Wind tunnel study of multiple wake interactions in wind farm with different layouts

G. V. Iungo[1], J. Coëffé[1], W. Zhang[2], C. Markfort[2] and F. Porté-Agel[1,2]

[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental Engineering (ENAC), Wind Engineering and Renewable Energy (WIRE), 1015 Lausanne, Switzerland
[2] St. Anthony Falls Laboratory, Department of Civil Engineering, University of Minnesota, Minnesota, USA.

(valerio.iungo@epfl.ch, juliette.coeffe@epfl.ch, zhangwei@umn.edu; mark0340@umn.edu; fernando.porte-agel@epfl.ch)

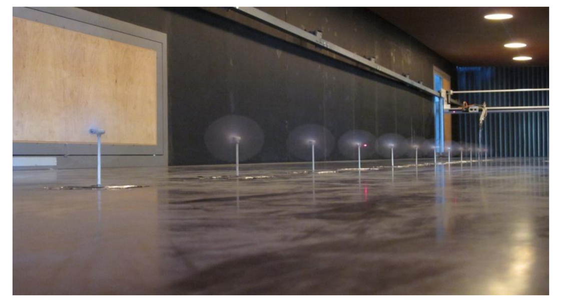
Abstract

The interaction between atmospheric boundary layer and wind farms leads to flow modifications, which have a strong effect on wind farm performance. Therefore, optimizing the wind farm layout is of key importance for the maximization of power production. In this study, a wind tunnel investigation was carried out, using hot-wire anemometry and multi-hole pressure probes, in order to study turbulence statistics of the atmospheric boundary layer inside and above wind farms. First, the wake flow generated from a single wind turbine is surveyed. It is characterized by a strong velocity defect in the proximity of the rotor. The magnitude of this velocity defect and the cross-dimensions of the wake are found to be related to the wind turbine performance and strongly affect the efficiency of the wind turbines placed downstream. The distance of recovery of the wakes, and thus the performance of downstream turbines, is found to depend on the characteristics of the incoming atmospheric boundary layer (mean velocity and turbulence intensity profiles). An increased turbulence level is typically detected downstream of each wind turbine for heights comparable to the top-tip of the blades. The effect of the wind farm layout on power production was also investigated. Aligned and staggered wind farm layouts were analysed. The results obtained from the present experimental campaign shed light on how wind farm performance could be affected by different flow features like, e.g., the atmospheric boundary layer characteristics, the flow turbulence and the wind farm configuration. The measurements are also being used to test and guide the development of improved parameterizations of wind turbines in high-resolution numerical models, such as large-eddy simulations (LES).

Experimental Set-up

WIRE BOUNDARY LAYER WIND TUNNEL

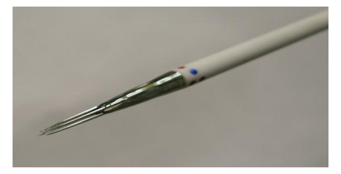
- Testing chamber: **30 m x 2.5 m x 2.5 m**;
- **Adjusting ceiling**;
- Maximum velocity 8 m/s;
- Minimum turbulence level 2%;
- Use of spires and roughness to adjust the boundary layer.



MEASUREMENTS

- 3 velocity components through a miniature **COBRA** 4-hole pressure probe by TFI; sensor diameter 1.5 mm;
- 2 velocity components through DANTEC **cross-wire anemometers**; A.A: Lab System AN-1003 CTA system;
- Blade rotation velocity through **laser tachometer** by Monarch Instrument;

