

Large-Eddy Simulation of Deformable Wind Turbines

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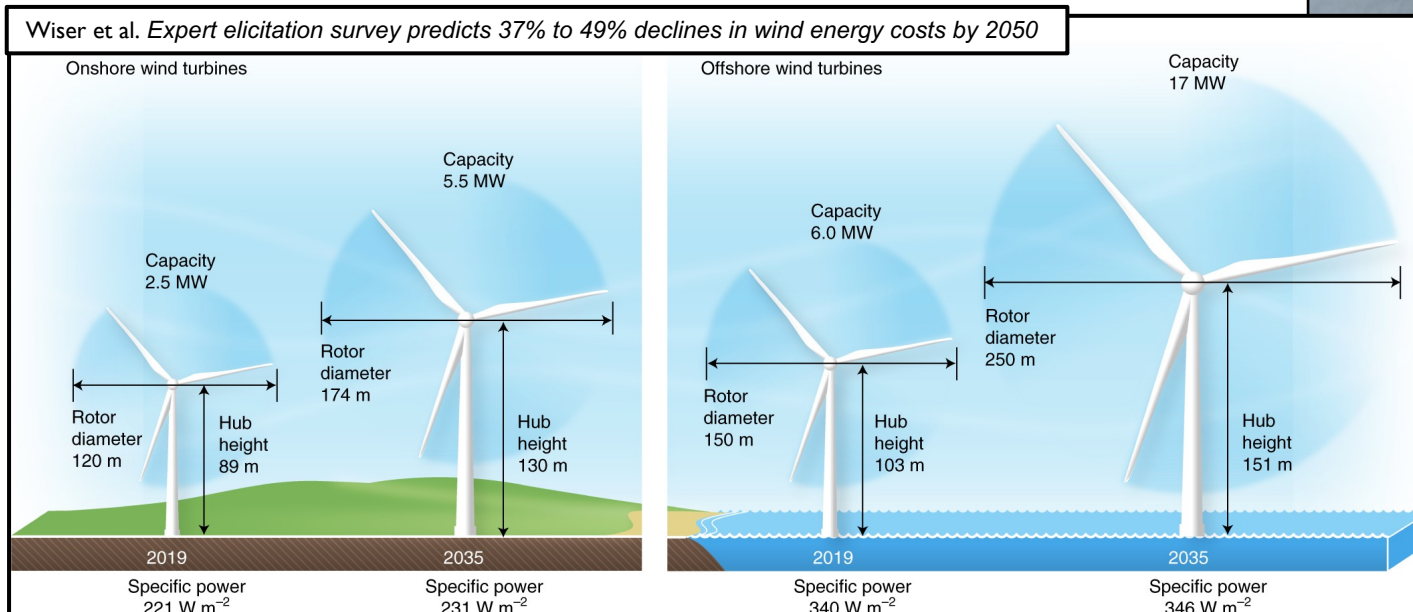


Renewable energy from the wind: challenges

Growing demand for renewable energies: new **offshore wind turbines** increasing the electrical output and reducing the LCOE are needed⁽⁶⁾

New challenges:

- **Bigger rotors with flexible blades**
- Complex multi-physics problem: **aero-servo-elasticity**^(7,8)
- Accurate simulation of the wake
- Wind farms⁽²⁾: **interaction between rotor and wake**



How blade deformations affect the near and far wake, the loads and the power output for an industrial wind turbine via high fidelity LES?

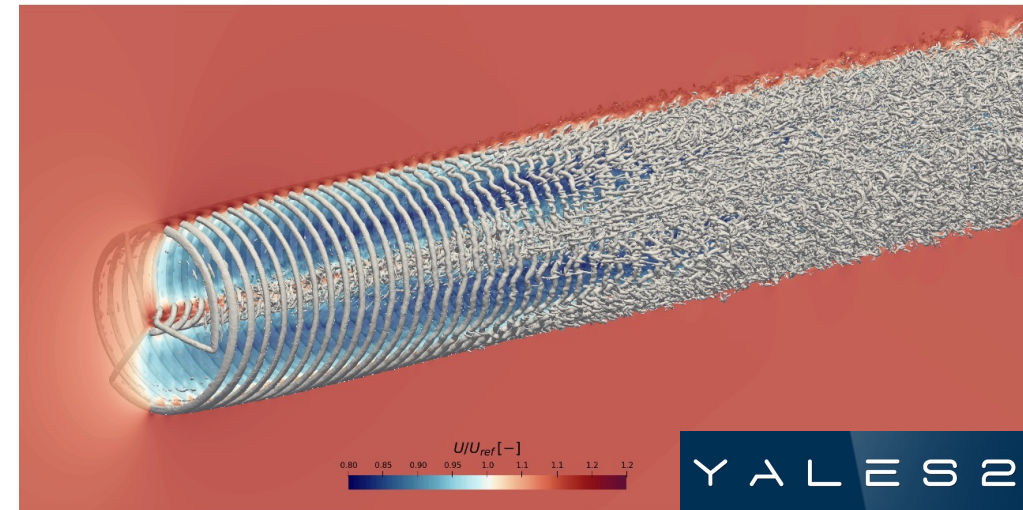
Multi-physics Simulation

Aero-servo-elasticity linking: required the coupling between an “aero” and a “servo-elastic” solver

YALES2 - Aerodynamic field

YALES2 for simulating 3D unsteady flows^(1,3)

- Low Mach-number **massively-parallel** finite-volume Large-Eddy Simulation (LES) flow solver on **unstructured meshes**



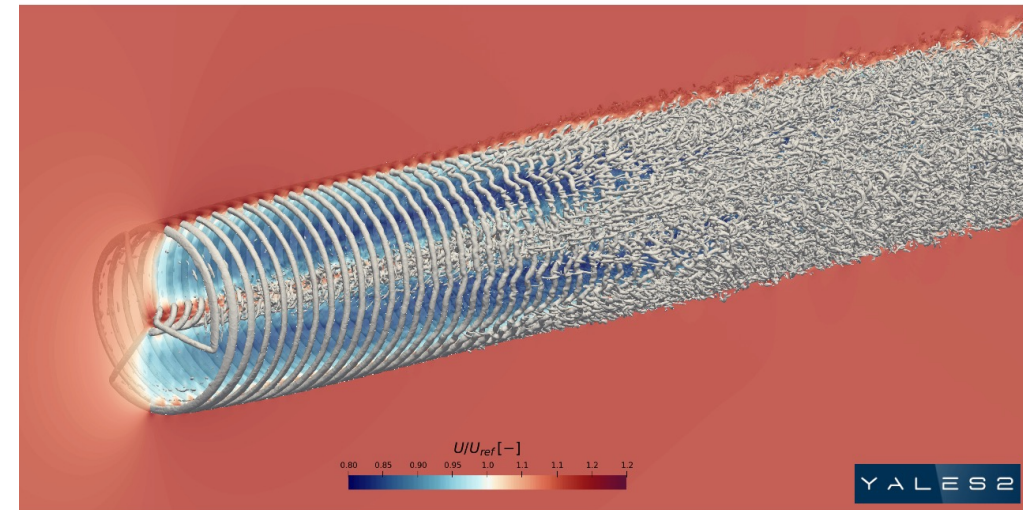
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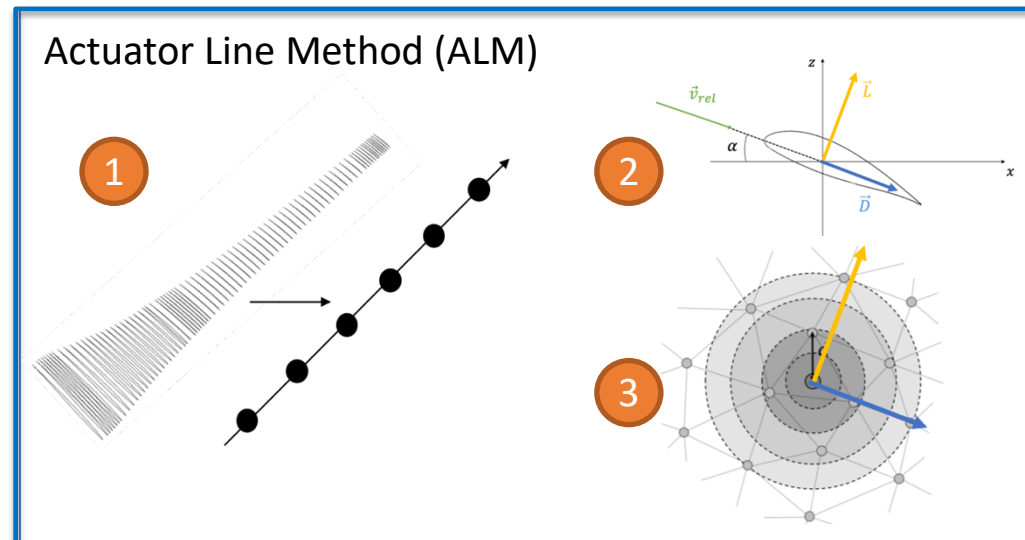
YALES2 for simulating 3D unsteady flows^(1,3)

- Low Mach-number **massively-parallel** finite-volume Large-Eddy Simulation (LES) flow solver on **unstructured meshes**



