WIND FARM MODELLING STRATEGIES

GDR EMR: SIMULATION ET OPTIMISATION POUR LES ENERGIES MARINES RENOUVELABLES

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WIND TURBINES WAKES


Horns Rev 1, Vattenfall, Christian Steiness

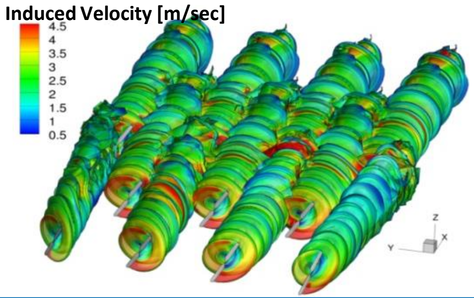
- Wind farm arrangement
  - Turbine wakes = inflow conditions of downstream rotors
- Wake effects
  - Reduced wind velocity
    - ⇨ Power loss up to 20% (Barthelmie et al., 2010)
  - Increased turbulence levels
    - ⇨ Increased loads on downstream turbines, affecting fatigue and life time (Burton et al., 2001)
- Various active wake control strategies
  - Wake steering by yaw misalignment
  - Axial induction-based control by individual blade pitching and/or torque (TSR) control

IFPEN DEVELOPMENTS IN WAKE SIMULATIONS

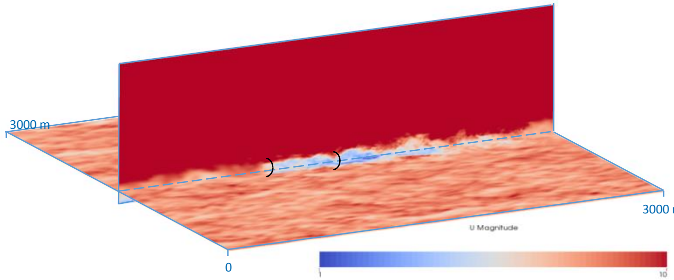
- Advanced aerodynamic modelling for near wakes
  - R&D lifting-line code with free wake (CASTOR) for near wake simulations

    ⇨ part of Mexnext project
- Early developments in intermediate/far wake and farms modelling
  - Engineering wake models with the **FarmShadow** rigid-body solver

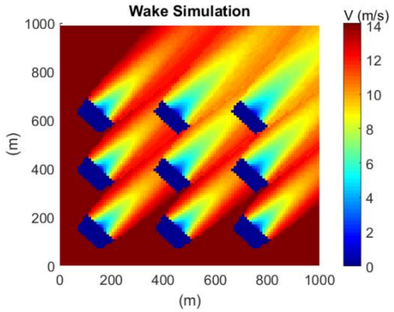
    ⇨ part of Wakebench project
  - Coupled CFD / actuator approaches
    - Intermediate and far wake simulations **(SOWFA)**
    - Mesoscale approach with coupling between actuator methods and meteorological solver - PhD thesis with MESO-NH solver (MeteoFrance)