Cross-wire anemometer



Cobra probe

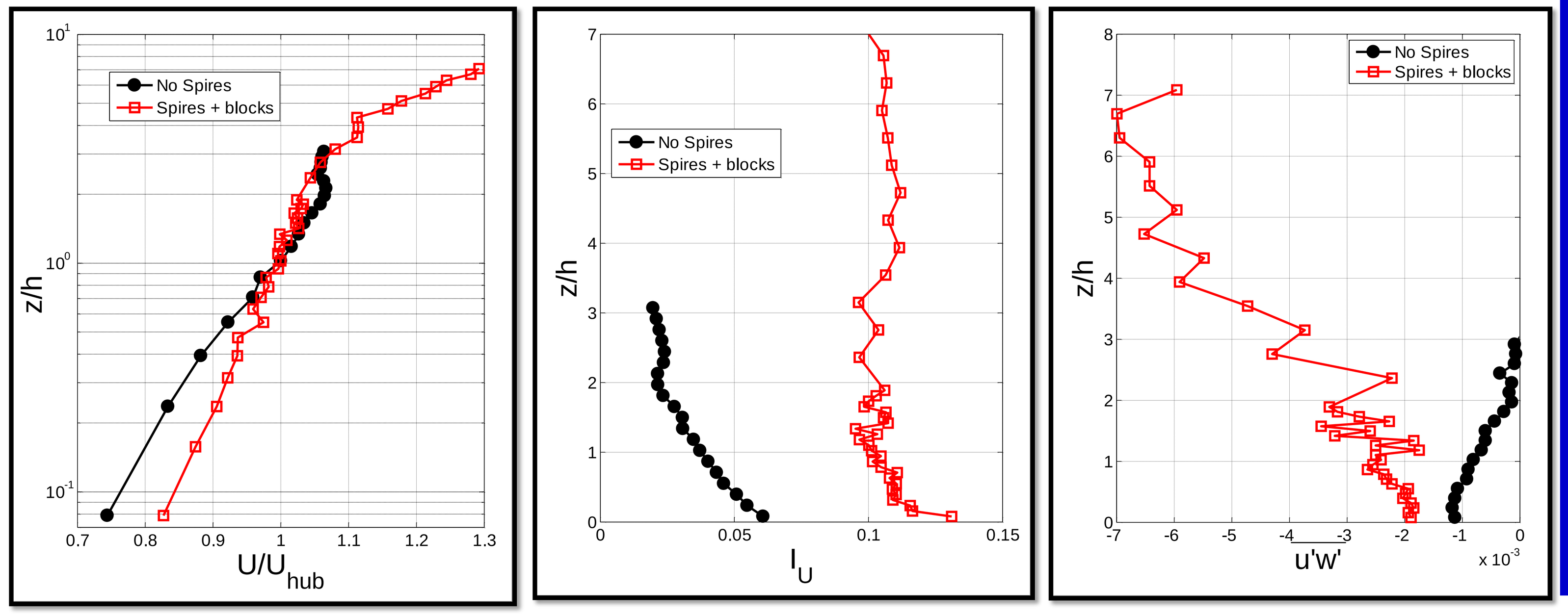
WIND TURBINE MODEL

- **3 blades GSW**; D = diameter 152 mm;
- h = hub height 127 mm;

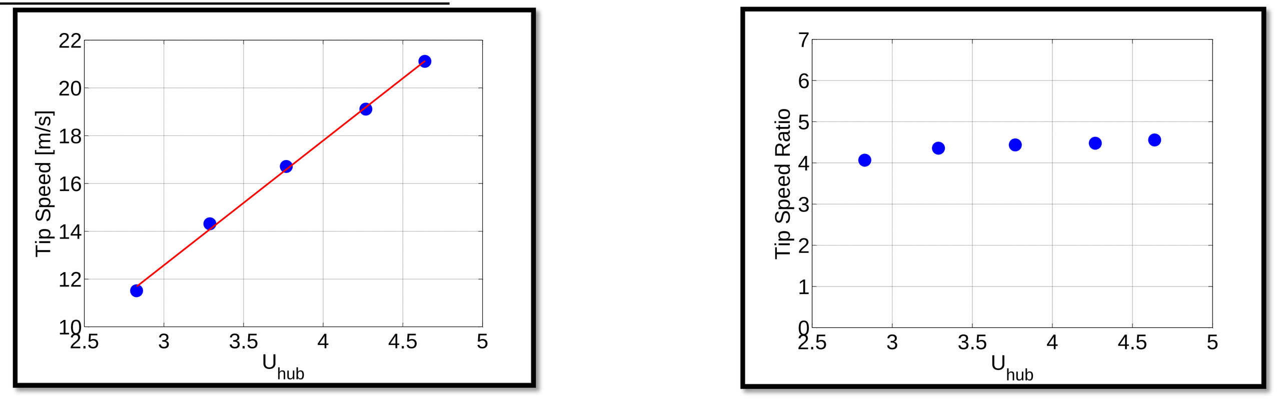
Spires + blocks

Incoming flow

No Spires	Spires+blocks
Z_0=0.0016 mm;	Z_0=0.0001 mm;
u_*=0.23 m/s;	u_*=0.13 m/s
δ=270 mm;	δ=950 mm;
$Re_\tau = u_*\delta/\nu$=4170;	$Re_\tau = u_*\delta/\nu$=8290;
U_{hub} 1st row = 6.6 m/s.	U_{hub} 1st row = 4.6 m/s.