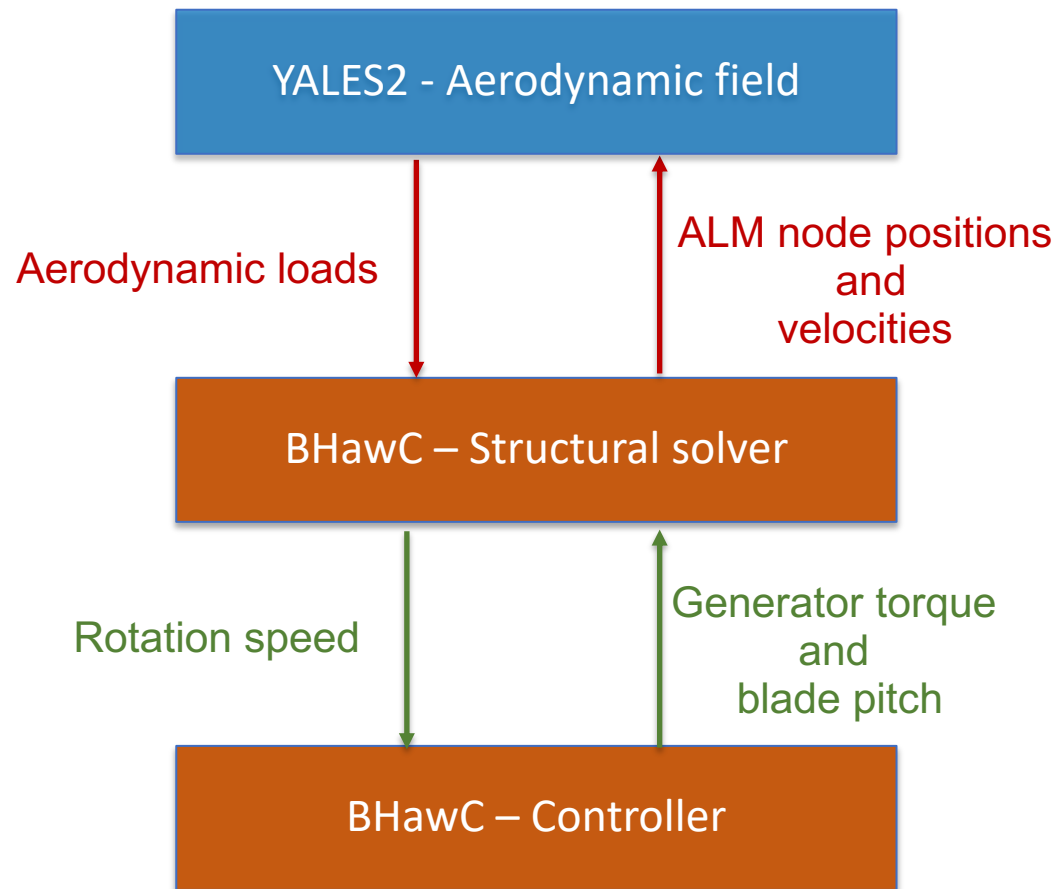
Blade modelling: **Actuator Line Method**⁽⁵⁾

1. Blade discretization as line
2. Force evaluation based on C_L and C_D
3. Force mollification on the aerodynamic mesh

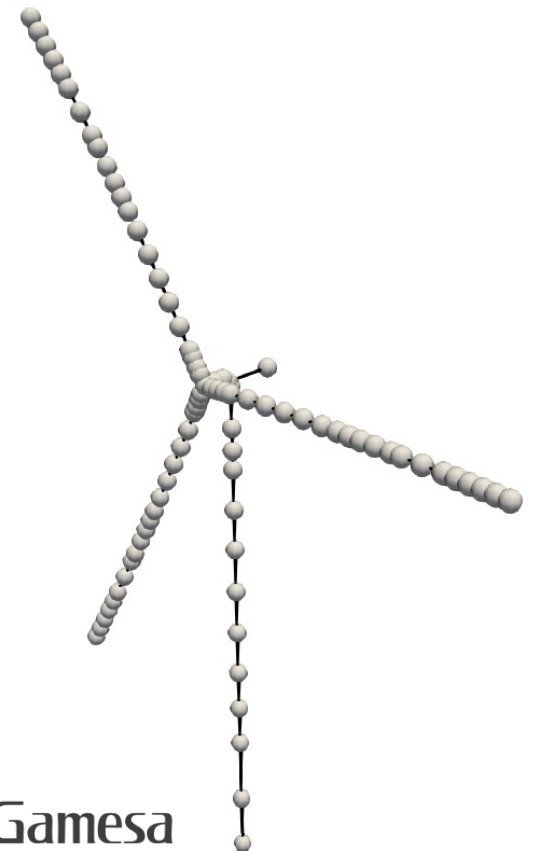


Multi-physics Simulation

Aero-servo-elasticity linking: required the coupling between an “aero” and a “servo-elastic” solver



BHawC: servo-elastic code for simulating structure deformations⁽⁴⁾
(equivalent to FAST and HAWC2)

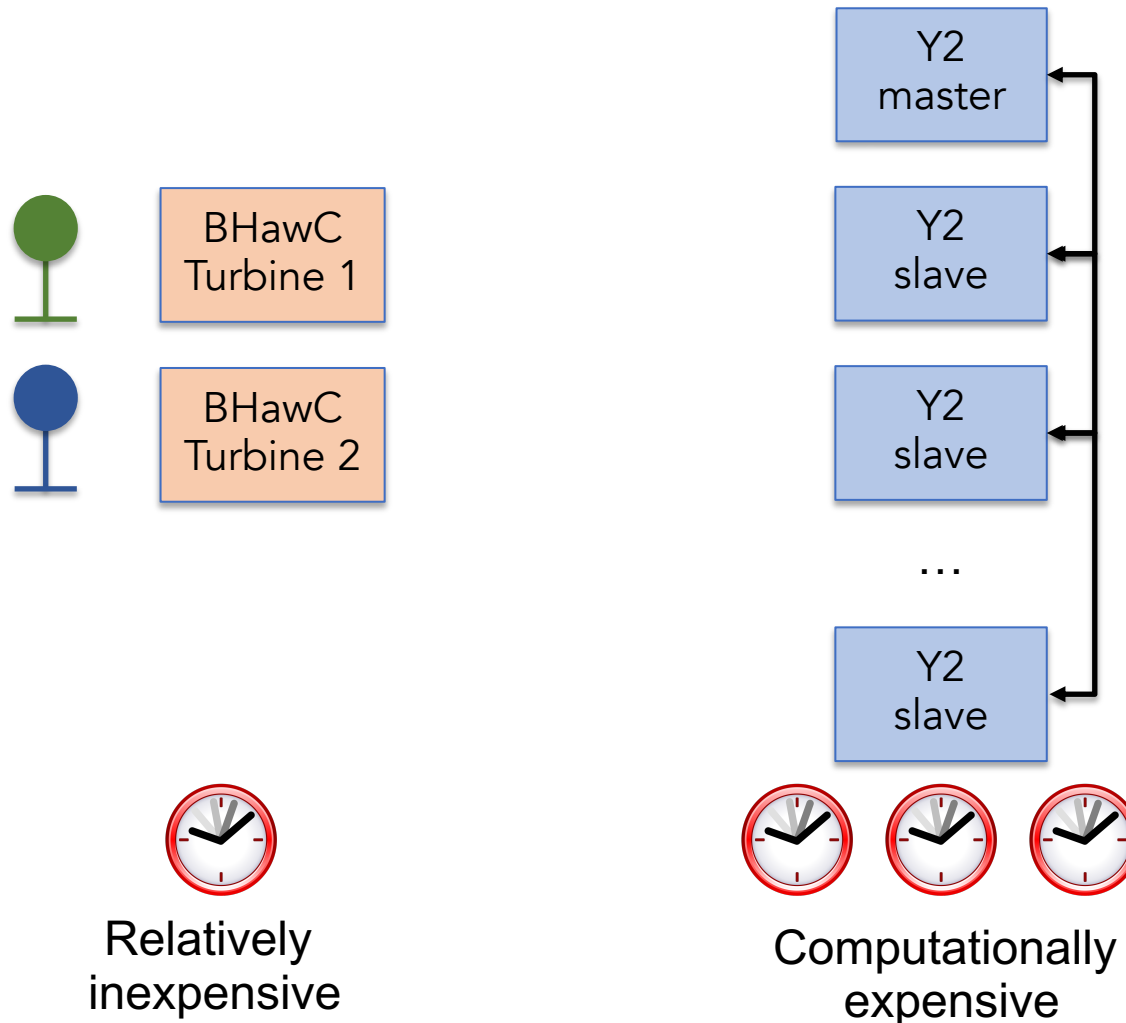


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YALES2-BHawC Coupling - Parallel Implementation

Message Passing Interface (MPI) handles communications between processors:

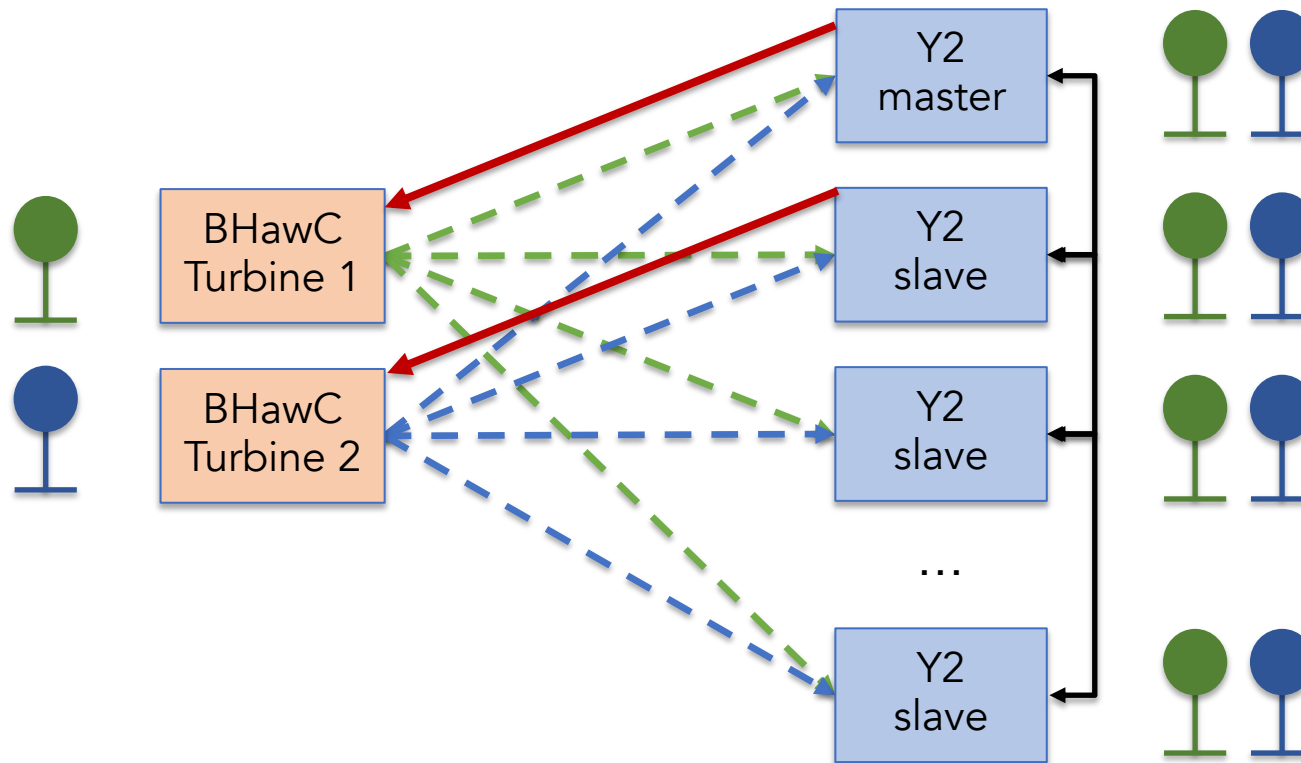
- Implementation of communicators in **external DLL** for more flexibility
- One processor assigned to each BHawC instance (i.e. wind turbine)
- Yales2 workload distributed on several processors



YALES2-BHawC Coupling - Parallel Implementation

Message Passing Interface (MPI) handles communications between processors:

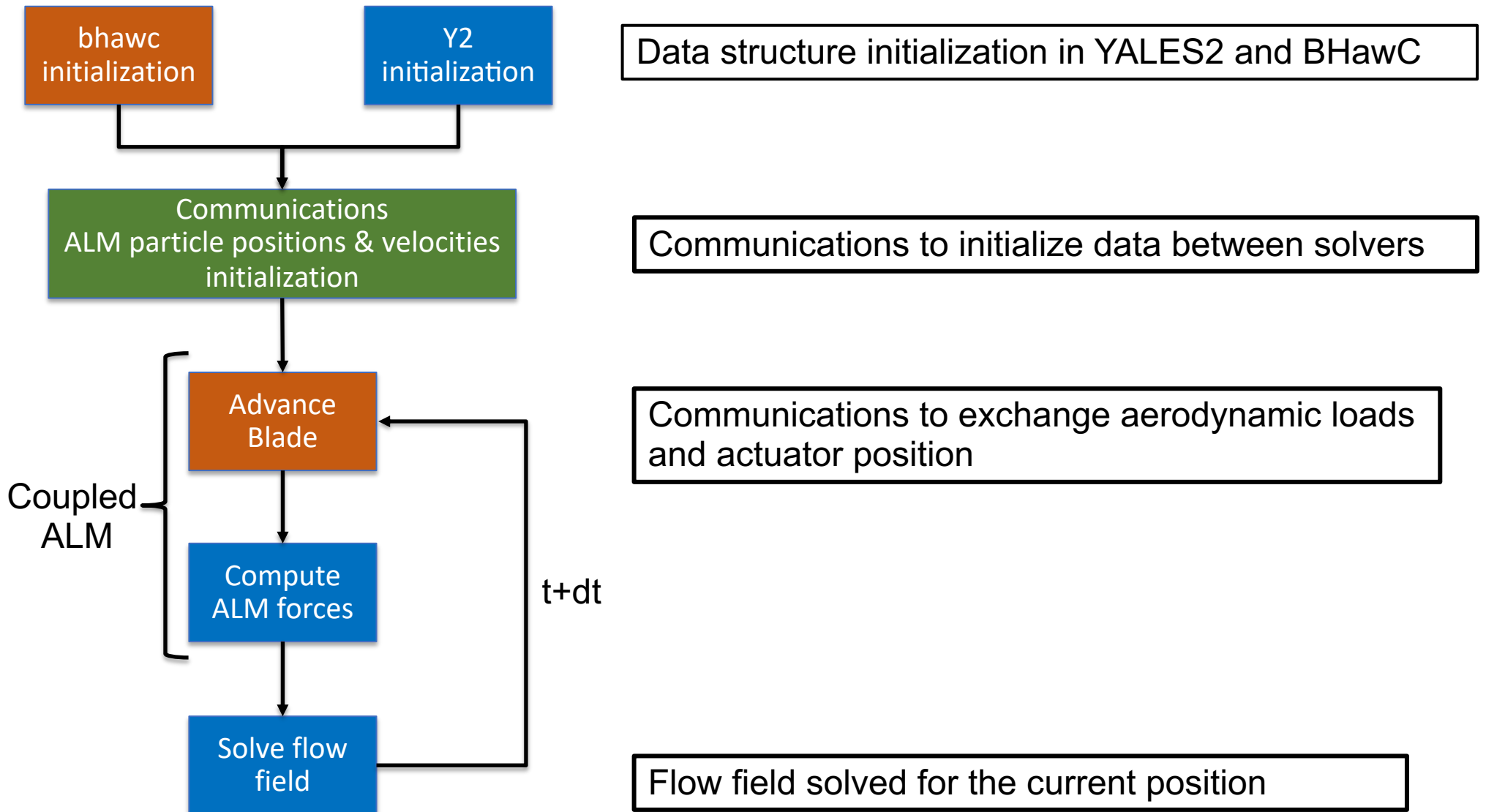
- **BHawC proc BROADCAST** to all Y2 procs: all Y2 processors are aware of all wind turbines (- - ->)
- **One Y2 proc SEND** data to one BHawC: synchronous communication (———>)
- BHawC waiting time can be neglected for large simulations



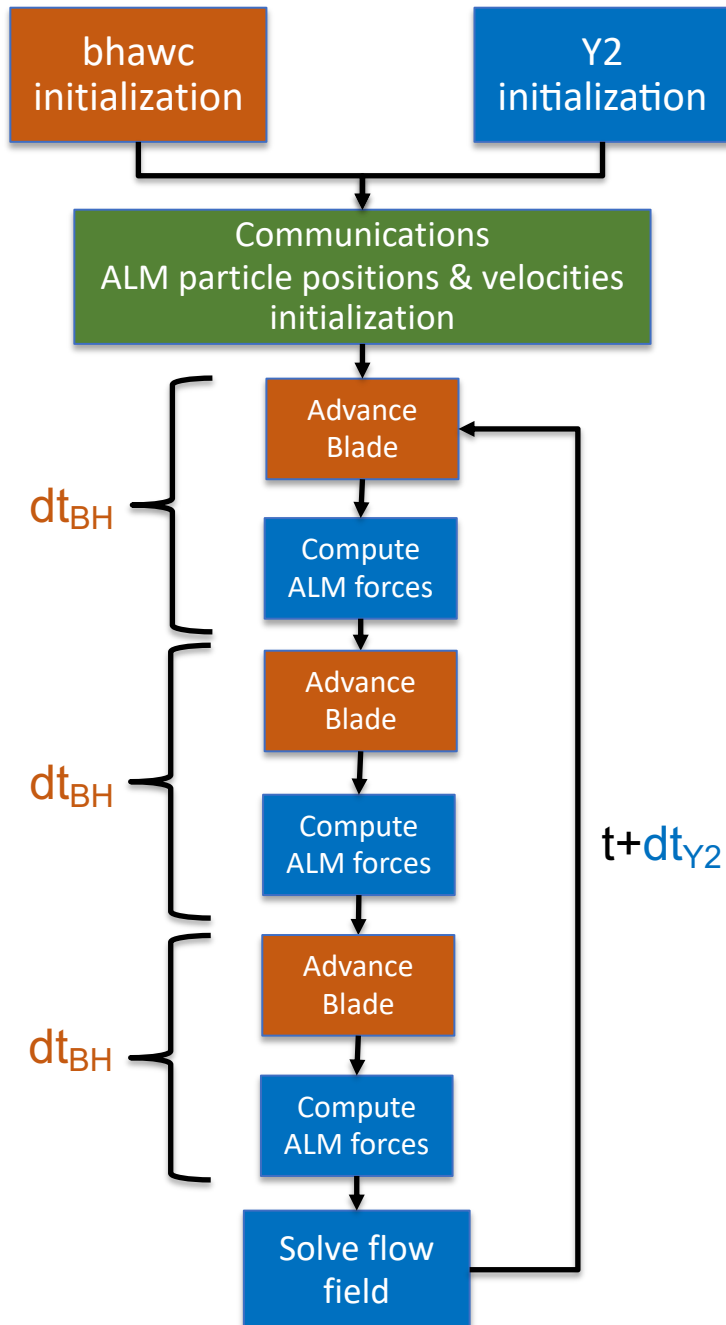
This implementation:

