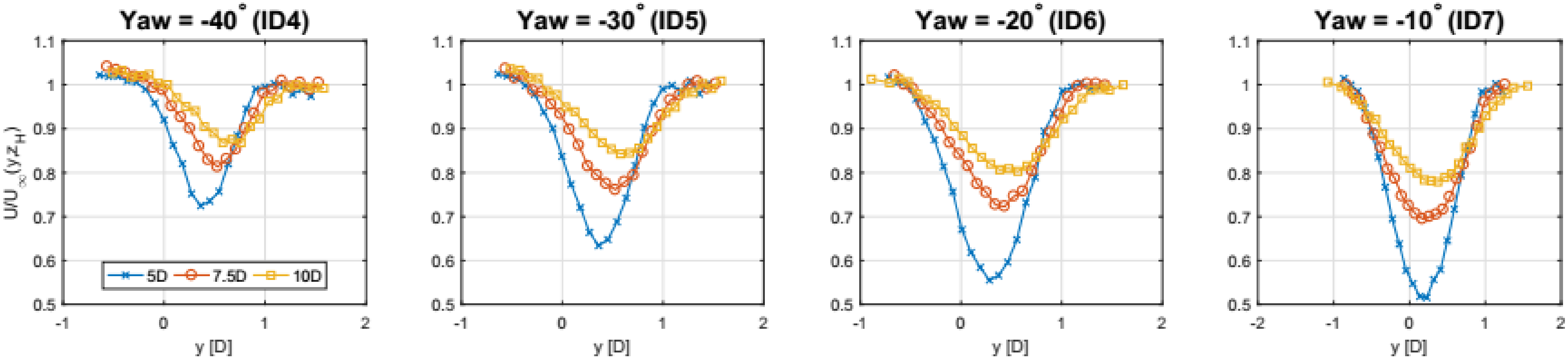


Flow measurement

Wake measurement for different wind turbine conditions:

- Yaw Misalignment

HORIZONTAL PROFILE - OFFSHORE WIND @WT1

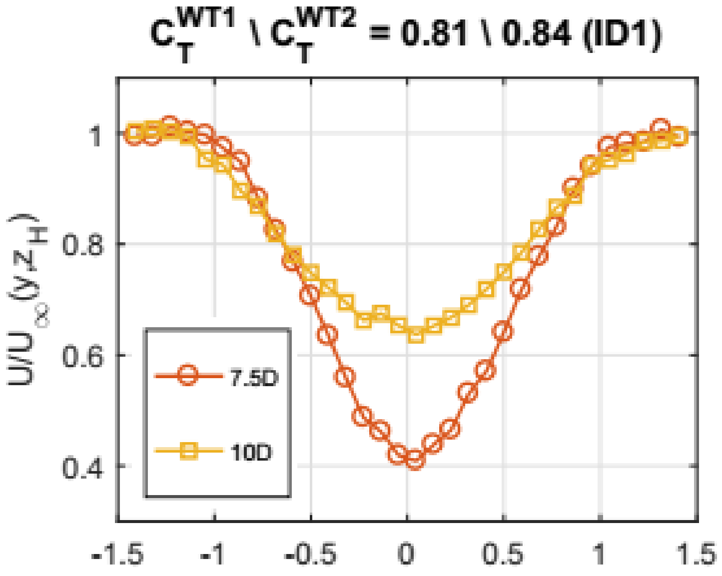


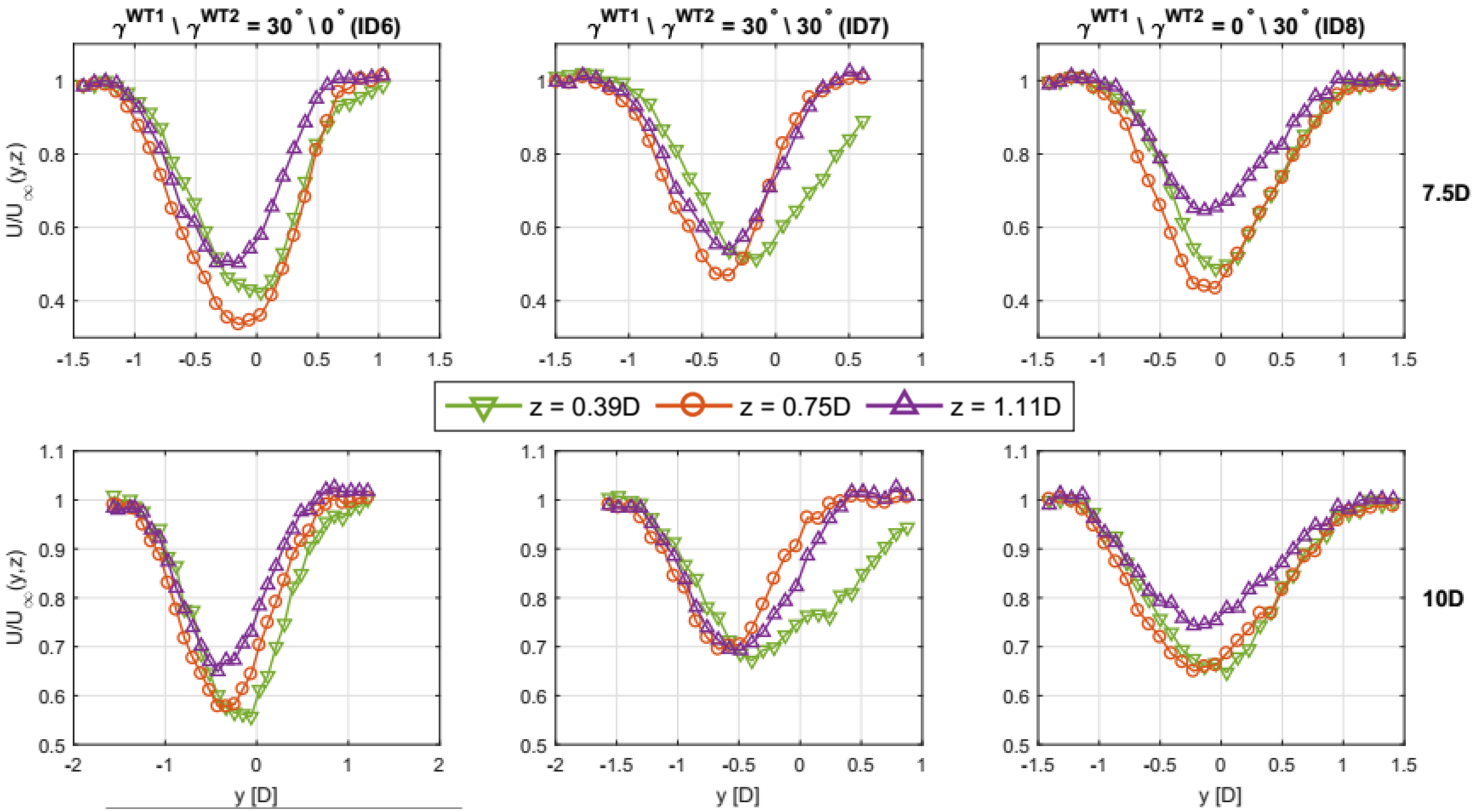
Flow measurement

Wake measurement

for multiple wind turbines

in different yaw conditions

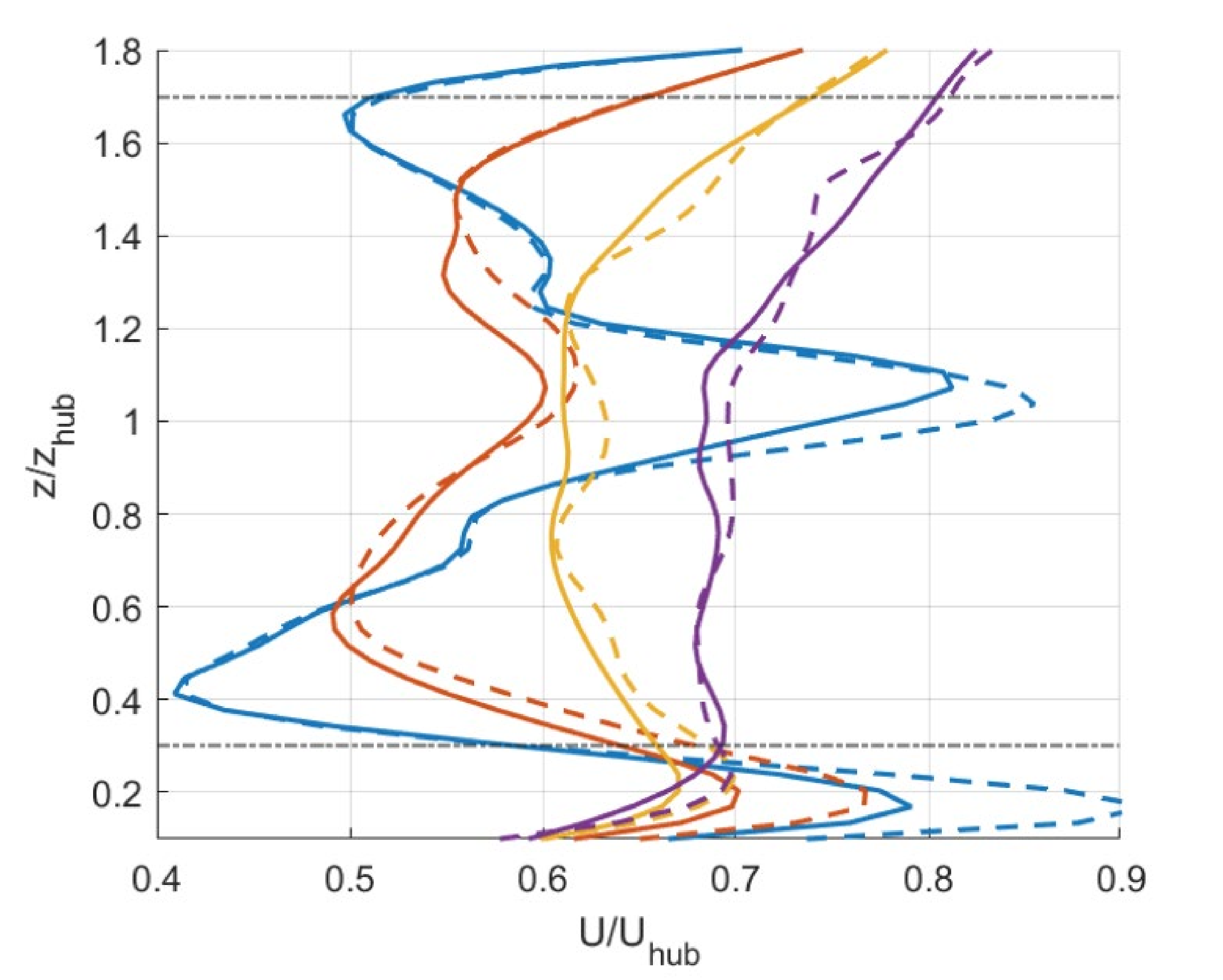




Flow measurement

- A large database of wind tunnel testing of wind turbines data is available.
- Wake characteristics and turbine performance data are monitored as a function of the inflow conditions.
- Data allow for tuning static and dynamic wake modelling tools.
- The wind tunnel setup allows for testing the performance of wind farm controllers in static and dynamic condition.