Wind turbine characterization

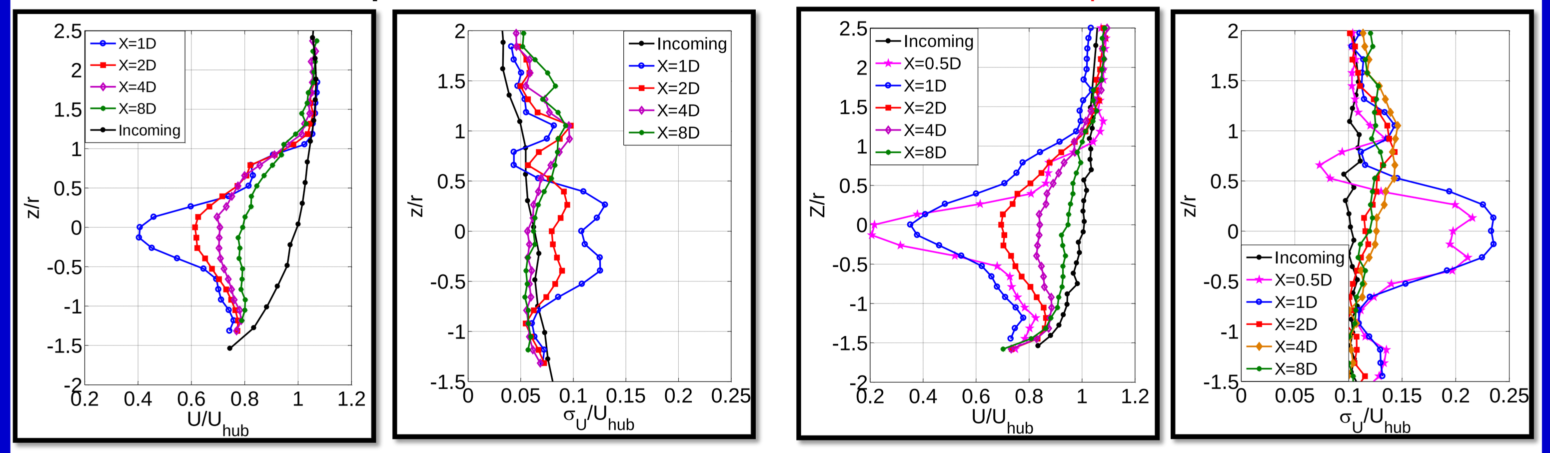


Tip speed of the wind turbine is **linearly proportional** to the **incoming velocity** at the hub height, i.e. roughly constant tip speed ratio.