- handles arbitrary number of turbines
- is efficient for massively parallel simulations (required for high-fidelity simulations)

YALES2-BHawC Coupling Implementation



YALES2-BHawC Coupling - Substepping

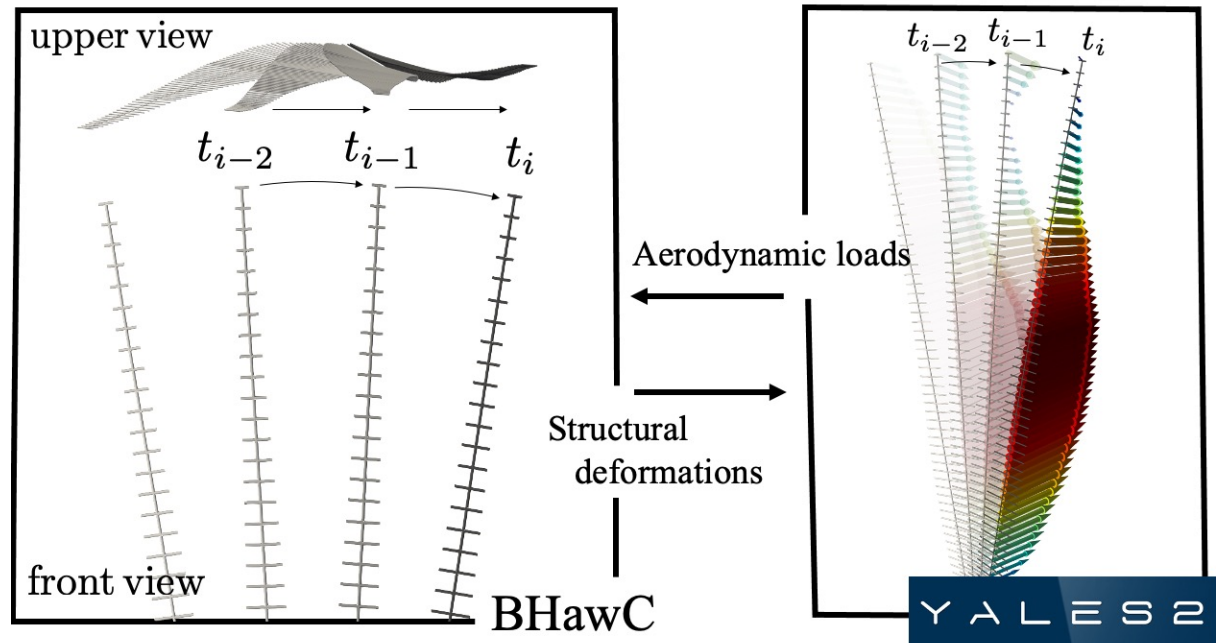


Is it possible to minimize the Y2 calls?

Generally $dt_{Y2} > dt_{BH}$:

- Aerodynamic field is solved every n structural steps
- Number of substeps n **constrained by CFL condition**

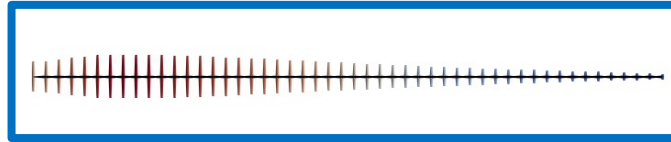
Example with 3 substeps:



Test Cases and Computational Setup

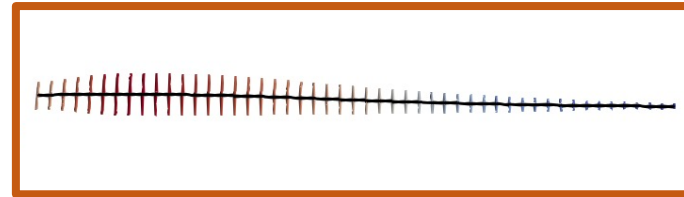
Y2 standalone simulation

- **Rigid blade**
- Constrained rotation speed
- Simplified geometry (straight blade)



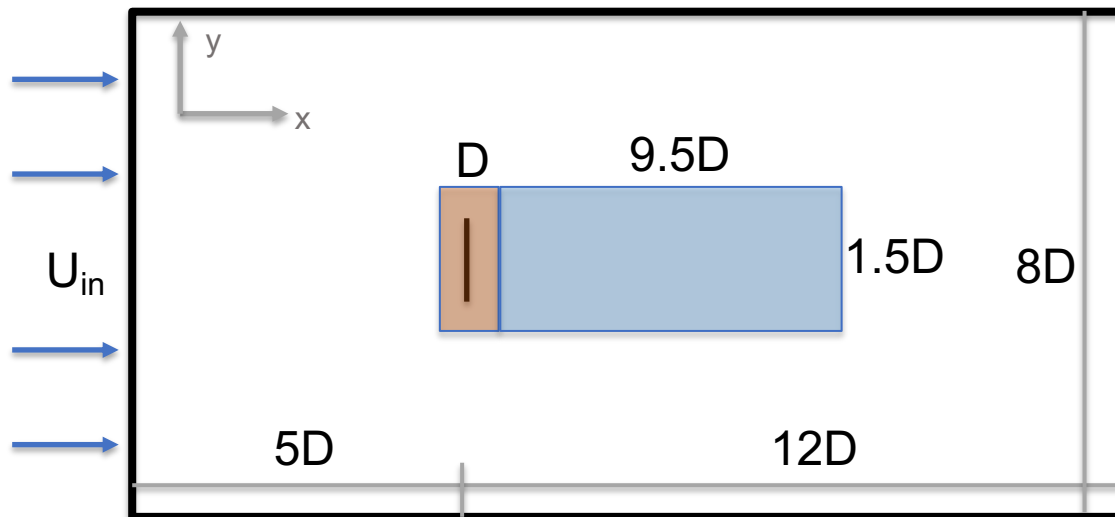
Y2-BH coupled simulation

- **Flexible blade**
- Rotation speed: controller
- Realistic geometry (sweep + prebend)



BEM Blade Element Momentum:

- Same as Y2-BH
- Results used as reference:**
validated with experimental data



Flow condition: $U_{in} = 8 \text{ m/s}$

Industrial wind turbine spec:

- $D_{rotor} = 154 \text{ m}$
- $P_{rate} = 7 \text{ MW}$
- $L_{blade} = 75 \text{ m}$
- $TSR = 9.3$

Number of cells: ~ 64 million

Mesh size rotor: $0.013D$ ($\sim 2 \text{ m}$)

Mesh size wake: $0.026D$ ($\sim 4 \text{ m}$)

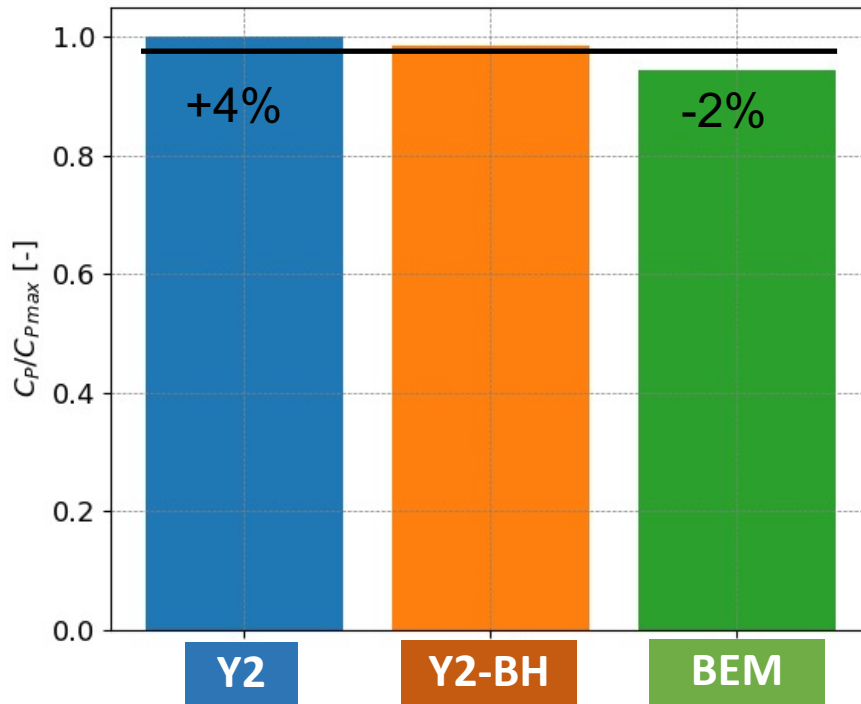
$\tau = 192,5 \text{ s}$ flow through time **stats accumulated** over 2τ