Vortex method



CFD/Actuator methods

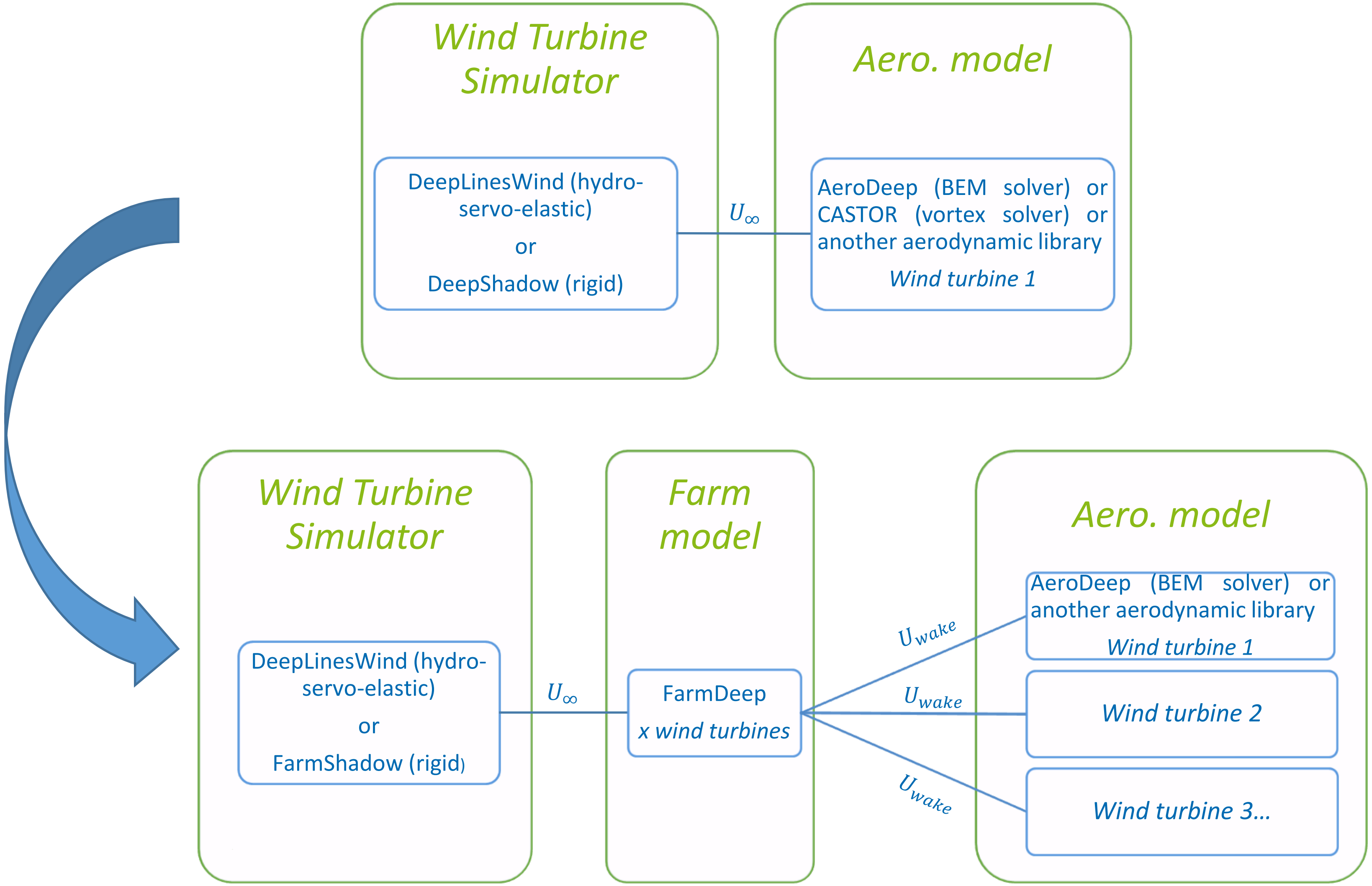


Wake model

Ability to simulate near/intermediate wakes → to far wakes

FROM ONE ROTOR TO N ROTORS

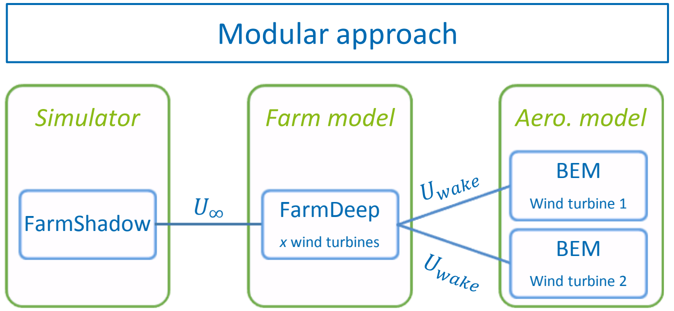
Going from one rotor to a wind farm thanks to modularity