Characterization of the wake produced from a single wind turbine

No Spires

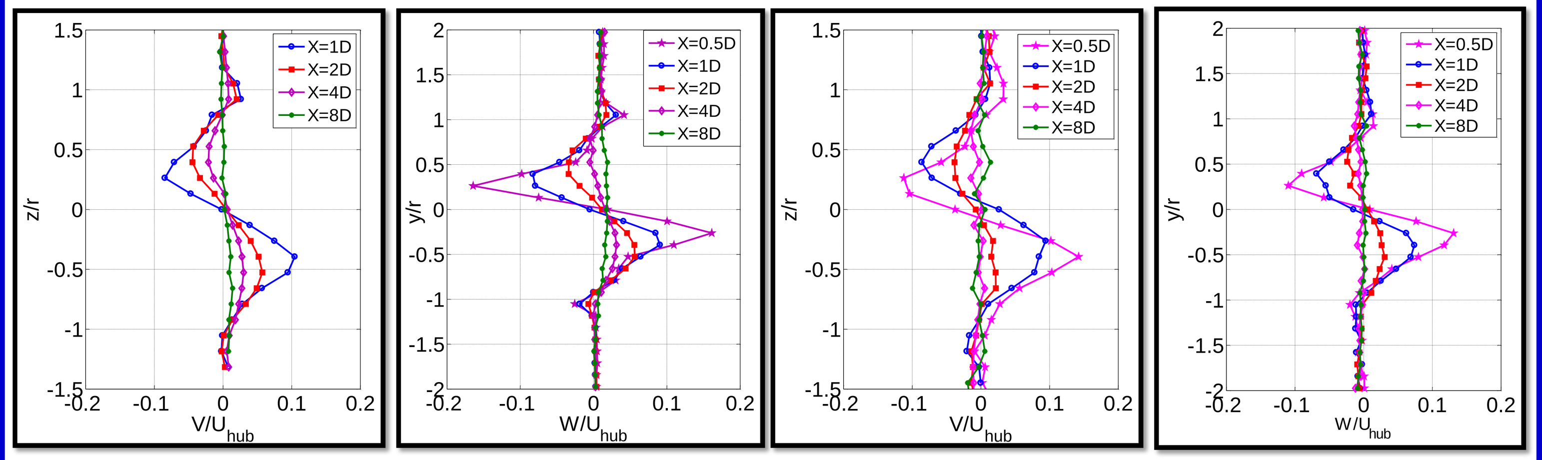
Spires + blocks



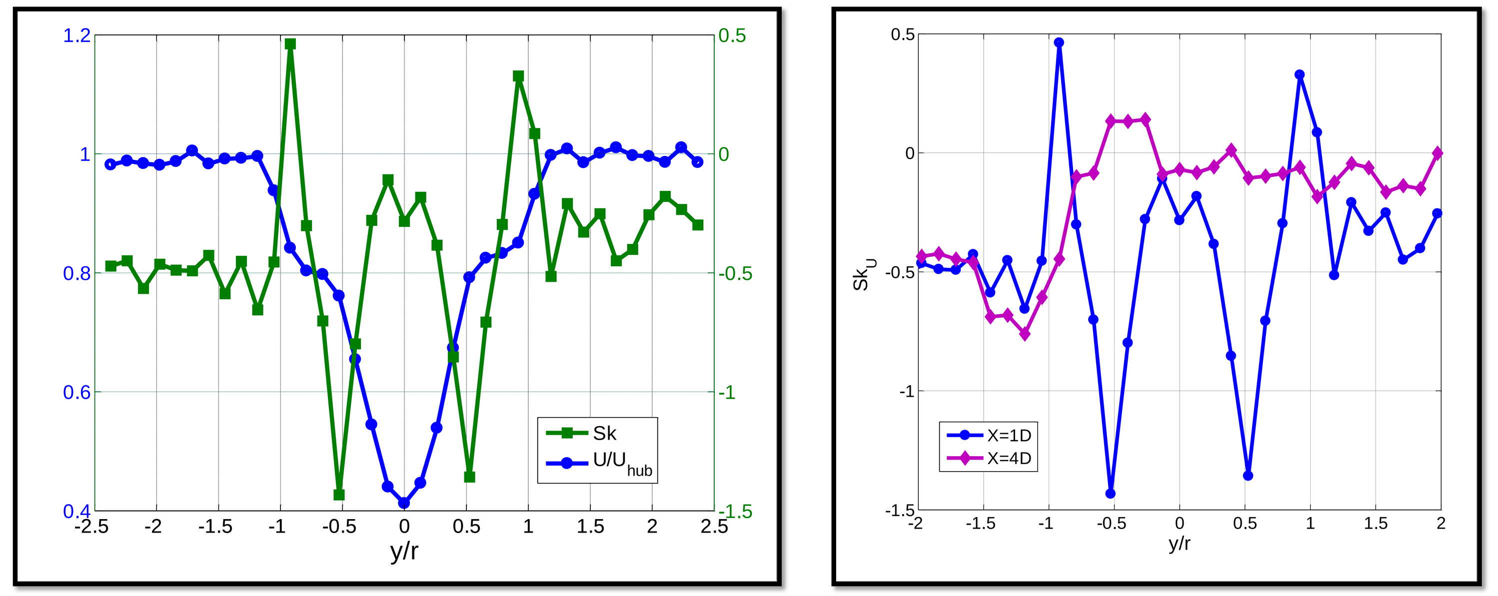
- Similar mean wake flows are produced with different incoming flows;
- For the incoming flow with higher background turbulence level, a slightly higher turbulence is produced in the wake of the wind turbine;
- By proceeding downstream the wake is **recovering faster for the case with higher turbulence** level and also the turbulence is diffusing earlier;
- While the turbulence is diffusing into the wake by moving downstream, a certain **flow unsteadiness** is still present in proximity of the **top tip of the blade** (z/r ≈ 1) .