Database can be used to tune/validate high-fidelity and engineering models



- LES simulations (SOWFA)
- turbulent ABL inflow

1D blue
3D orange
5D yellow
7D purple

Montenegro Montero, M.; Arcari, V.; Cacciola, S.; Croce, A., *Effectiveness of Dynamic Induction Control Strategies on the Wake of a Wind Turbine*, The Science of Making Torque from Wind (TORQUE 2022), Journal of Physics: Conference Series, 2022, 022054 (10 pages) DOI: 10.1088/1742-6596/2265/2/022054

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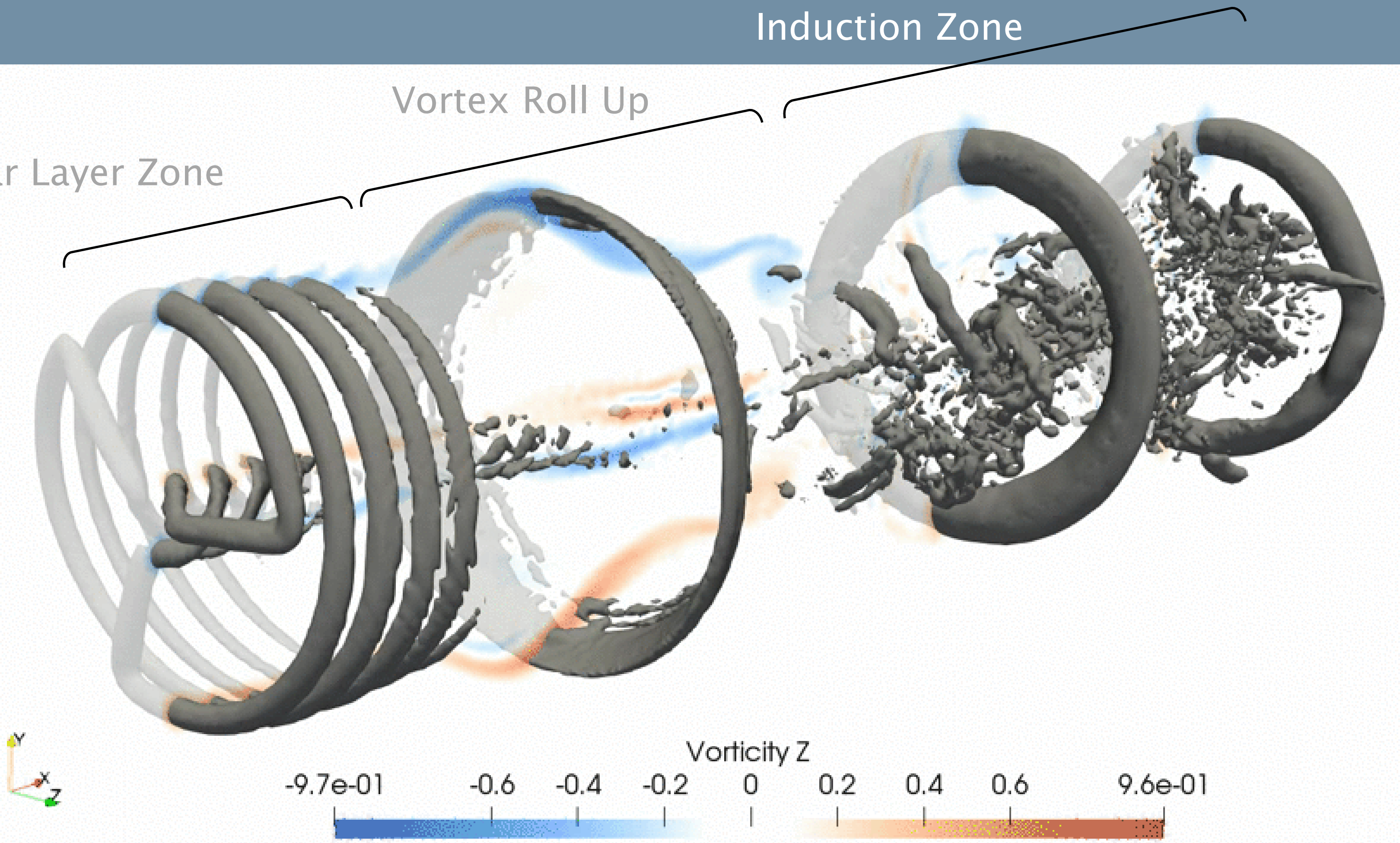
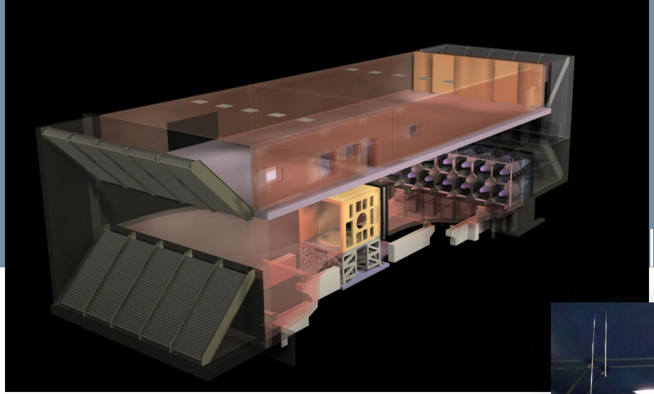


FLOAWER
FLOAting Wind Energy netwoRk

Alessandro Croce, Stefano Cacciola, Mariana Montero Montenegro, Sebastiano Stipa, Roberto Praticó, *A CFD-based analysis of dynamic induction techniques for wind farm control applications,* https://doi.org/10.1002/we.2801

Outline



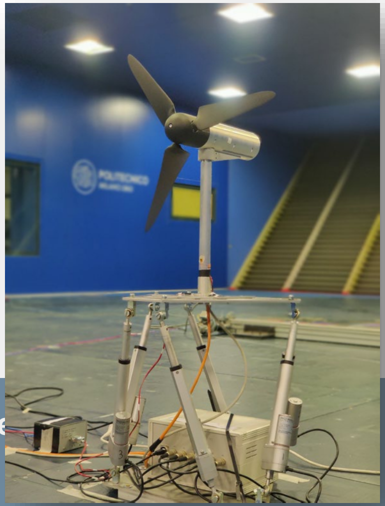
The Politecnico di Milano Wind Tunnel – GVPM

Passive & Passive/Active Load Alleviation in Waked Conditions

Wind Turbine Wake Interactions and Wind Farm Controls

Measurements test

Floating cases

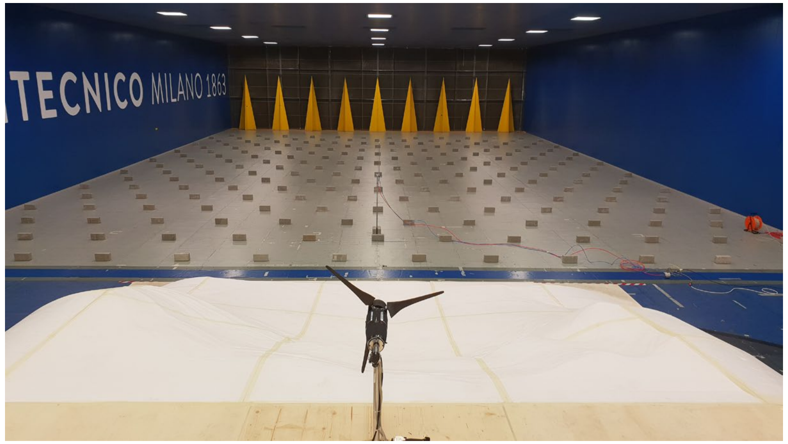


Applications: Complex Terrain

Configuration: single wind turbine on complex terrain

Applications: Complex Terrain and PIV

Configuration: single wind turbine on complex terrain



- Design of the terrain model from Stöttener Berg (Baden-Württemberg, Germany
- Evaluation of blockage effects
- Wind tunnel measurements with PIV:
  - Nd:Yag double pulsed laser with 200 mJ/pulse and
  - 2 Mpx double shutter camera mounted on a traversing system
  - Measurement overall domain 3m long x 1.2m high (divided into several smaller sections of 0.75mx0.4m slightly overlapped

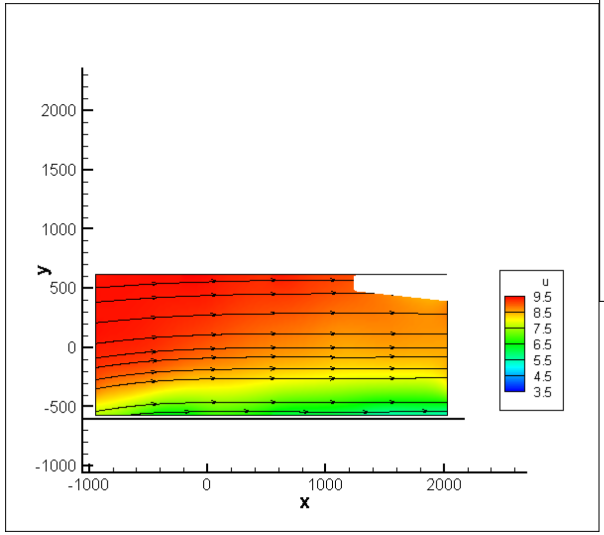
J Wang et al 2017 J. Phys.: Conf. Ser. 854 012048