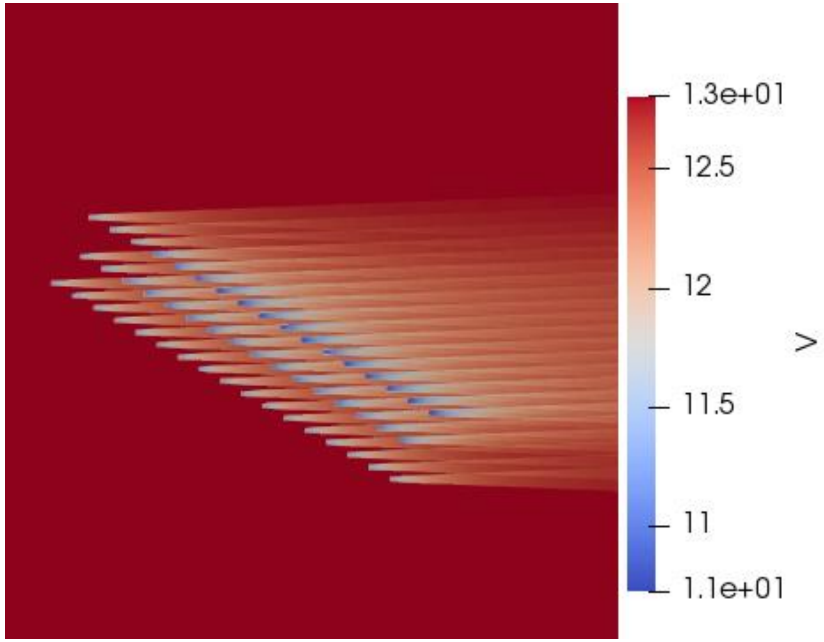
OUTLINE

- FarmDeep: an engineering wake model developed at IFPEN
- Validation process
  - FLORIS, NREL engineering wake model
  - CFD simulations
  - Code-to-code comparisons
- Future developments

FARM MODELLING – ENGINEERING WAKE MODEL (1)



- FarmShadow
  - Rigid wind turbine
  - In-house simplified aerodynamic models (BEM…)
  - Modularity
- FarmShadow computation and setup
  - Definition of the farm (location of each turbine, type of turbine)
  - Definition of the turbine(s)
    - Parameters for the hub, tower, nacelle…
    - Definition of the blades (center, twist, chord and associated airfoils)
    - Definition of the controller (set ω and blade pitch as a function of the wind)
  - Definition of the wind
    - Uniform and constant wind (U_x, U_y) or TurbSim plugin
  - Description of the wake model, FarmDeep
    - Jensen wake model
    - Cumulative velocity

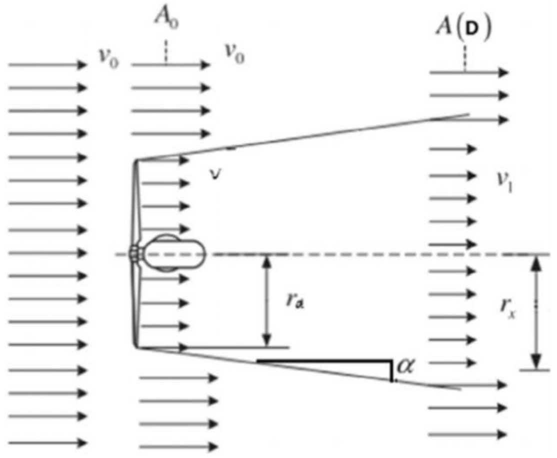


FARM MODELLING – ENGINEERING WAKE MODEL (2)

- Early developments
- Jensen wake model *(Katic formulation – used in WASP, windPro, WindFarmer, OpenWind…)*
  - Assumptions:
    - Wake expands proportionally to the axial downstream distance from the rotor
    - Uniform wind velocity in the lateral direction

$$U(x) = U_0\left(1-\left(1-\sqrt{1-C_t}\right)\left(\frac{R}{R+\alpha x}\right)^2\right)$$