No Spires

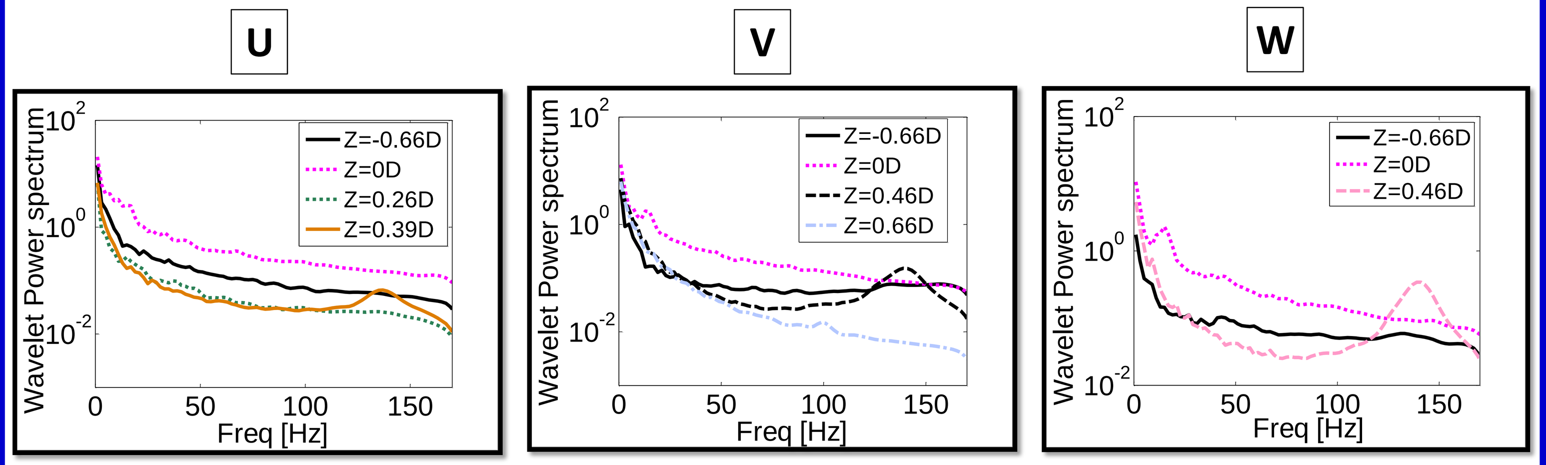
Spires + blocks



A small but evident **axial vorticity**, i.e. a rotational wake, is present in the central part of the wake; this azimuthal momentum is in the opposite direction of the blade rotation.



The average position of the **tip-helicoidal vortices** is clearly detectable from a positive peak of the skewness of the axial velocity. The tip vortices can be considered completely diffused for downstream distances larger than 2D.