Power and Thrust Coefficients

Comparison between **Y2** , **Y2-BH** and **BEM**

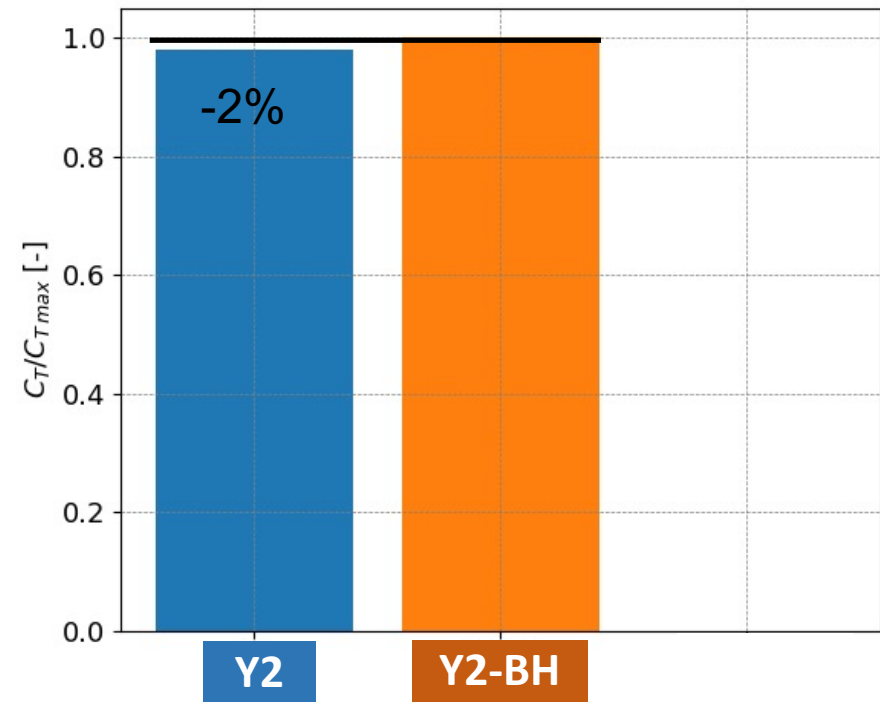
$$c_P = \frac{P_{aero}}{0.5\rho U_{in}^3}$$

Power Coefficient



$$c_T = \frac{T}{0.5\rho U_{in}^2}$$

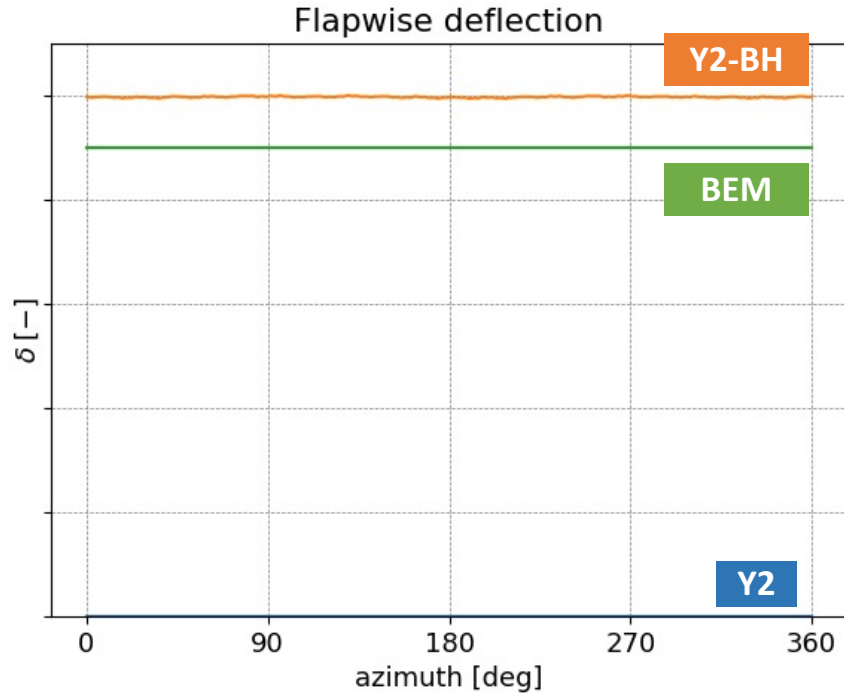
Thrust Coefficient



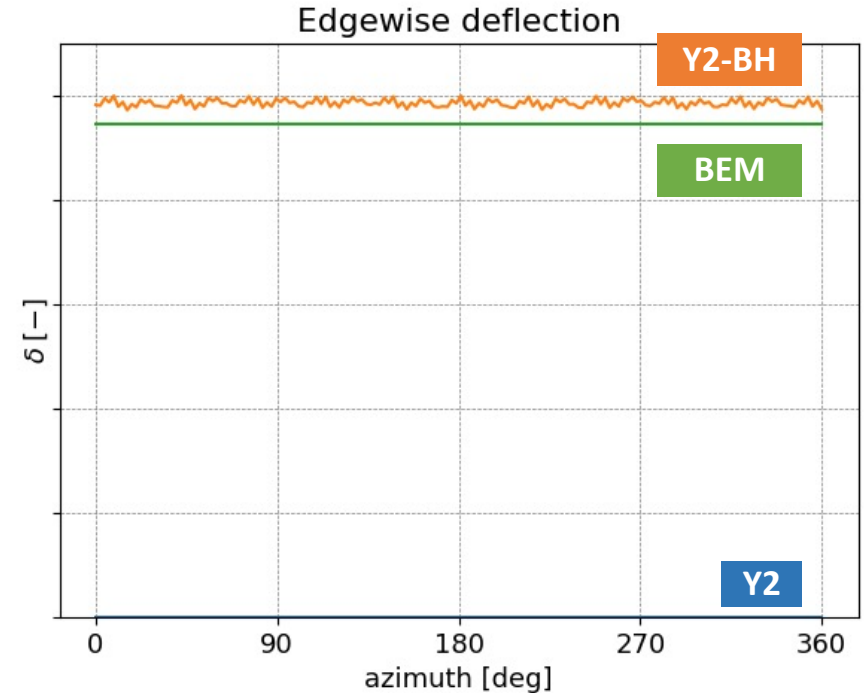
Good agreement of the **global performance** of the wind turbine:

- Thrust coefficient for **BEM** not available
- Cp more affected than CT by the **blade geometry differences** and **flexibility**

Blade Tip Deformations



Flapwise: deflection in flow direction

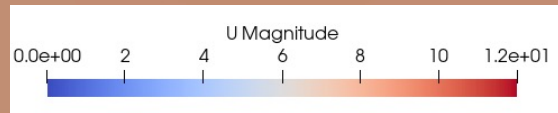


Edgewise: deflection in blade-chord direction

- Uniform inlet condition \rightarrow constant deflection of the blade
- **Y2**: no deformations in both directions (rigid blade)
- Small fluctuations for **Y2-BH** due to flow unsteadiness
- Good agreement with **BEM**

Velocity Field

Y2

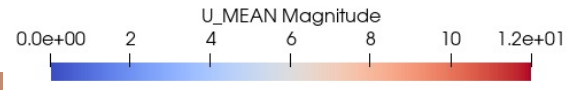


Instantaneous Velocity Field:

- Similar for **Y2** and **Y2-BH**
- Uniform injected flow for these validation cases

$\langle U \rangle$

Y2



3D 4D 5D 10D

Y2-BH

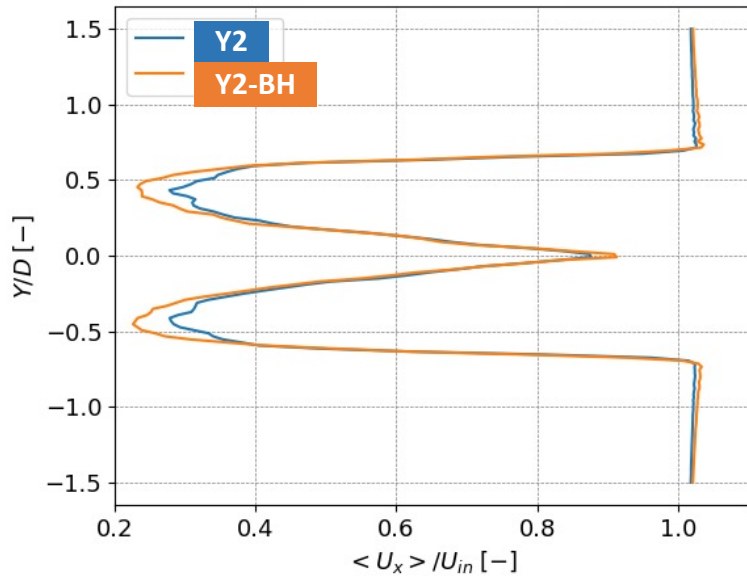
Mean Velocity Field:

- Velocity in the wake is lower for **Y2-BH**
- Wake is wider in **Y2-BH**

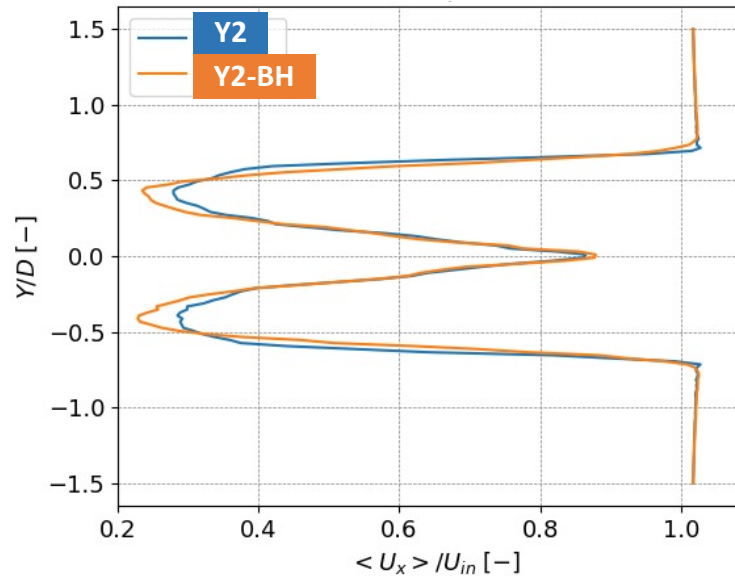
Visualization of velocity profiles in the wake at distance from the rotor: 3D, 4D, 5D, 10D

Mean Velocity Profiles – Wake Region

3D from rotor

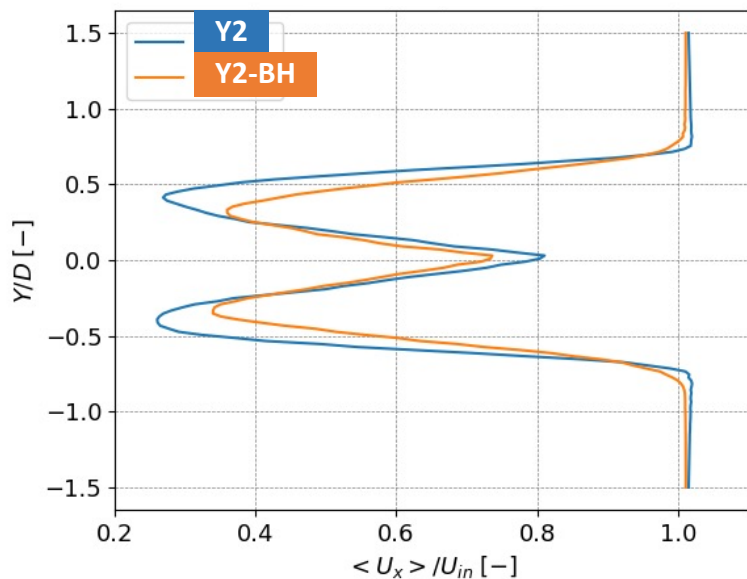


4D from rotor

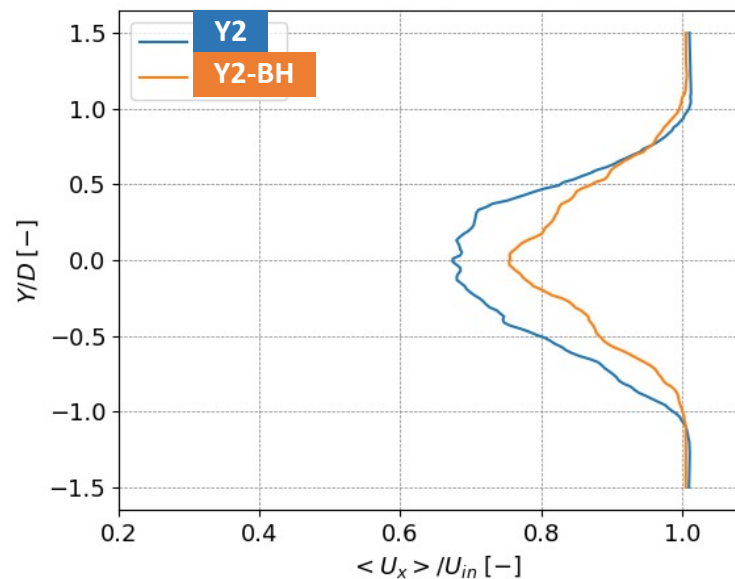


- Y is the vertical direction
- In the near wake behaviour is similar
- Flow slower for **Y2-BH**

5D from rotor

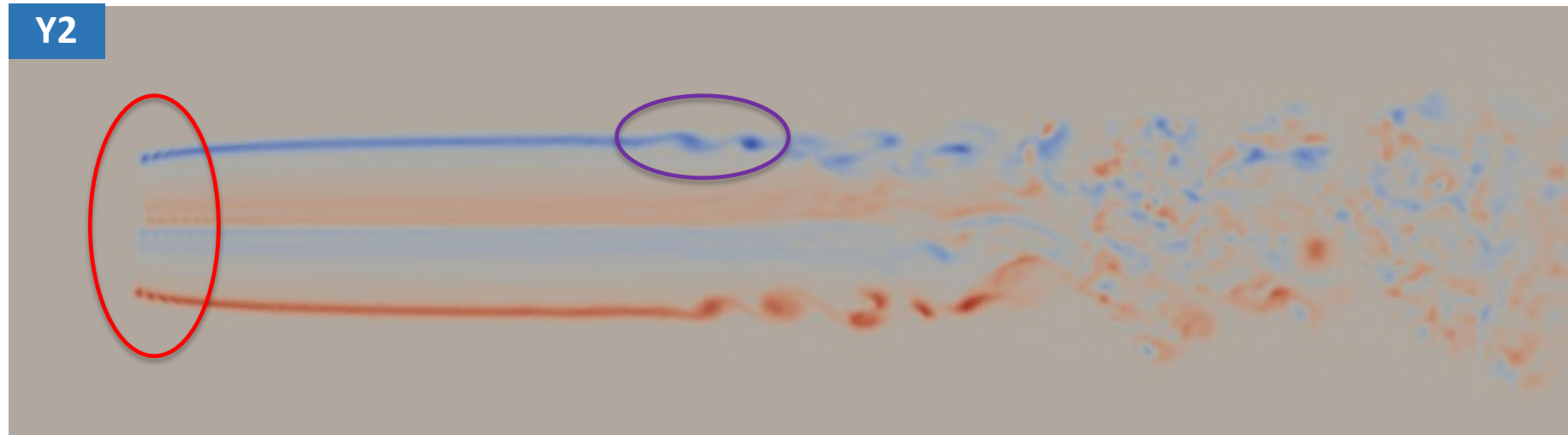


10D from rotor



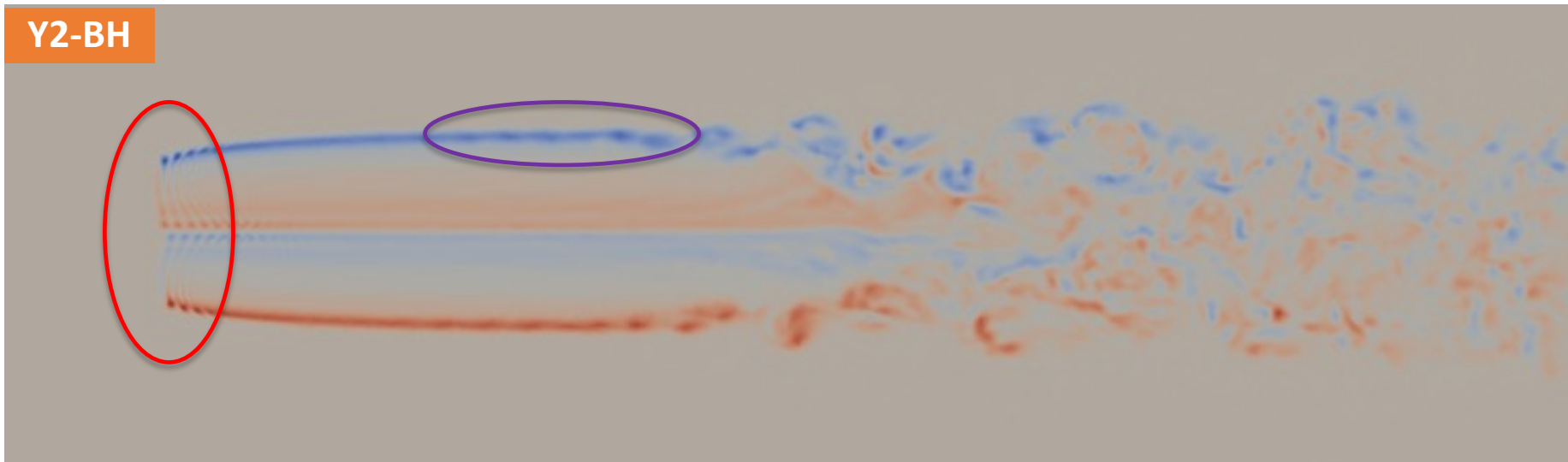
- Velocity deficit for **Y2-BH** is starts to recover **faster** at 5D
- Wake wider for **Y2-BH**
- Velocity deficit not recovered after 10D, but profiles are getting closer