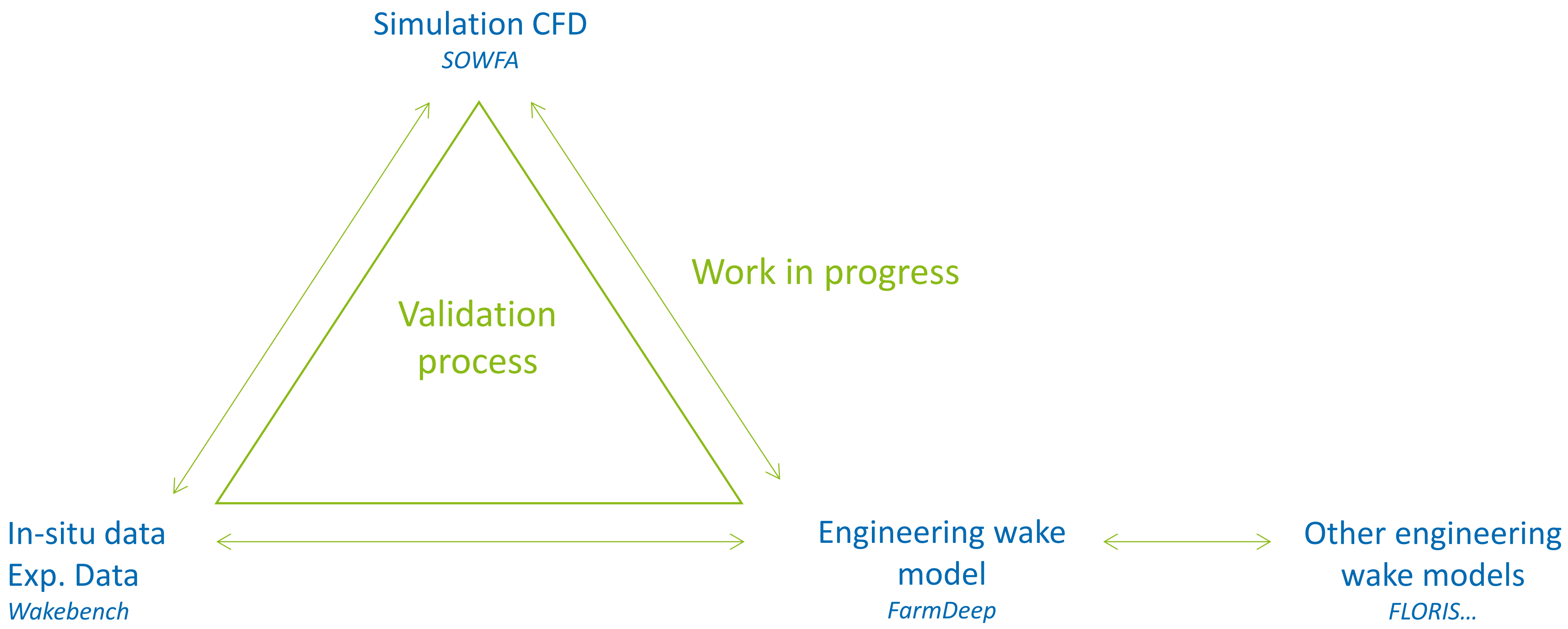
with R the radius of the turbine, C_T the thrust coefficient, α the wake decay coeff, $\alpha = 0.04$ for offshore applications



  - Accurate in far wake regions (6-8D for offshore and 3-5D for onshore turbines)
- Cumulative velocity – multiple wake effects

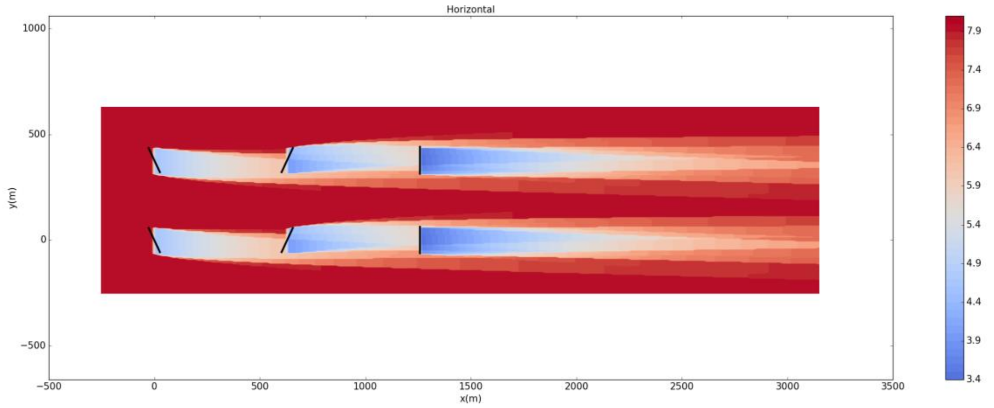
$$U_i = U_0\left(1-\sum_i\left(1-\frac{U_i}{U_0}\right)\right) \text{ or } U_i = U_0\left(1-\sqrt{\sum_i\left(1-\frac{U_i}{U_0}\right)^2}\right)$$