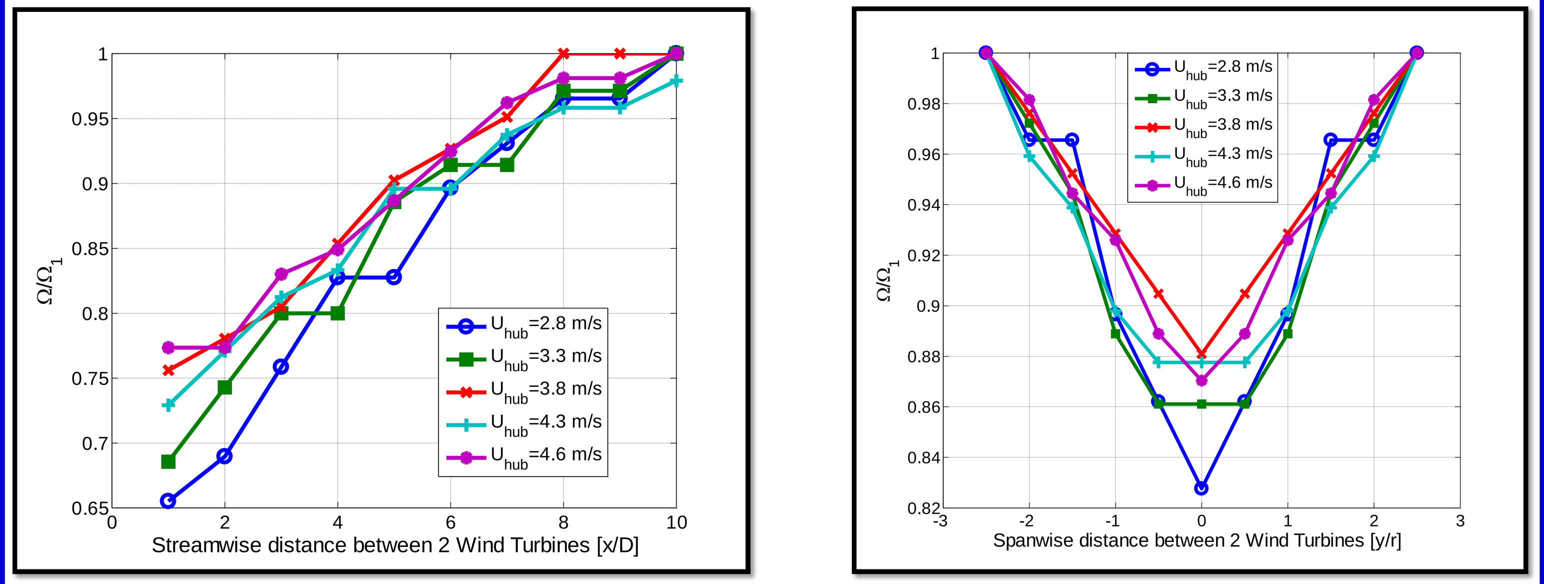


- From a **spectral analysis** of the velocity signals an increased energy at very **low frequencies** is observed by moving towards the **central part of the wake** (peak at 15 Hz). This spectral component, typically ascribed to the **wake wandering**, is rapidly reduced by moving downstream;
- In proximity of the top-tip of the blade an energy peak is clearly detected at a **higher frequency** related to the shedding of the **tip-helicoidal vortex**.

Flow interaction between wind turbines

Two wind turbines in column

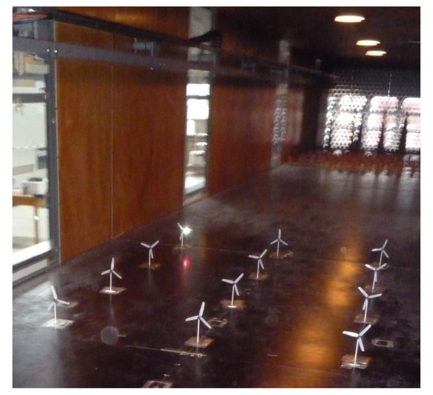
Two staggered wind turbines Δx=5D

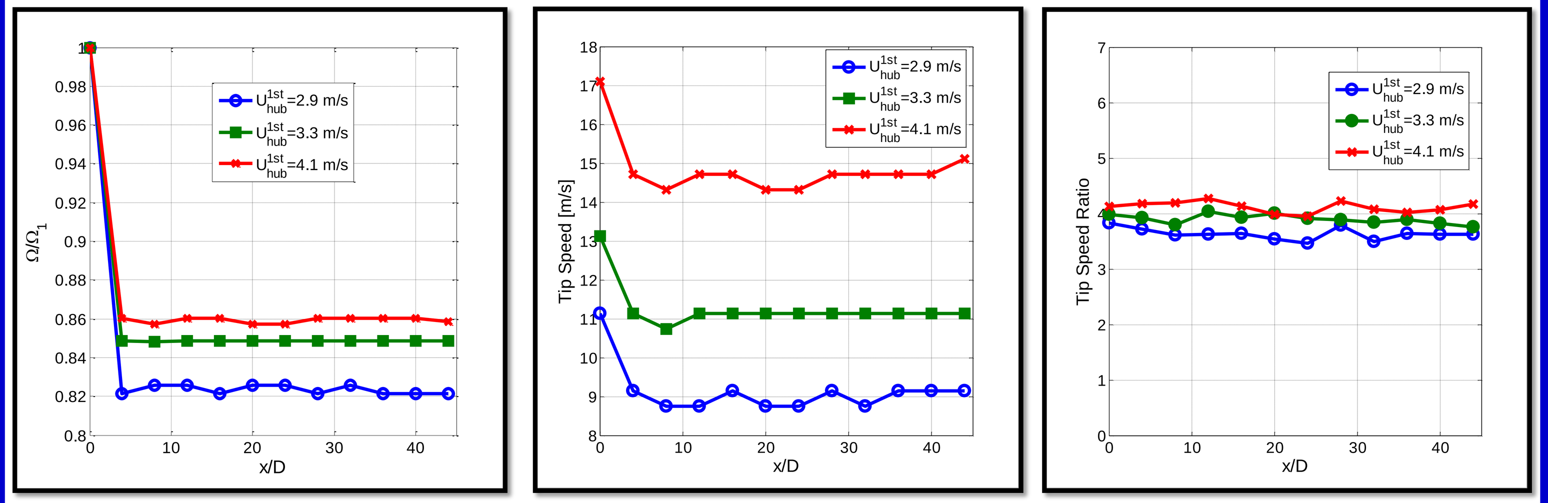


- The rotation velocity of the following wind turbine reaches the one of the wind turbine placed in front for streamwise distances larger than 8 diameters;
- Staggering a wind turbine has a larger effect on its rotation velocity than increasing the streamwise distance from the wind turbine placed upstream.