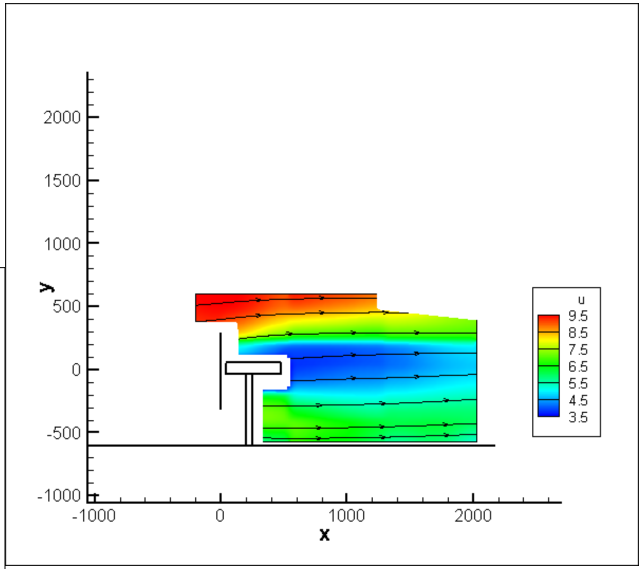
Emmanouil M Nanos *et al* 2020 *J. Phys.: Conf. Ser.* **1618** 032041

Applications: Complex Terrain and PIV

Configuration: single wind turbine on complex terrain

PIV measurements





J Wang et al 2017 J. Phys.: Conf. Ser. 854 012048

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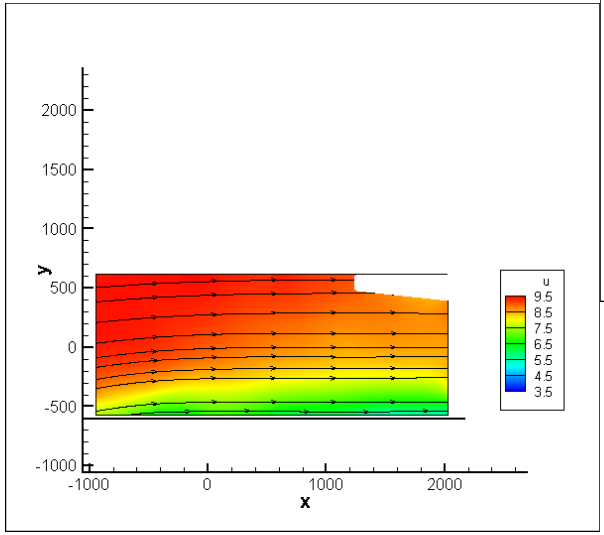
G.7 scaled wind turbine provided by TUM

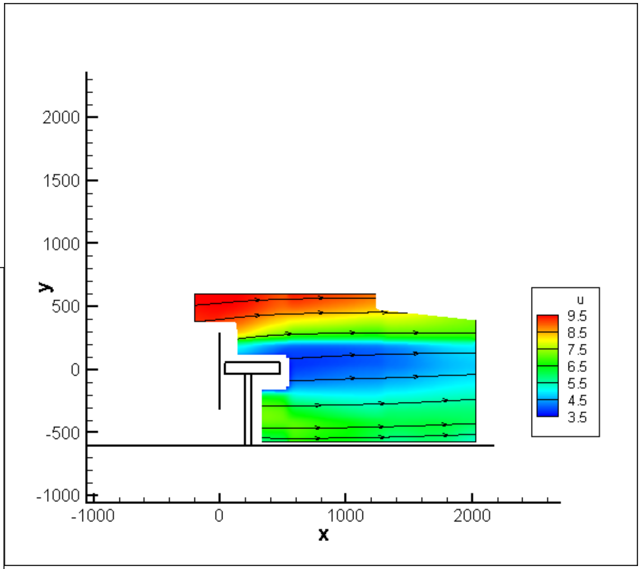
Wind Energy Institute Technische Universität München

Applications: Complex Terrain and PIV

Configuration: single wind turbine on complex terrain

PIV measurements





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Applications: New Flow Measurements – Short Range LIDARs

Short Range Lidar Wake Measurements

- Two Short Range Lidars
- Two component flow map
- Detailed 2D flow field data over a large Wind Tunnel volume
- Effective wake modelling experimental validation data

- collaborative efforts of ForWind–Oldenburg, TUM, Technical University of Denmark and POLIMI

M F van Dooren et al 2016 J. Phys.: Conf. Ser. 753 072032

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- ❑

M F van Dooren et al 2016 J. Phys.: Conf. Ser. 753 072032

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- collaborat
  ForWind–
  Technical
  Denmark

M F van Dooren
Ser. 753 07203

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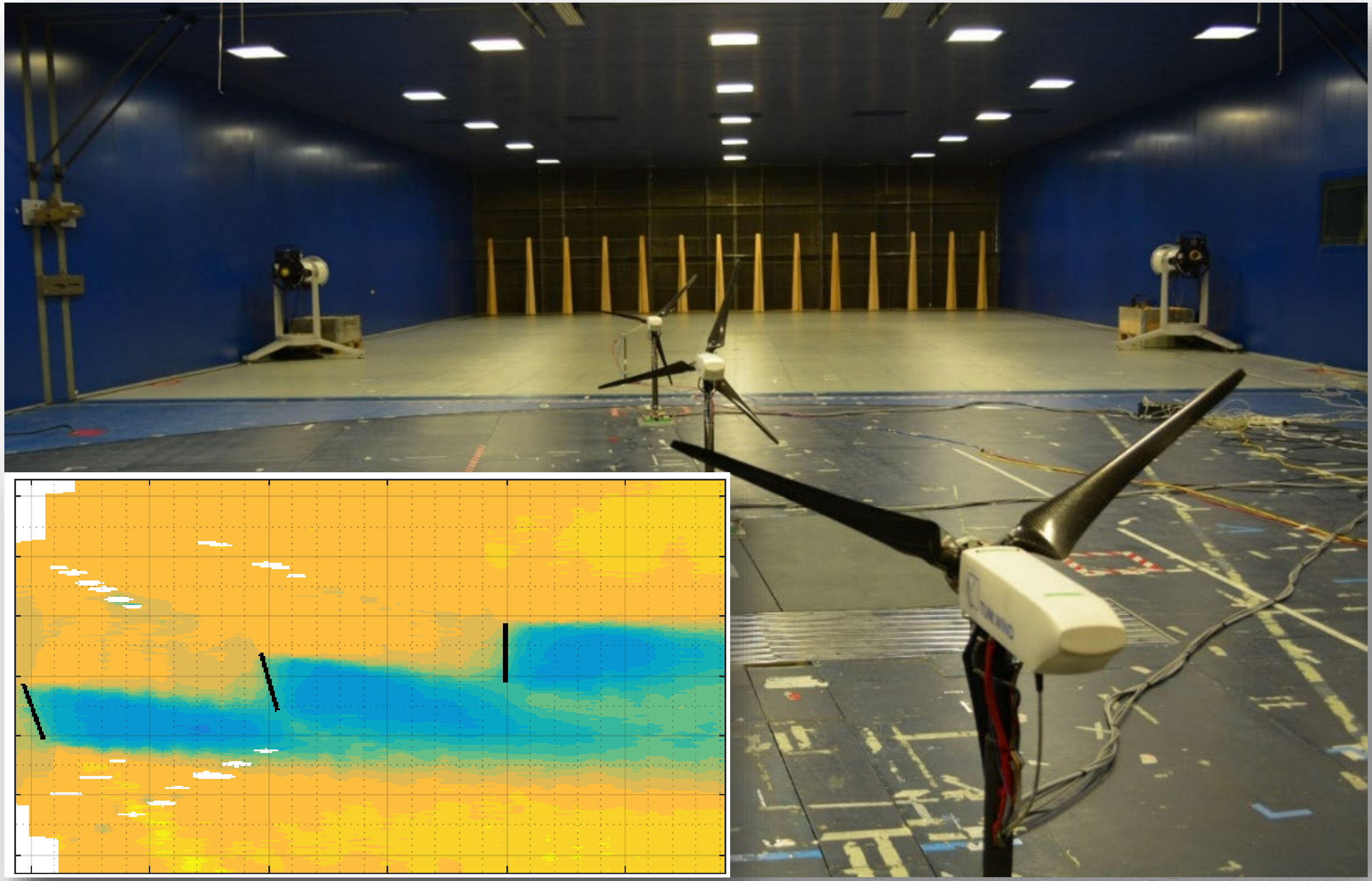
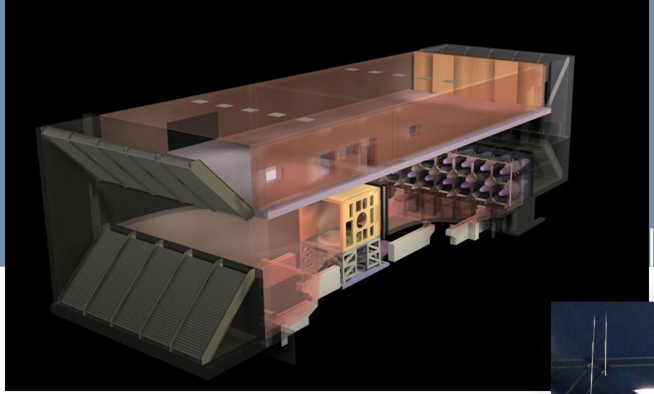