VALIDATION PROCESS



FLORIS, NREL ENGINEERING WAKE MODEL

- FLOw Redirection and Induction in Steady state (FLORIS)
  - Parametric model for wake effects
  - Stationary wind (power law)
  - Depends on a **Cp/Ct/wind speed table**
  - **Optimization** of axial induction and yaw angle for each rotor in a wind farm
- Predicts:
  - Steady state wake locations and effective flow velocities at each turbine
  - Resulting turbine electrical energy production



Yaw angles
Turbine 0 yaw = 25.0
Turbine 1 yaw = -25.0
Turbine 2 yaw = 0.0
Turbine 3 yaw = 25.0
Turbine 4 yaw = -25.0
Turbine 5 yaw = 0.0

Power
Turbine 0 power = 1520956.71865
Turbine 1 power = 934116.40872
Turbine 2 power = 663153.120808
Turbine 3 power = 1520956.71865
Turbine 4 power = 934116.40872
Turbine 5 power = 663153.120808

Effective Velocities
Turbine 0 velocity = 8.0
Turbine 1 velocity = 6.77678286493
Turbine 2 velocity = 5.68237148175
Turbine 3 velocity = 8.0
Turbine 4 velocity = 6.77678286493
Turbine 5 velocity = 5.68237148175

FLORIS – IMPACT OF THE CUMULATIVE MODEL

- Wake superposition models
  - Freestream linear superposition

$$U = U_\infty - \sum_j U_\infty - U_j$$

  - Local velocity linear superposition

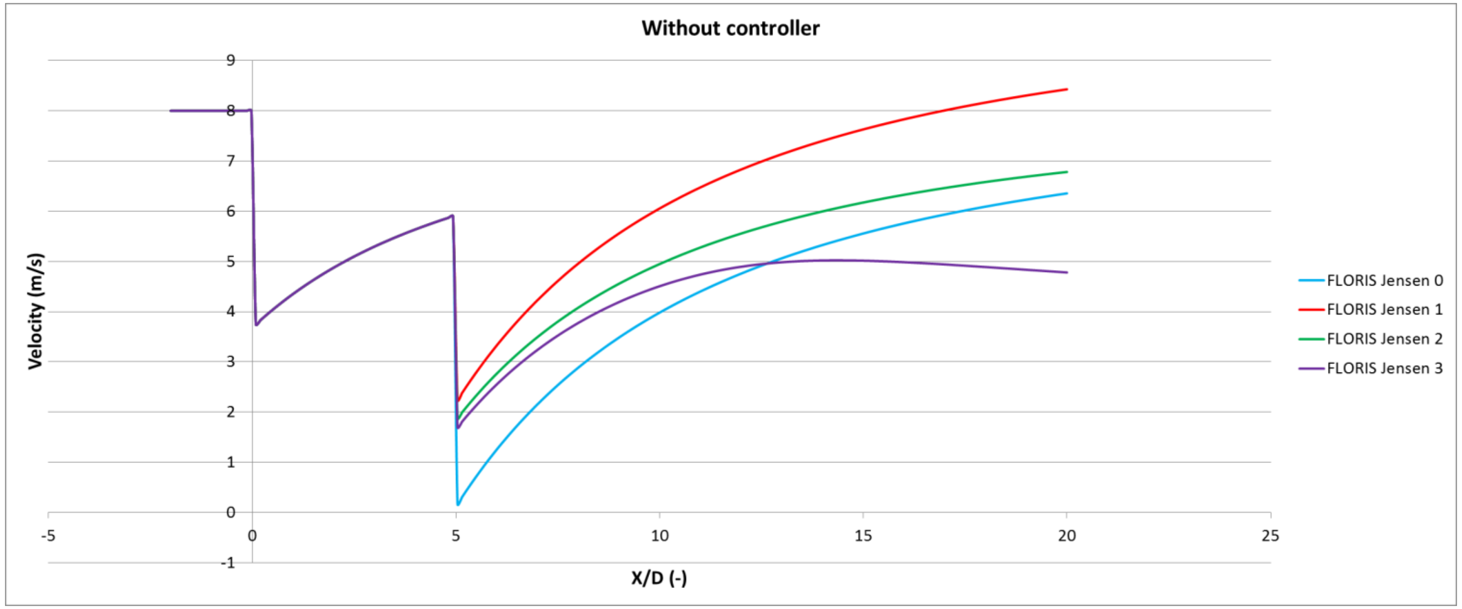
$$U = U_\infty - \sum_j U_{local} - U_j$$