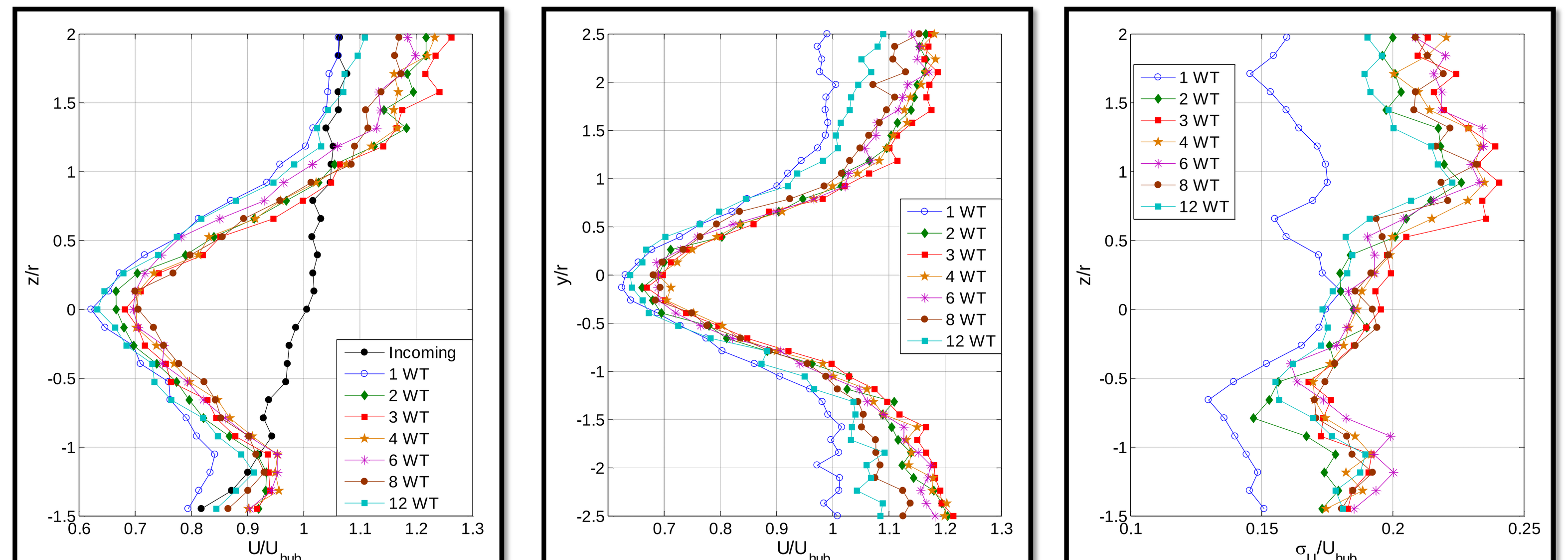
Aligned wind farm

- 3 wind turbines for each row with a cross-distance of 7D;
- 12 rows of wind turbines with a streamwise distance of 4D.





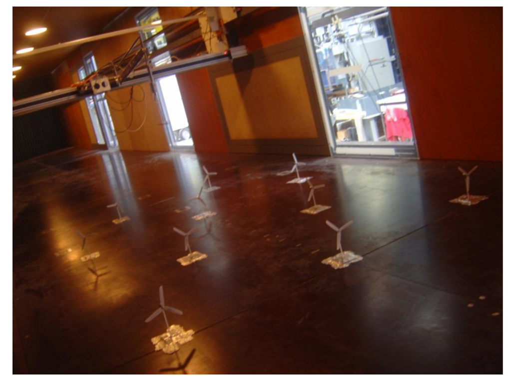
The rotational velocity of the **second wind turbine** is roughly **20% smaller** than the one of the first wind turbine . For the following wind turbines the rotational velocity remains roughly unchanged.