Vorticity Field Comparison

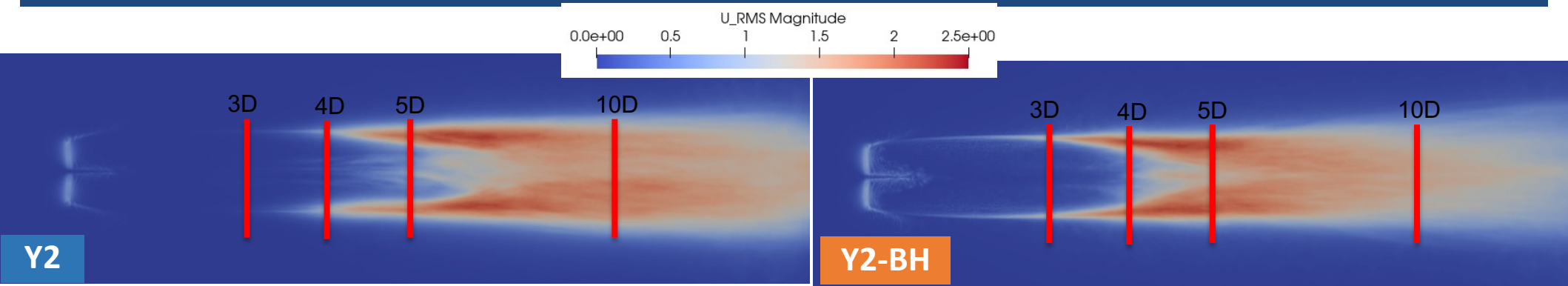


Vorticity fields:

- Wake instabilities appear sooner for **Y2-BH** (different behaviour at 5D)
- Different tip-vortex release (blade deformation)
- Wake width is slightly bigger for **Y2-BH**



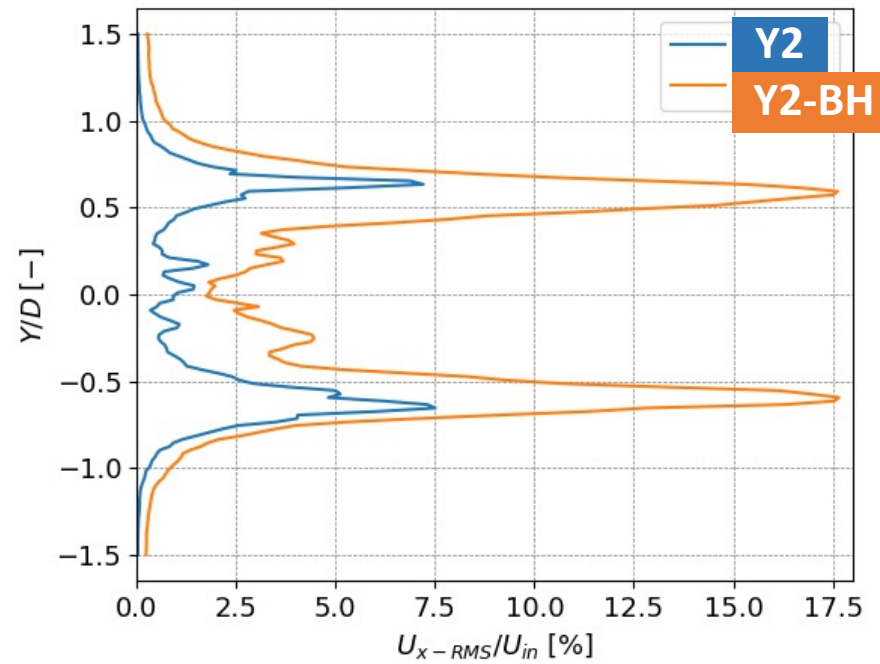
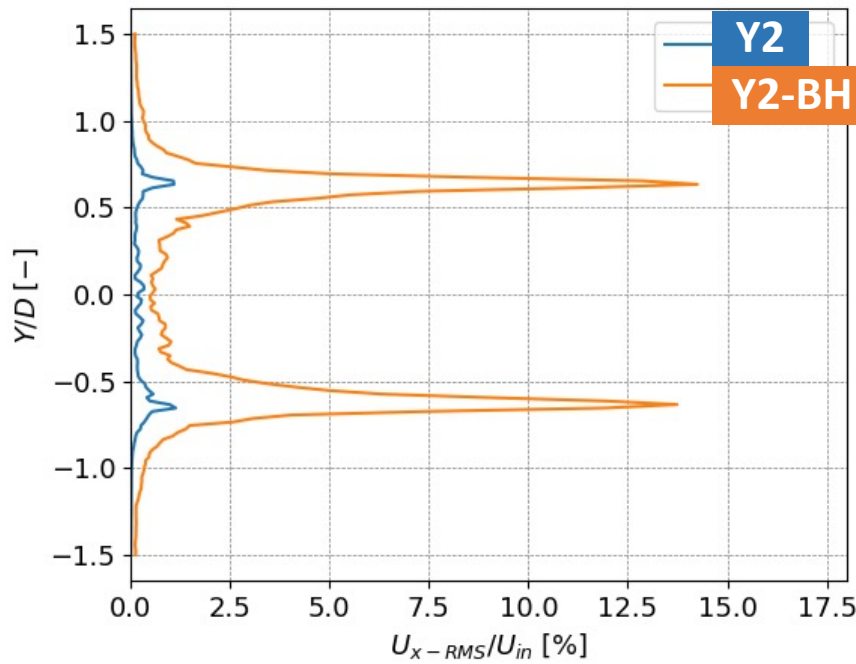
Velocity RMS – Near Rotor Region



Y2 Velocity RMS: higher intensity and different distribution

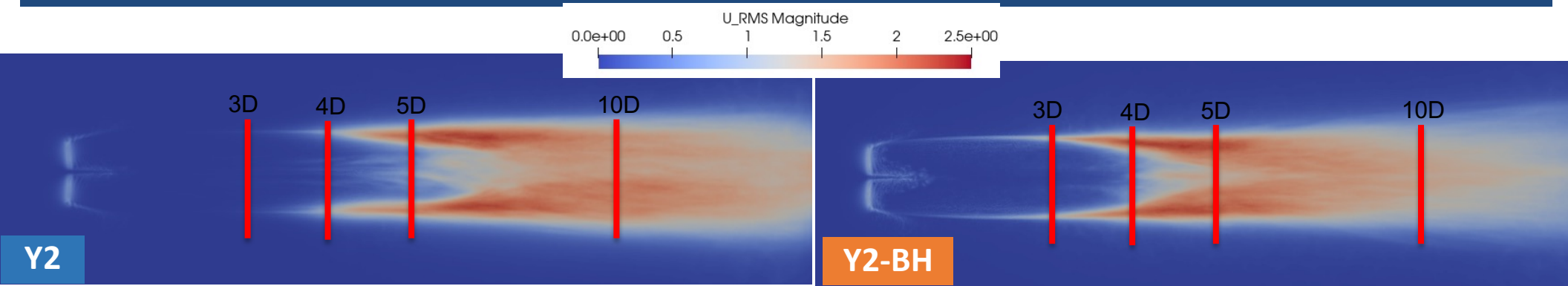
3D from rotor

4D from rotor



- **Y2:** fluctuations are smaller
- Fluctuation max where tip vortices are convected ($\sim 0.5D$)