  - Sum of squares freestream superposition

$$U = U_\infty - \sqrt{\sum_j (U_\infty - U_j)^2}$$

  - Sum of squares local velocity superposition

$$U = U_\infty - \sqrt{\sum_j (U_{local} - U_j)^2}$$



Various predictions
➡ Necessity to compare to a high-fidelity simulation or data

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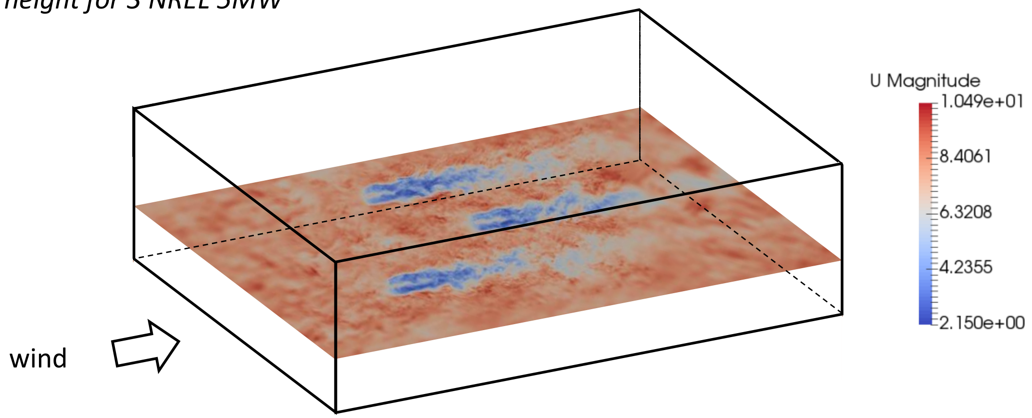
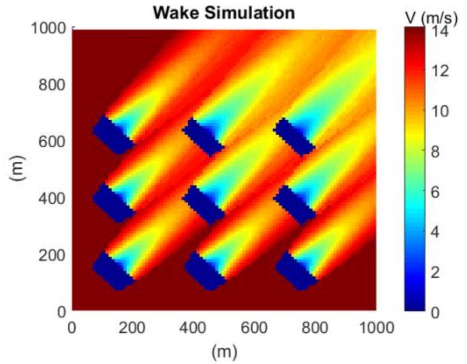
CFD SIMULATION WITH SOWFA

- Objective #1: identify significant phenomena with CFD
  - SOWFA, a solver based on the OpenFOAM CFD toolbox
  - Precursor simulation for atmospheric flow modelling
    - Large periodic domains with LES modelling ($3\text{km} \times 3\text{km} \times 1\text{km}$)
  - Hybrid simulation for the farm
    - Atmospheric inflow extracted from the precursor simulation
    - CFD-LES modelling of the airflow inside the domain
    - Actuator line method (wind turbines are considered as body forces)
    - Various refinement levels around the wind turbines ➔ final mesh : min 30×10^6 cells for a farm of 2-3 wind turbines
    - High CPU time (3 days on 80 processors for a 10-min simulation)

Instantaneous wind field at hub height for 3 NREL 5MW



- Objective #2: provide data to improve and validate the engineering wake model
  - Control and optimization of small farms: various configurations (yaw / pitch / position of the turbines / atmospheric conditions…)