Outline



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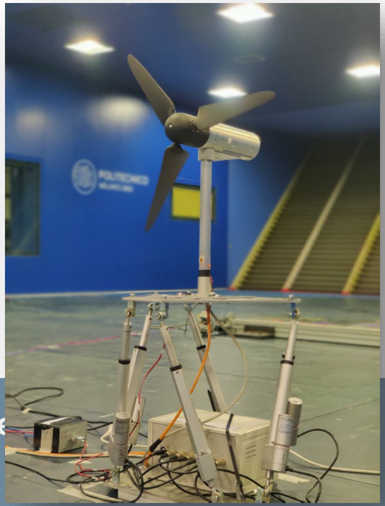
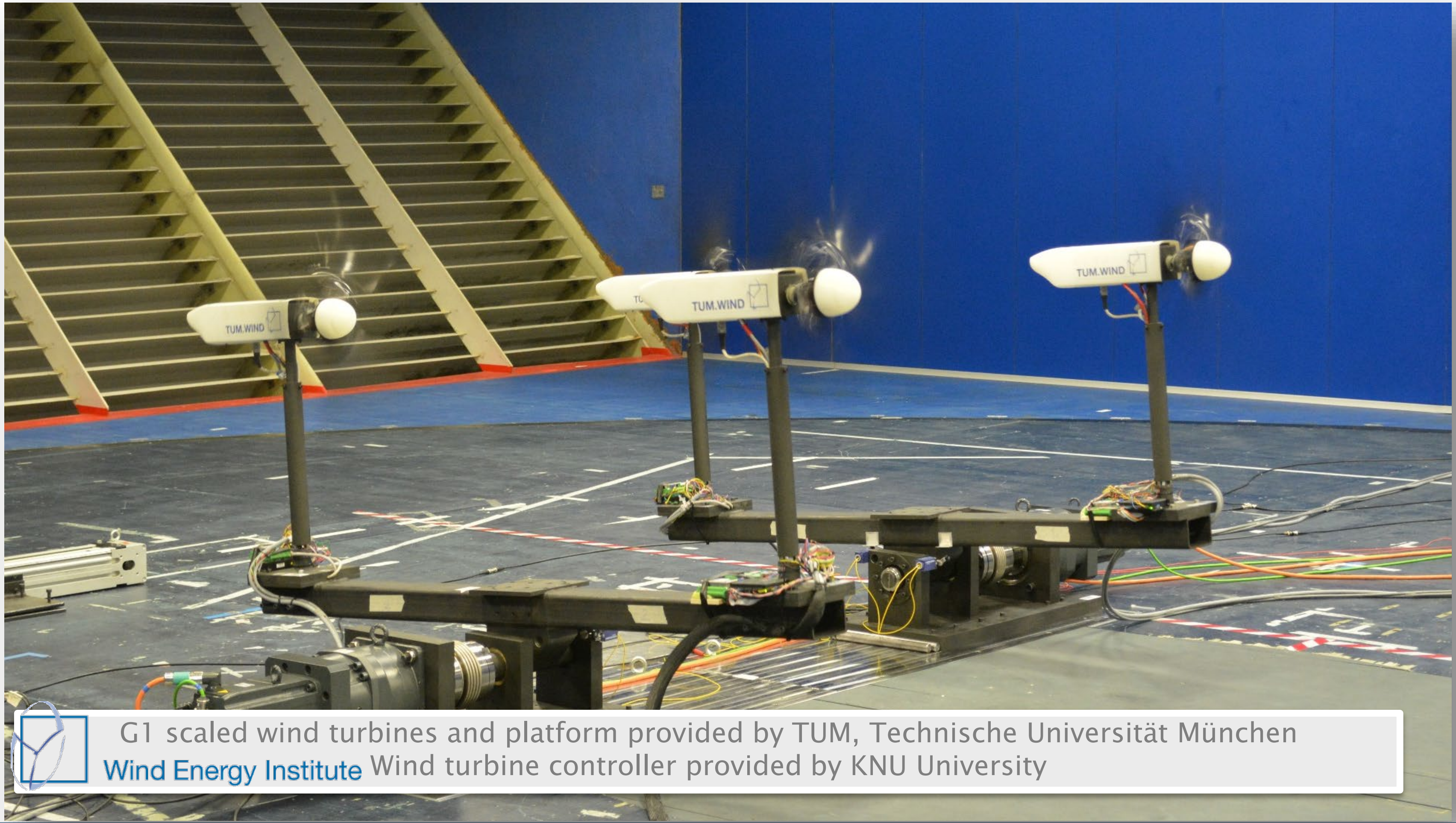


Applications: Compact Off-shore Configuration

Configuration: Compact Offshore Wind Farm, 4 models on floating platform



G1 scaled wind turbines and platform provided by TUM, Technische Universität München
Wind Energy Institute Wind turbine controller provided by KNU University

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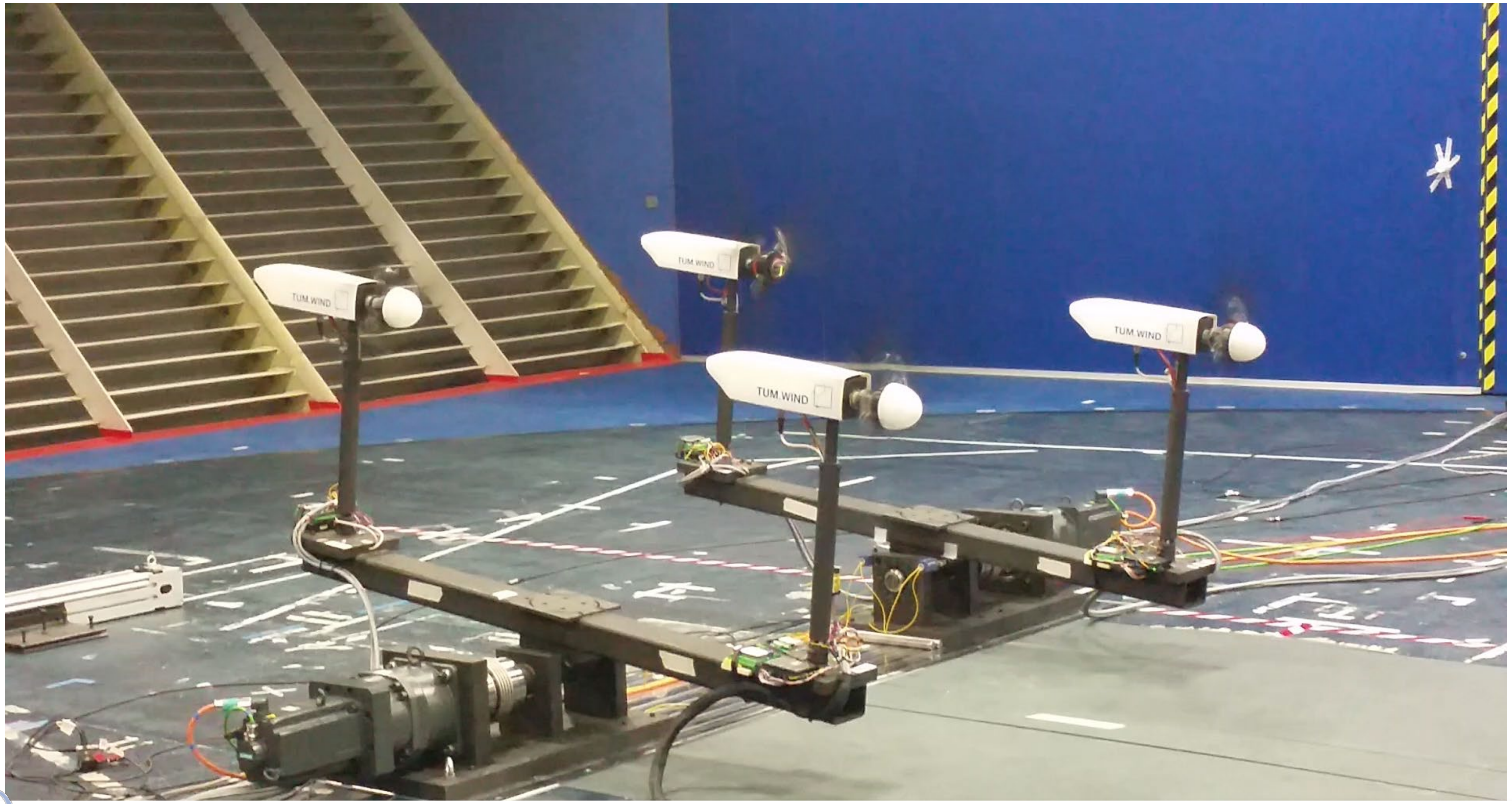

Wind Energy Institute G1 scaled wind turbines and platform provided by TUM, Technische Universität München
Wind trubine controller provided by KNU University

Applications: Scaled Model for Wave Tank testing

Froude-scaled rotor model (DAER-PoliMI)

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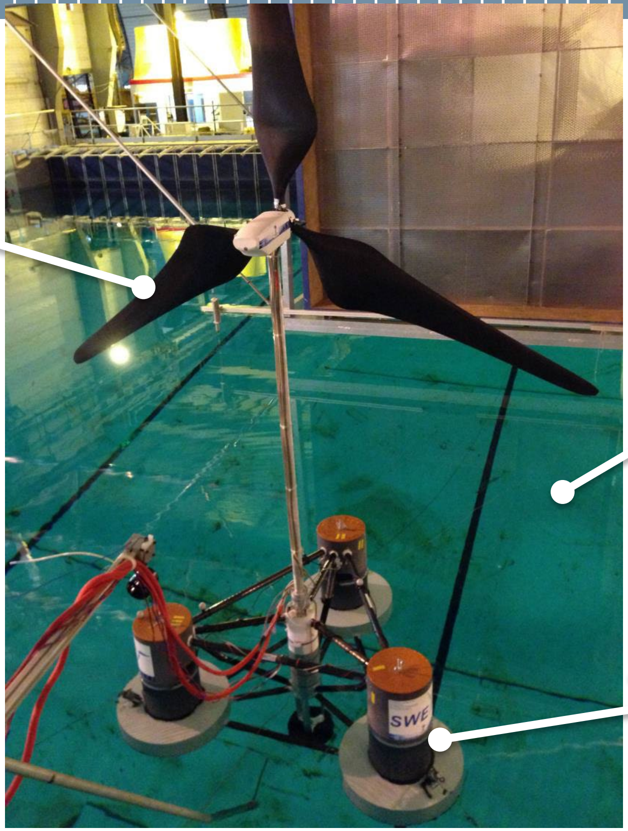


MARINET

Infrastructure access (MARINET-ECN Nantes)

Platform model (USTUTT)

