Investigation on wind turbine wakes: wind tunnel tests and field measurements with Lidars

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• Motivation;
• Boundary layer wind tunnel @ EPFL;
• Velocity measurements and characterization of wind turbine models;
• Field measurements with Doppler Wind Lidars;
• Simultaneous measurements with 2 or 3 Lidars and data retrieval of 2D velocity fields.
Motivation

Wind energy: synergistic investigation with different tools

Numerical Simulations

Field Measurements

Wind Tunnel
Objectives of wind tunnel tests and field measurements:

• Assessment of numerical codes (i.e. LES simulations);

• Characterization and modeling of wind turbine wakes;

• Wind turbine wake interaction and wind farm design;

• Evaluation of topography effects;

• Wind farm siting;

• Interaction between wind farms.
Wind Tunnel Experiments

Boundary Layer Wind Tunnel @ EPFL:
• Testing chamber: 28 m x 2.5 m x 2.5 m;
• Adjusting ceiling;
• Maximum velocity 8 m/s;
• Minimum turbulence level: 2%.

Instrumentation:
• 4 hole pressure-probe COBRA by TFI;
• Hot-wire anemometry;
• Laser tachometer.

Models:
• 3-bladed GSW wind turbines;
• d=152 mm; h=127 mm;
Characterization of the wake produced from a single wind turbine: streamwise velocity field

\[ y/d = 0 \]

The analysis of the mean flow is fundamental to evaluate the wake recovery, thus to design the streamwise distance between rows of a wind farm.
Streamwise velocity field

Wake recovering by proceeding downstream

\[ x/d = 0.5 \]

\[ x/d = 3 \]
Streamwise velocity field

\[ y/d = 0 \]
Streamwise velocity field

\( y/d = 0 \)
Streamwise velocity field

$y/d = 0$
When the incoming flow is removed, vertical sections of the streamwise velocity are well fitted by Gaussian functions.
Swirling wake in the near-field

$x/d=0.5$

Spanwise velocity       Vertical velocity

Presence of axial vorticity, which vanishes rapidly by moving downstream.
Wake turbulence diffuses, while fluctuations of the axial velocity are still observed in the far-wake in proximity of the top-tip of the blades.
Turbulent Stresses

\[ x/d=0.5 \quad [(m/s)^2] \]

\[ x/d=3 \quad [(m/s)^2] \]

\[ u'v' \]

\[ u'w' \]

\[ v'w' \]
Spectral Analysis

$x/d=0.5$

High energy at very low frequencies at the central part of the wake (peak ~ 15 Hz). In proximity of the top-tip of the blades an energy peak is clearly detected at a higher frequency related to the shedding of the tip-helicoidal vortices.
Wind Farm Power Production

Aligned wind farm

Staggered wind farm

\[ S_x = 4 \]
\[ S_y = 4 \]
LIDAR (LIght Detection And Ranging) is a remote sensing instrument, which enables to evaluate the velocity component along the direction of the emitted laser beam from the Doppler effect on the backscattered ray.

Halo Photonics Wind LIDAR Characteristics:

- **Wavelength**: 1.5 μm;
- **Repetition rate**: 15 kHz;
- **Maximum Sampling rate between two consecutive scans**: 0.77 Hz;
- **First point distance**: 40 m;
- **Maximum spatial resolution**: 18 m;
- **Maximum distance**: 3 km;
- **Telescope**: 50 mm.
Wind turbines

• @ Martigny: «Mont d’Ottant»; Enercon E-90, 2050 kW; rotor diameter 91 m; hub height 100 m;

• @ Collonges: «Cime de l’Est»; Enercon E-70, 2050 kW; rotor diameter 71 m; hub height 95 m.
The signal-to-noise ratio of the Lidar could be increased by increasing the number of rays emitted for each measurement. It is strictly dependent of the aerosol conditions.

**Number of rays = 1**
The signal-to-noise ratio of the Lidar could be increased by increasing the number of rays emitted for each measurement. It is strictly dependent of the aerosol conditions.

**Number of rays = 2**
The signal-to-noise ratio of the Lidar could be increased by increasing the number of rays emitted for each measurement. It is strictly dependent on the aerosol conditions.

Number of rays = 4
The signal-to-noise ratio of the Lidar could be increased by increasing the number of rays emitted for each measurement. It is strictly dependent of the aerosol conditions.

Number of rays = 16
The signal-to-noise ratio of the Lidar could be increased by increasing the number of rays emitted for each measurement. It is strictly dependent of the aerosol conditions.

**Number of rays = 64**
RHI, Range Height Indicator, i.e. maps of the streamwise velocity over the symmetry vertical plane of the wake. Each map made of 40 elevation angles; number of rays 1; sampling time 41 seconds.
RHI, Range Height Indicator, i.e. maps of the streamwise velocity over the symmetry vertical plane of the wake. Each map made of 40 elevation angles; number of rays 1; sampling time 41 seconds.

Mean value map

Standard deviation map
• Measurement performed with a fixed elevation angle;
• 1 Ray for each measurement;
• 512 Scans for each direction.
Stares: mean velocity

![Graph showing mean velocity as a function of x/D and (z-H)/D for different angles of attack.](image)

- Mean U [m/s]
- X/D
- (Z-H)/D

- Angles of attack: 17.71°, 19.2°, 23.1°, 28.8°, 37.7°, 52.5°
Detection of peaks of the fluctuating velocity...
Detection of peaks of the fluctuating velocity in proximity of the top-tip of the blade.
Peaks of turbulence at the blade top-tip

Wind tunnel

Lidar Measurements
Spectral analysis of Lidar signals

Stare at a fixed elevation angle 17°, 512 scans, sampling frequency 0.77 Hz

Characterization of the inertial subrange with Lidar measurements
Simultaneous measurements with 2 Lidars

- Lidar 1 placed at the wind turbine location and pointing downstream;
- Lidar 2 placed $x/d=6$ and pointing upstream;
- Measurements performed with 1 ray; 256 scans.
Simultaneous measurements with 2 Lidars

\[ x/d = 0.5, \ (z-h)/d = 0.5 \]
Simultaneous measurements with 2 Lidars

\[ x/d=5, \ (z-h)/d=0.5 \]
Simultaneous measurements with 2 Lidars

Statistics

Mean

Std

[\text{m/s}]

x/d

U

W
Summary

• Wind tunnel tests for the characterization of wakes produced from wind turbines;
• Lidar measurements enables to characterize the mean flow downstream of a wind turbine;
• Characterization of the inertial subrange with Lidar measurements;
• Retrieval of data obtained from simultaneous measurements from 2 Lidars;
• Wind tunnel tests and Lidar measurements highlight the presence of an increased turbulence intensity in correspondence of the top-tip of the blades.

Perspectives:
• Wind tunnel tests of wind farms, investigation on topography effects, interactions between wind farms;
• Improvement of the Lidar set-up; measurements of wind farms.

Thanks for your attention!
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