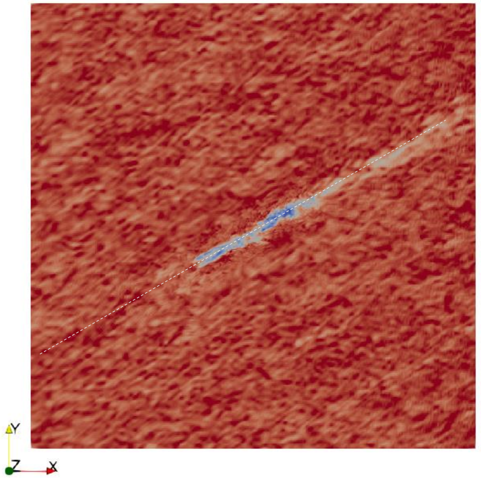


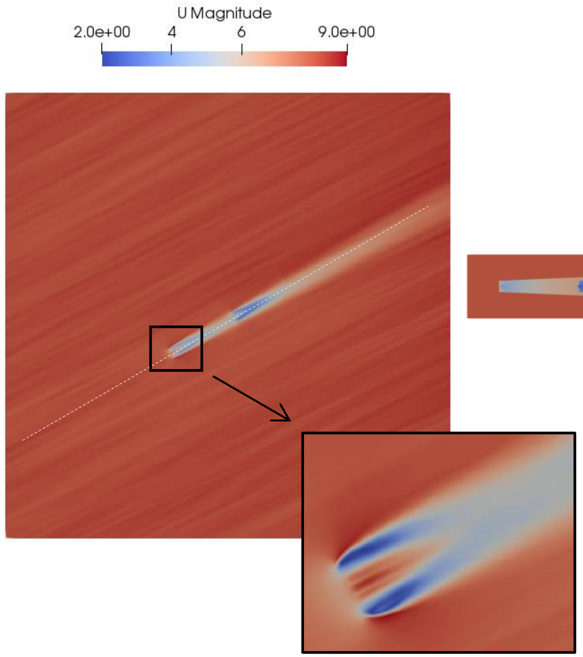
COMPARISONS (1)

- Simple example of validation: study of the wake of wind turbines in a small farm
  - Neutral atmosphere, surface roughness $z_0 = 1e-3$ m
  - Comparison SOWFA/FarmShadow/FLORIS
  - 2 NREL 5MW (5D spacing)