University of Stuttgart
Germany

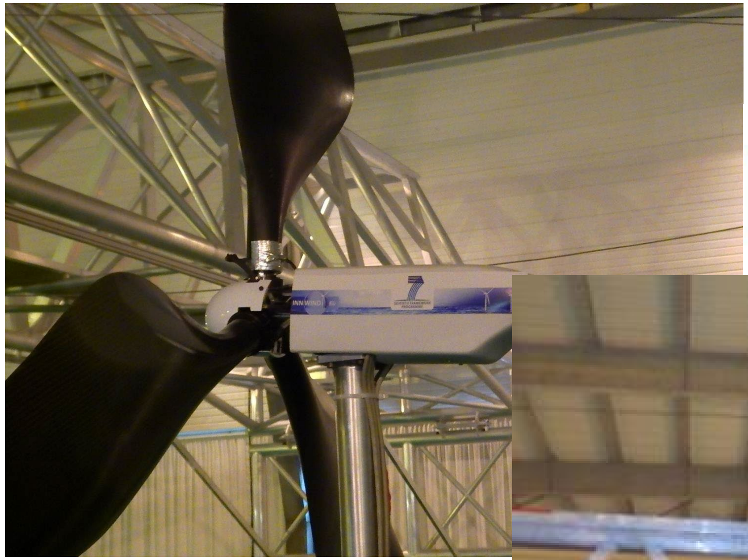
INNWIND.EU

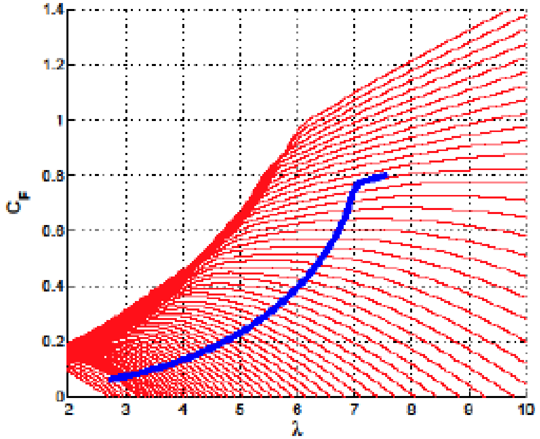
- Floating wind turbine model tests in collaboration with University of Stuttgart and MARINET–ECN (INNWIND.EU)
- Characterization of the scaled 10MW floating model
- Wind and wave model testing into water tank, for numerical codes validation

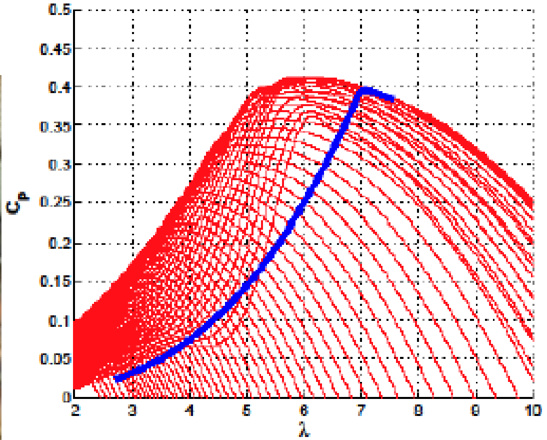
Applications: Scaled Model for Wave Tank testing

INNWIND MODEL

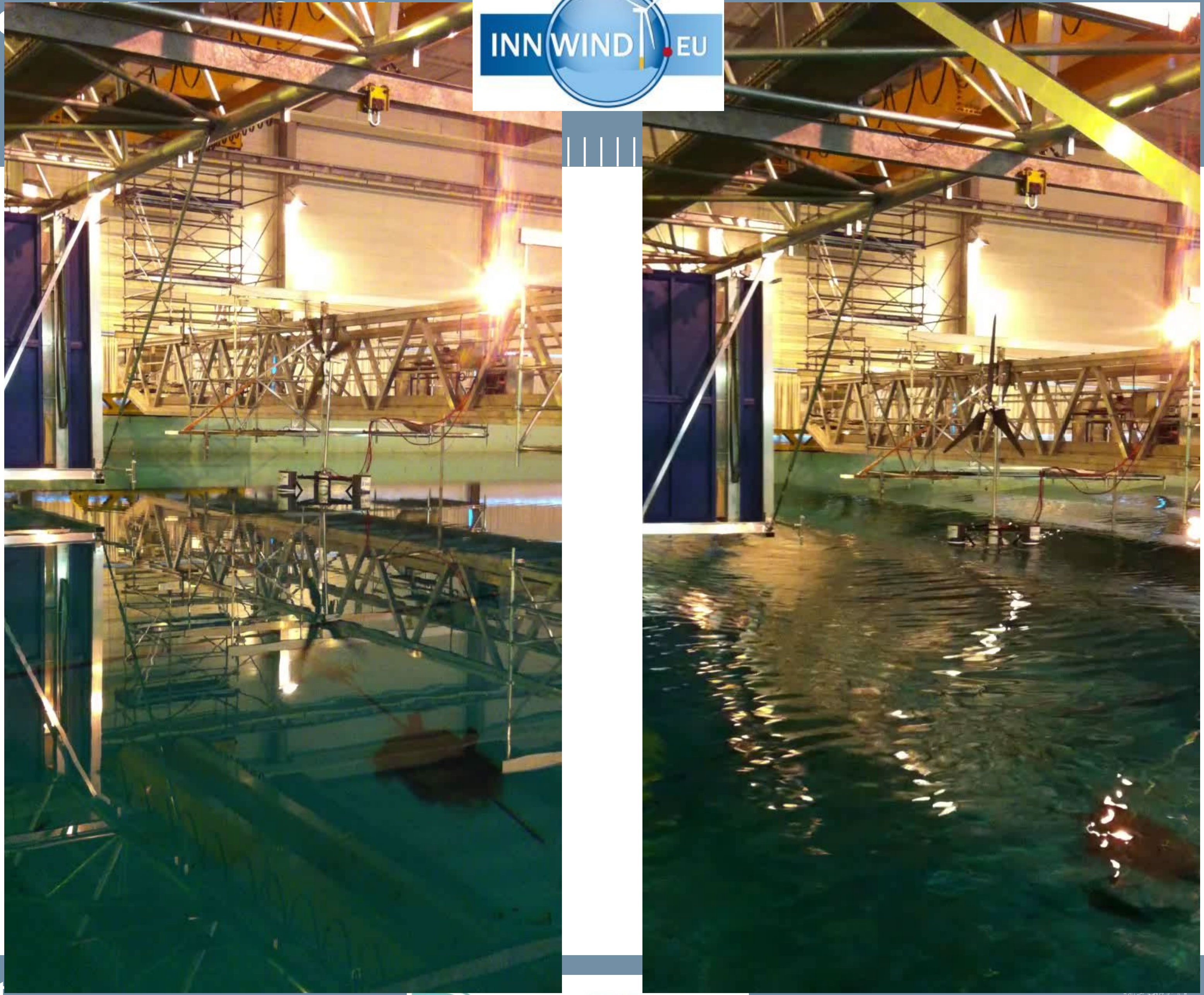
- ✓ Froude-scaled: Thrust force F_trst scaled correctly.
- ✓ Ω scaled correctly.
- ✓ v scaled correctly.
- ✓ TSR scaled correctly.
- ✓ c_T adjusted for correct F_trst.







Applications: Sc



Application: Floating Wind Turbine Testing

MoWiTO 0.6 mounted on a Stewart platform (designed and manufactured by Uni Oldenburg*)

Test 1: Cp–Ct vs. λ (U=3,5,7 m/s)

Test 2: power and thrust for a few moving cases

Test 3: wake measurement at 6D and 10D for 3 cases (fixed, surge, sway)

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FLOAWER FLOAting Wind Energy netwoRk