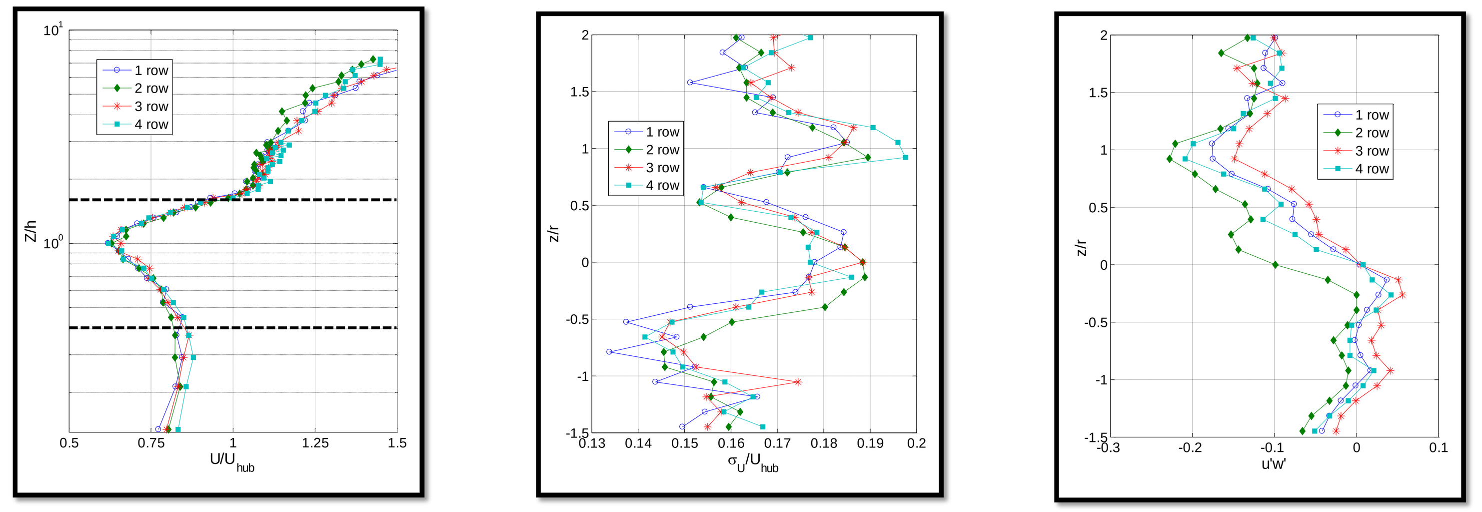


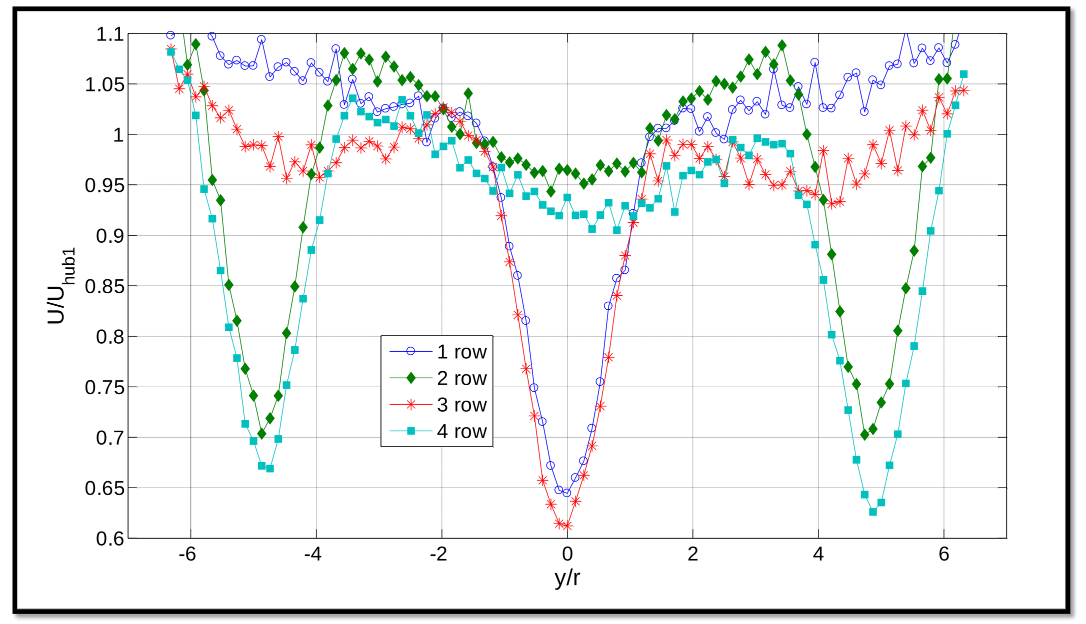
- Self-similarity of the wake profiles when velocities are non-dimensionalized with the respective axial velocity at the hub height;
- The turbulence produced from the wind turbines in the first row is slightly smaller than for the following ones.

Staggered wind farm

- 3/2 wind turbines for each row with a cross-distance of 5D;
- 4 rows of wind turbines with a streamwise distance of 5D.







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