SOWFA simulation

Instantaneous turbulent wind field → Mean 10-min wind field



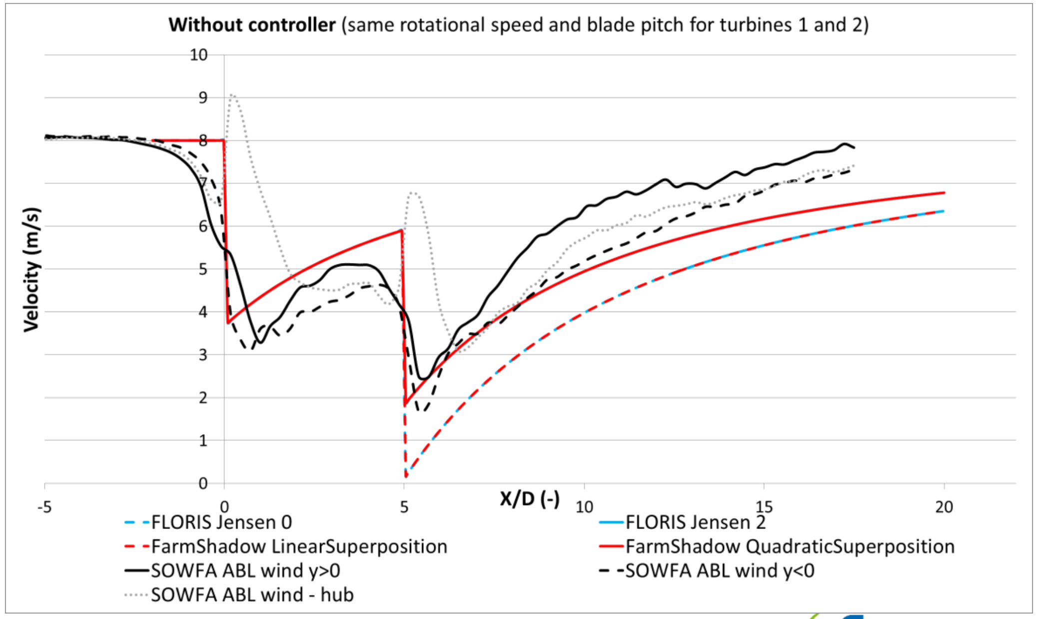


FarmShadow simulation

Stationary wind field

No hub

Comparison of the wake recovery at **mid-span**



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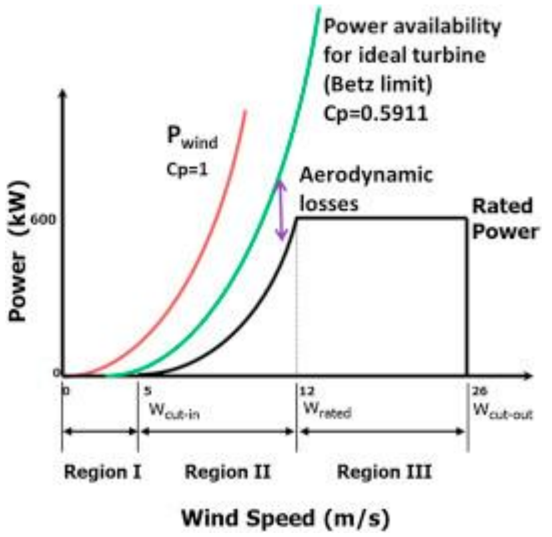
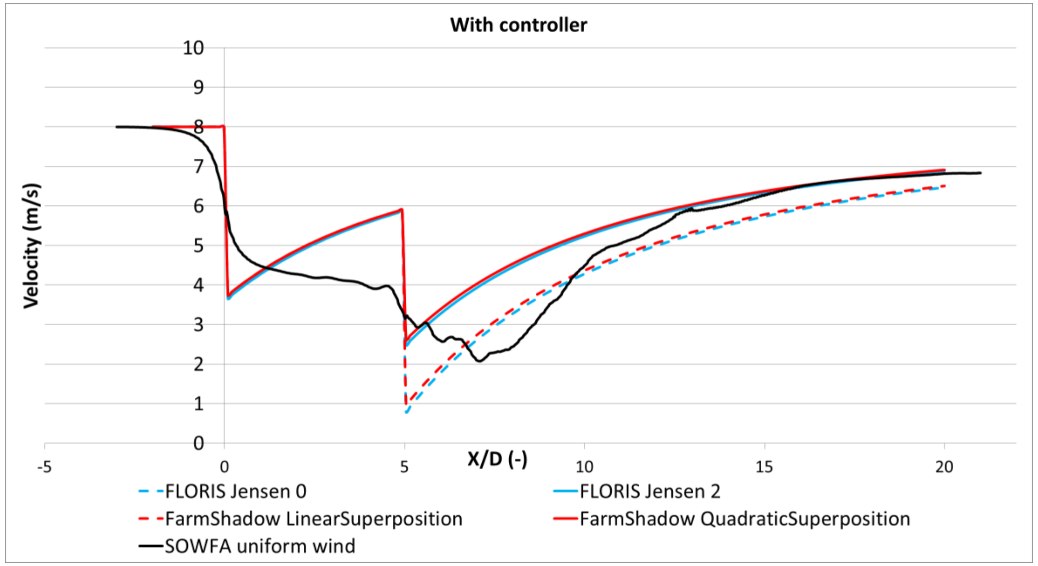
COMPARISONS (2)

- **Activation of the controller**
  - ➡ For a wind speed, optimum TSR and blade pitch angle based on the controller law
- **LES simulation with uniform wind**
  - -- for the wake recovery after upwind turbine
  - ++ good agreement after 8D downstream rotor 2





Comparison of the wake recovery at **mid-span**

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FUTURE DEVELOPMENTS

- Evaluation of our numerical tools against field/experimental data from the literature
- Increasing physical understanding of the interactions in a wind farm using CFD (e.g. SOWFA)
  - Turbulence intensity, atmospheric stability, meandering…
- A fast tool for
  - Wind farm control (deflection of the wake with yaw/wake steering) based on an optimization algorithm plugged on FarmShadow
- Perspectives: loads calculation in a wind farm
  - Evaluation of the DeepLinesWind/farm model coupling

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