CARL VON OSSIETZKY UNIVERSITÄT OLDENBURG

* Thomas Messmer et al 2022 J. Phys.: Conf. Ser. 2265 042015

Application: Floating Wind Turbine Testing

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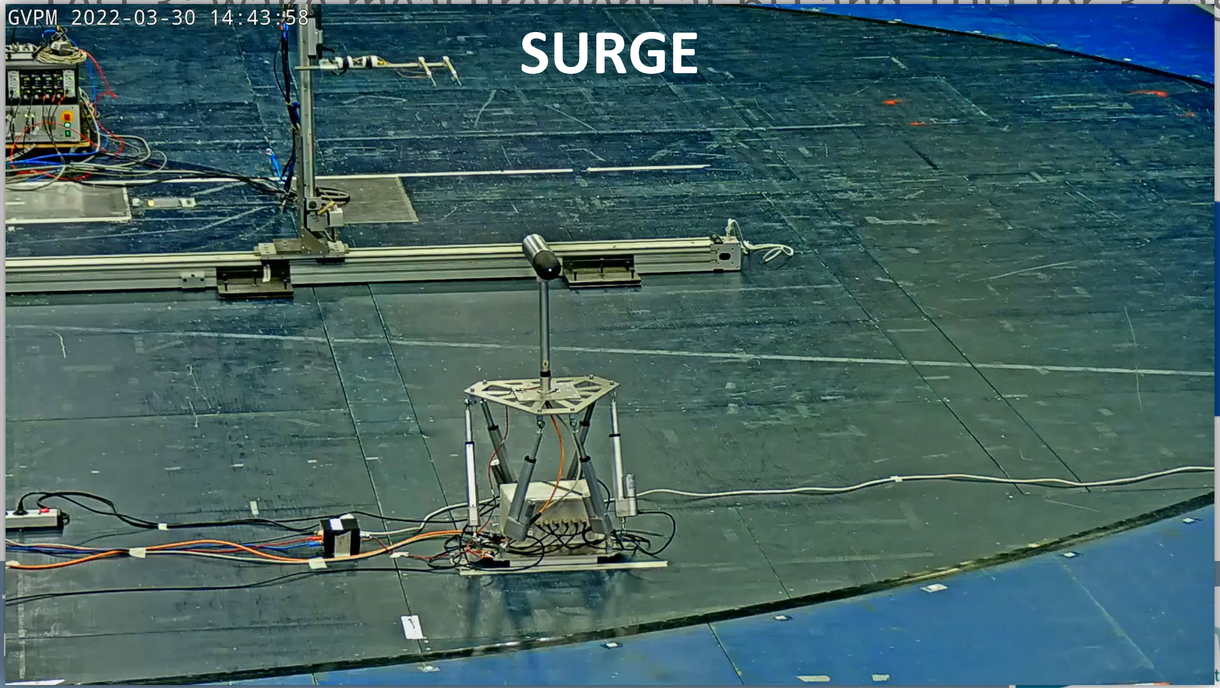
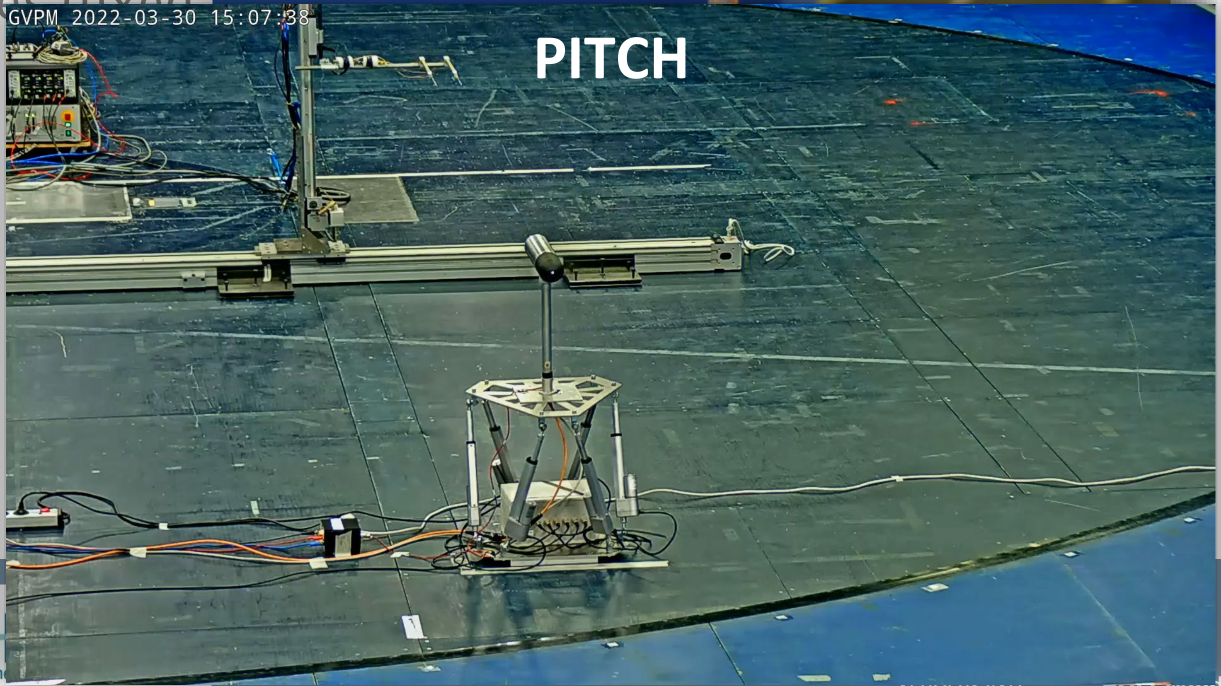
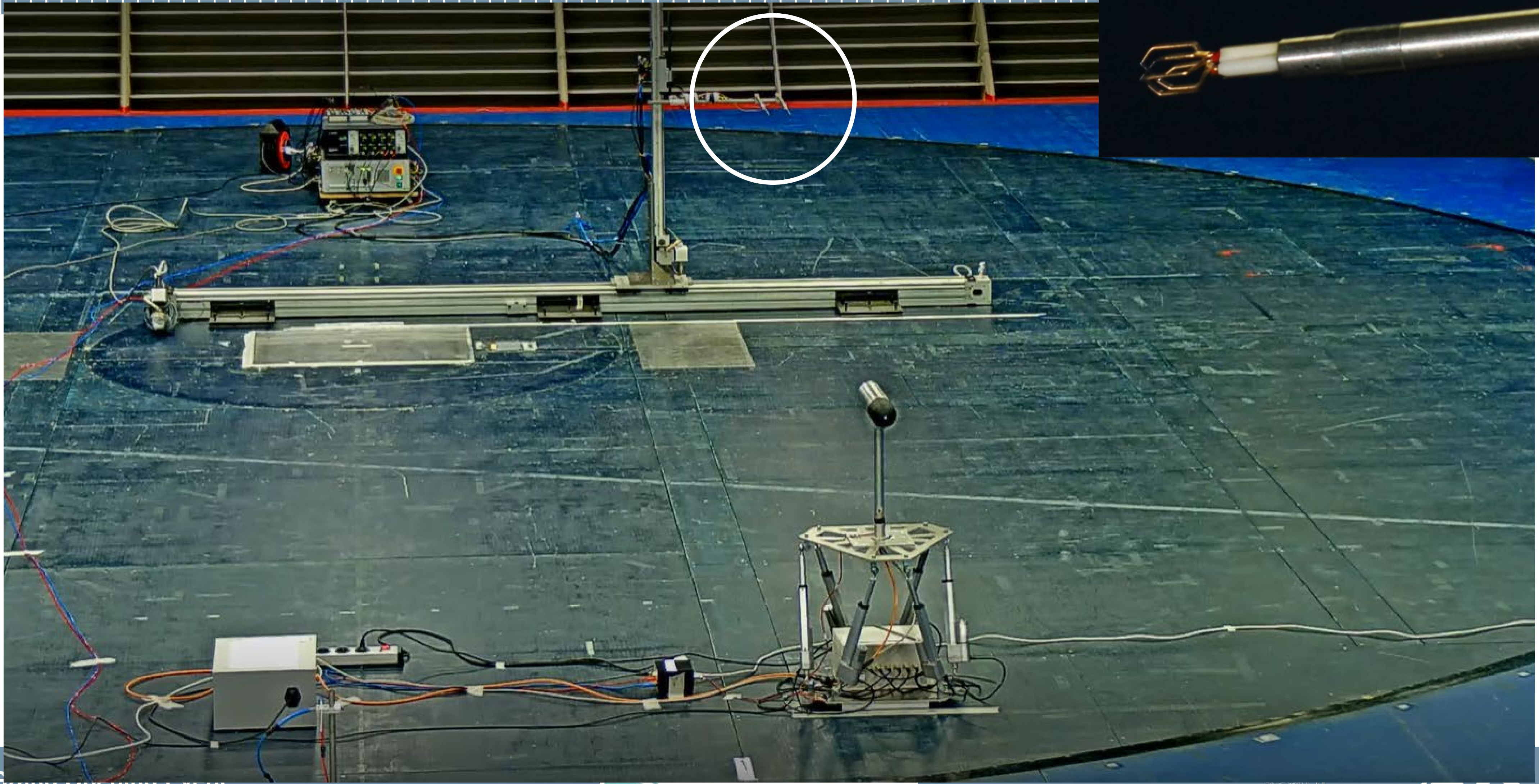




Floating Wind Turbine Testing



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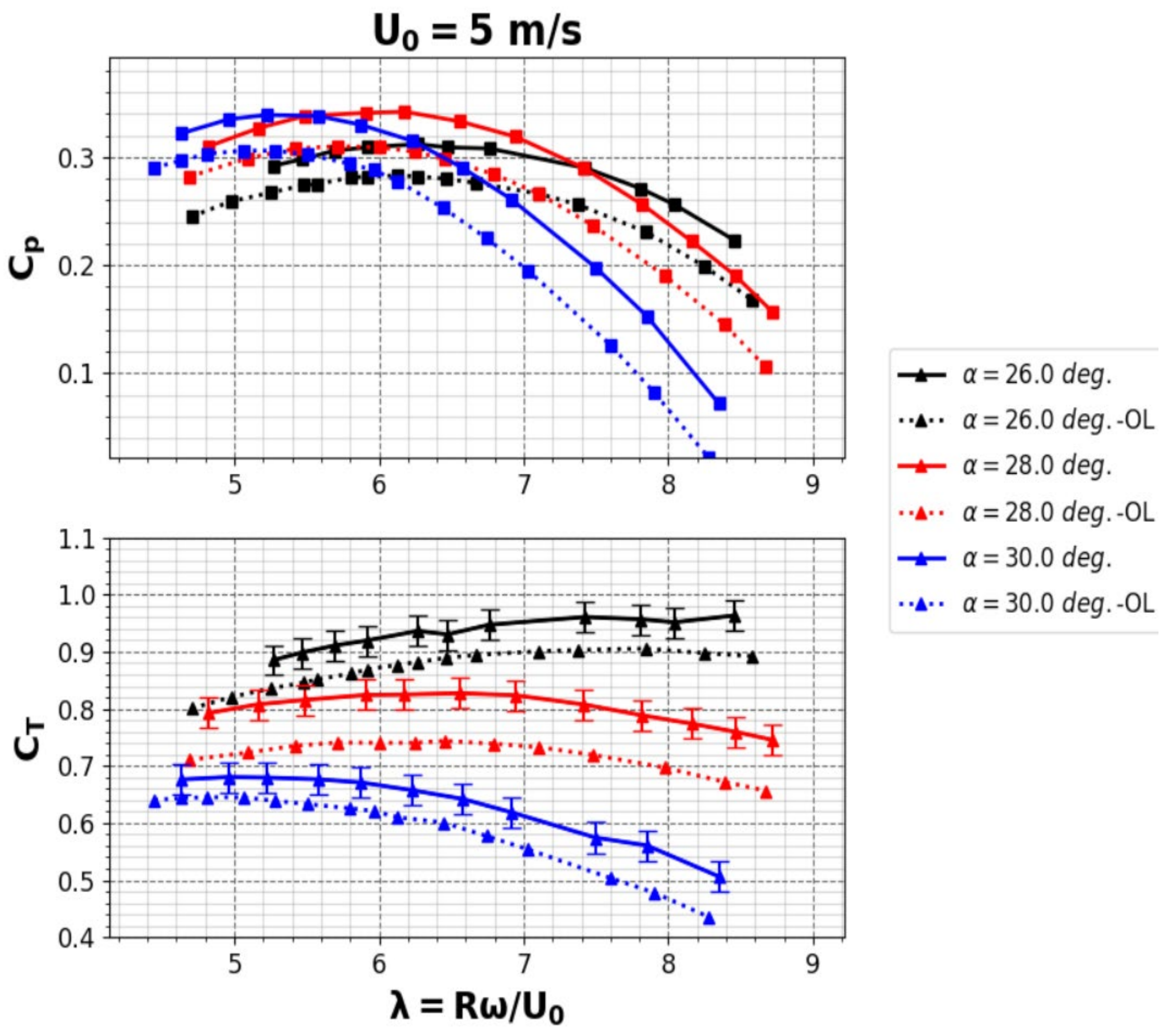

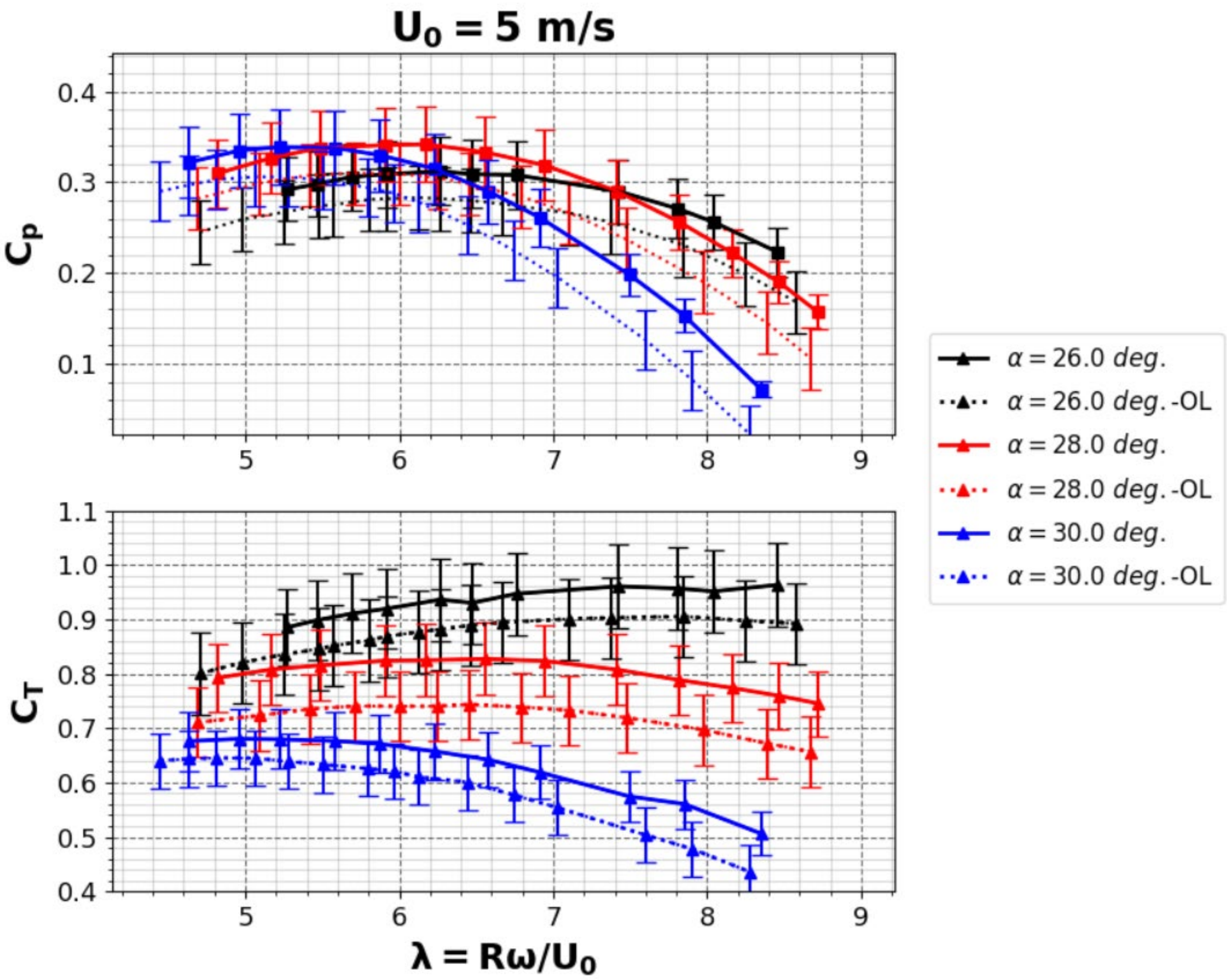

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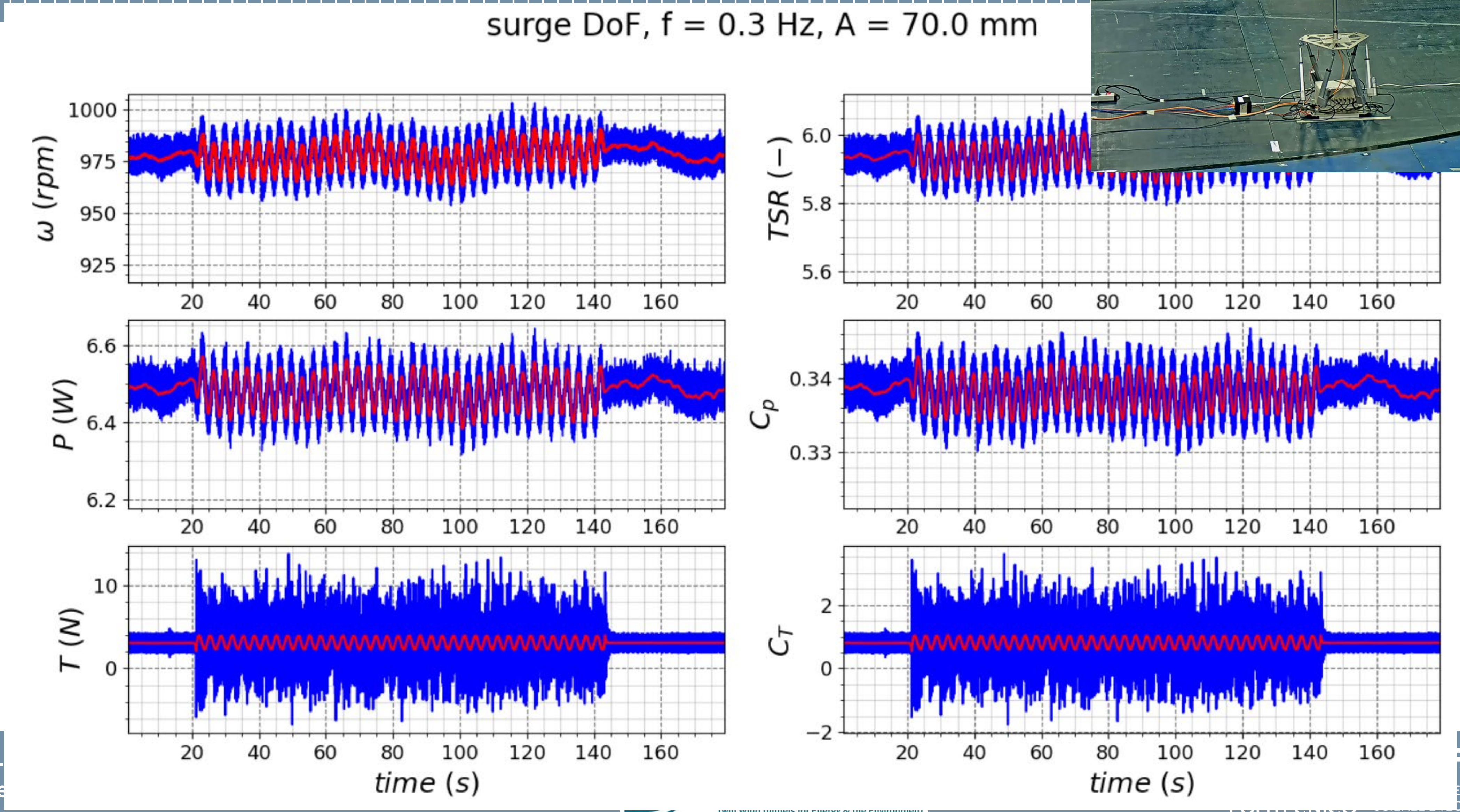
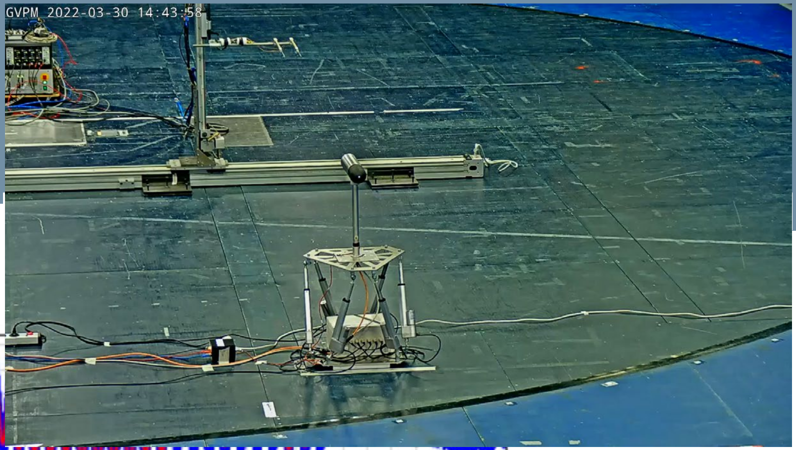
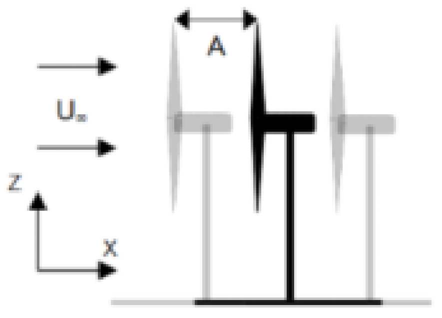


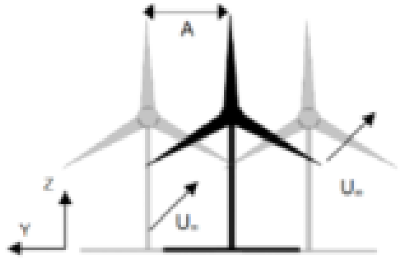


Floating Wind Turbine Testing

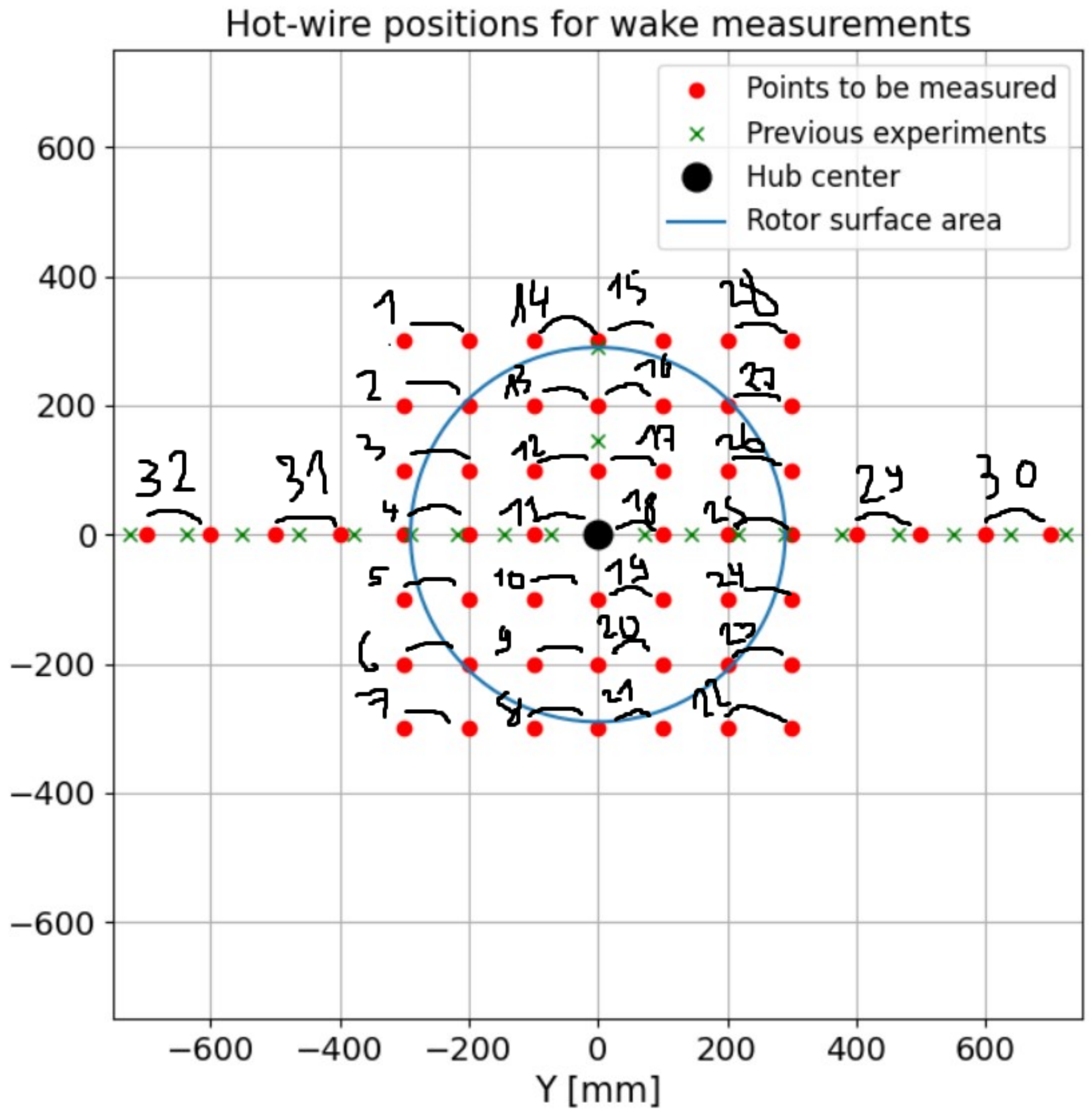
- 3 cases (fixed, surge and sway)
- Different planes
  (6D and 10D up to now)



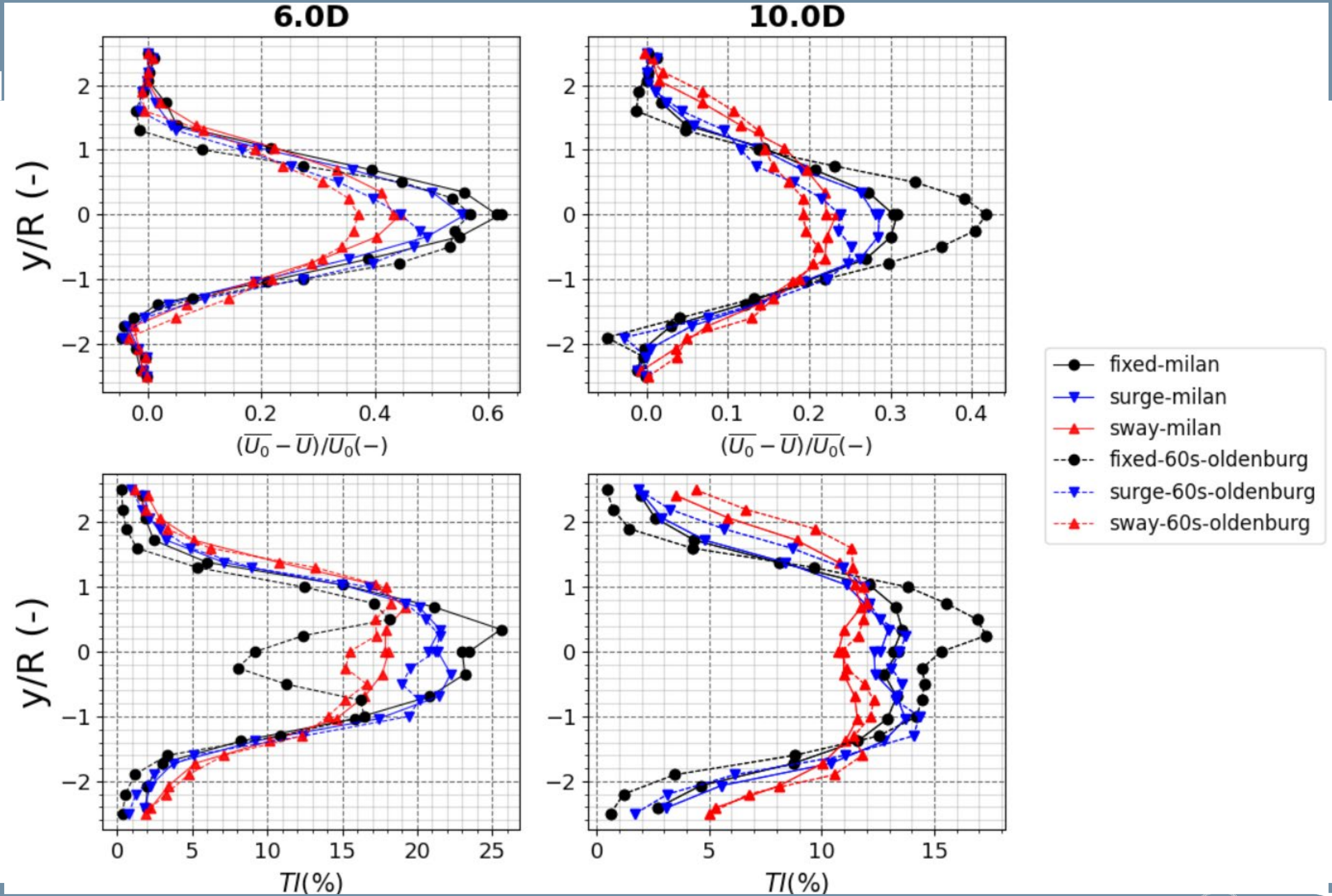
Surge, $f_p = 3.3$ Hz
A = 6 mm



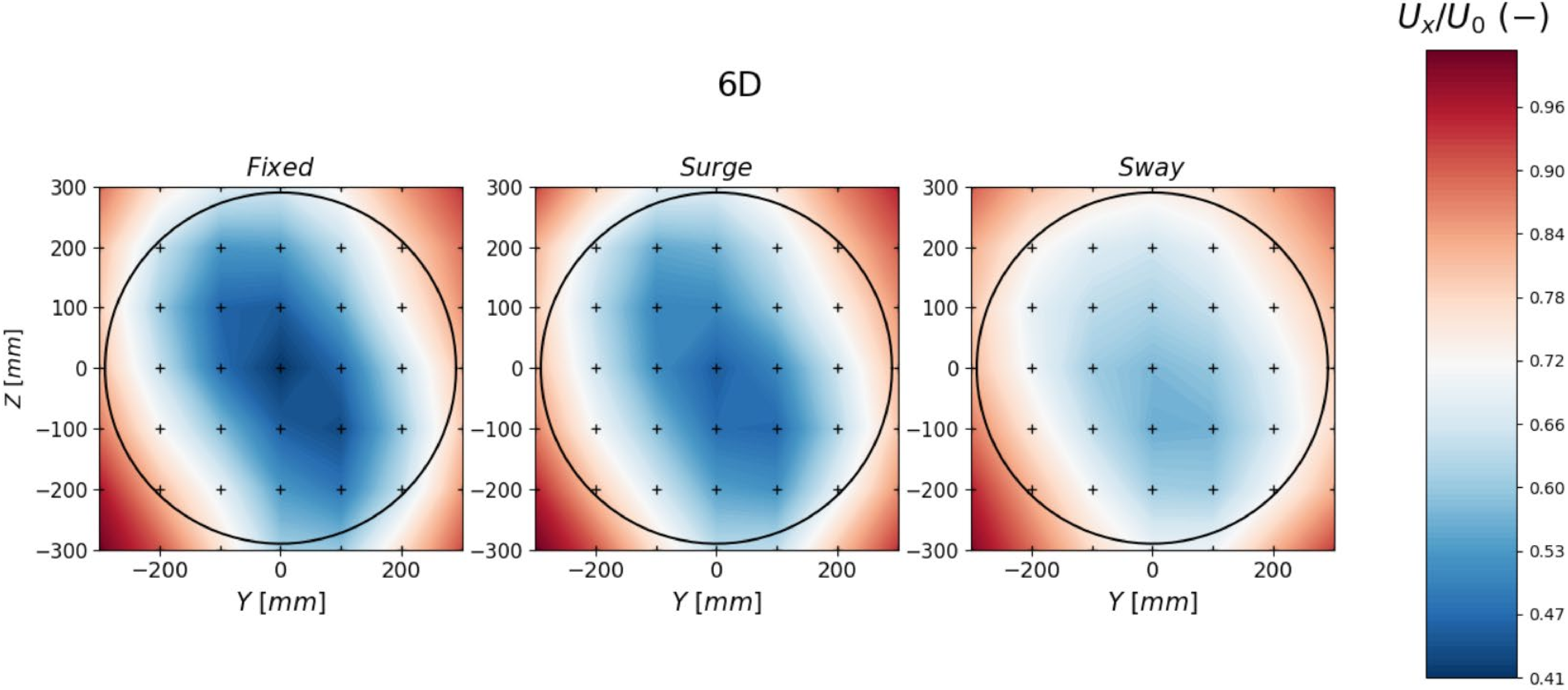
Sway, $f_p = 3.3$ Hz
A = 6 mm



Floating Wind Turbine Testing



Floating Wind Turbine Testing



TAKE HOME MESSAGE(s)

Review of current state of the art on measurement techniques and WT testing

- Great developments in the last decade of tunnel testing in the wind energy field
- Tunnel tests are much faster than simulations and less expensive (and more repeatable) than test in the field
- Tunnel tests fit in an intermediate range between tests in the field and numerical simulations
- Synergy between the three cases is necessary
- Wind Tunnel testing not only for aerodynamic testing