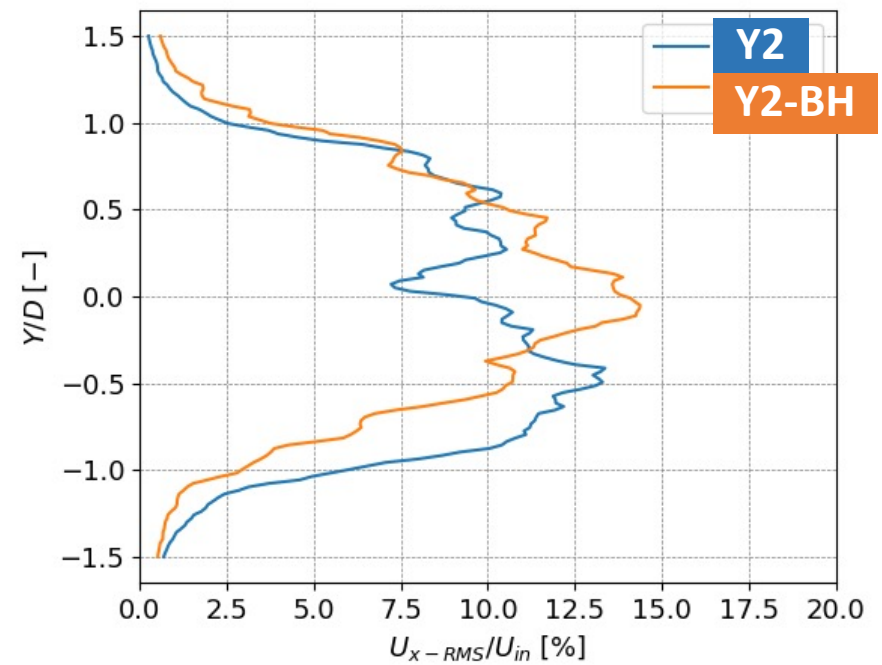
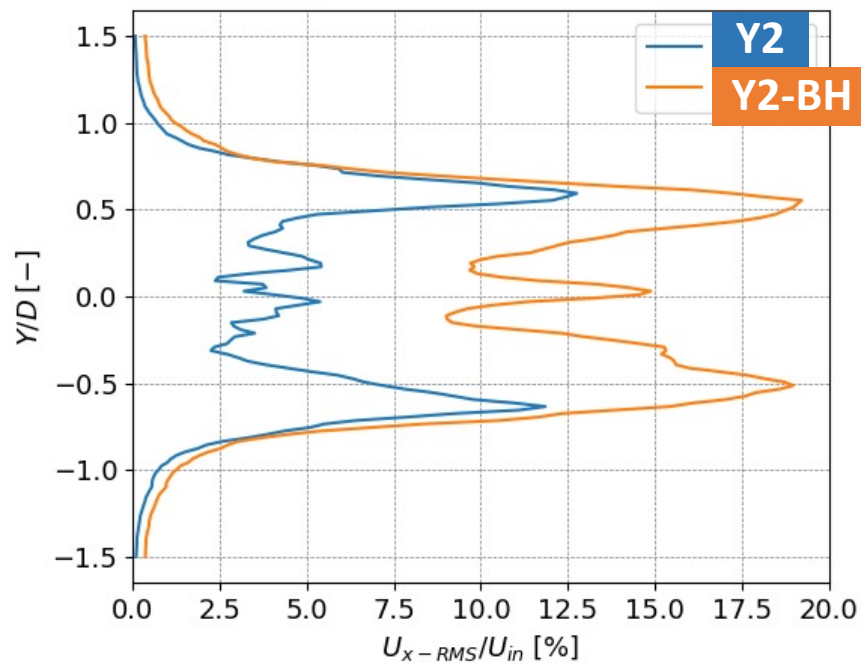
Velocity RMS – Far Wake Region



Y2 Velocity RMS: higher intensity and different distribution

5D from rotor

10D from rotor



- **Y2-BH** fluctuations are higher at 5D due to wake instabilities
- At 10D profiles are getting closer

Conclusions and Future Work

How blade deformations affect the near and far wake, the loads and the power output for an industrial wind turbine via high fidelity LES?

Preliminary comparison between **Y2 (rigid blade)**, **Y2-BH (coupled simulation)** and **BEM (reference)**:

- Wind turbine global performance in **good agreement**
- **Faster destabilization** of the wake for coupled simulation
- **Vorticity field** highlights some differences in **tip vortex behaviour**

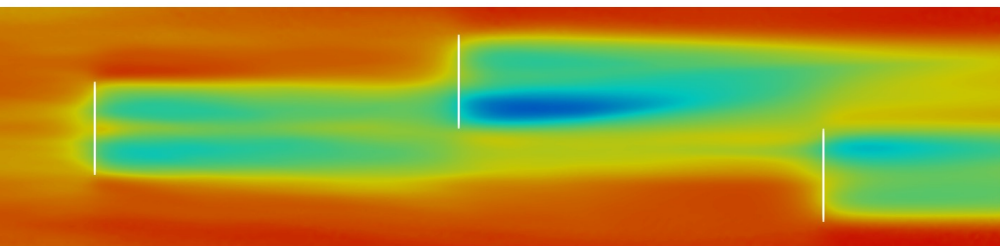
Efficient implementation of the coupling strategy for aero-servo-elastic simulations: coupling overhead

Nprocessor = 384	Y2	Y2-BH	Diff
Wall clock time for 200s [h]	4.17	4.65	11.5%

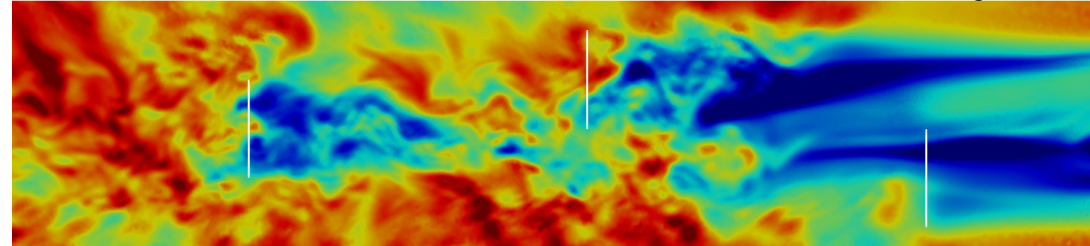
Future Work: this simulation framework can be used for more complex configurations

- Improve **coupling implementation** (optimization of MPI communications and memory usage)
- **Multiple rotors**: analysis of the interaction of the wake on blade deformation
- **Turbulence injection**
- Simulation of a **wind farm** (Lillgrund) and experimental data validation

Multi-rotor



Turbulence injection



Acknowledgement

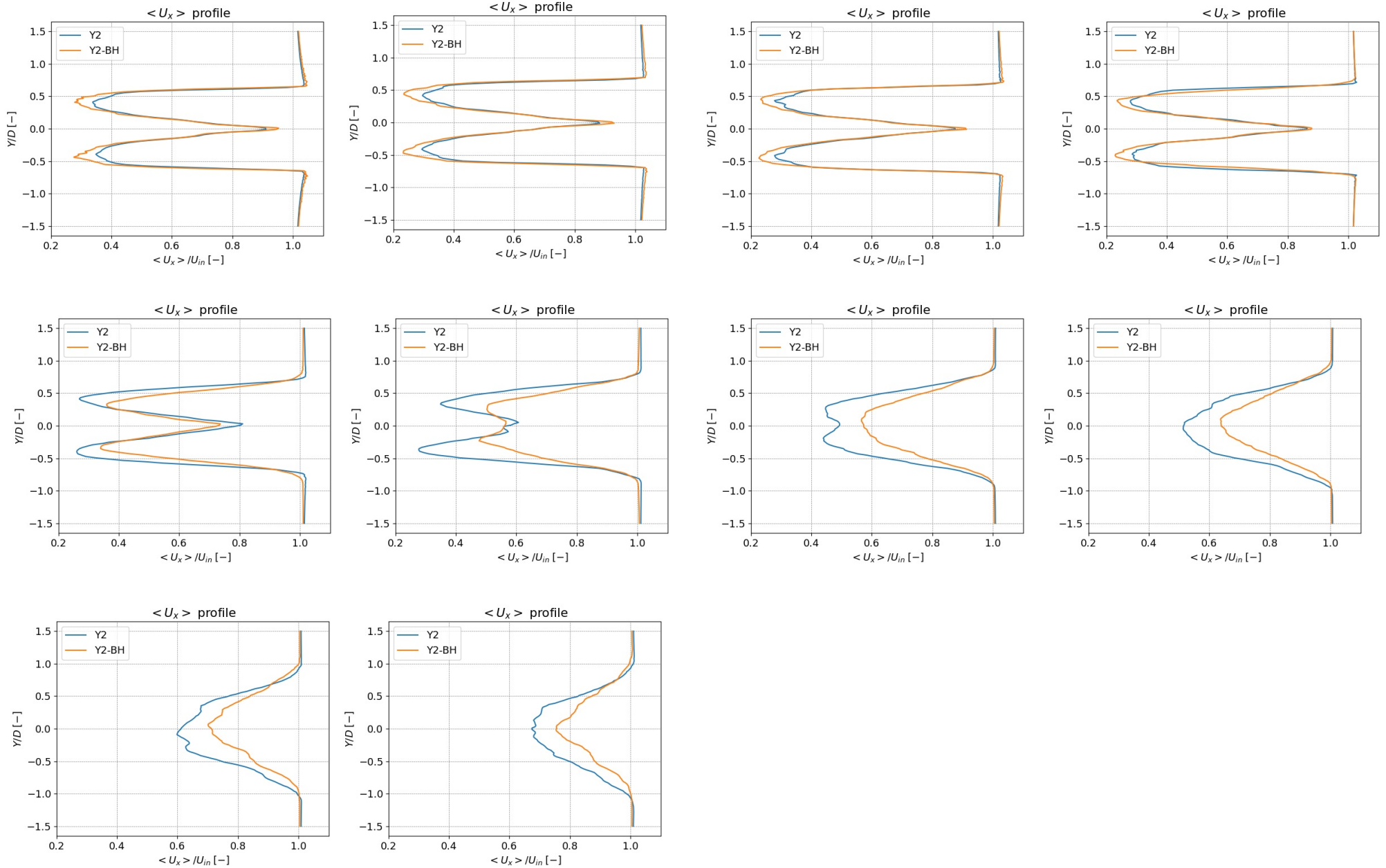


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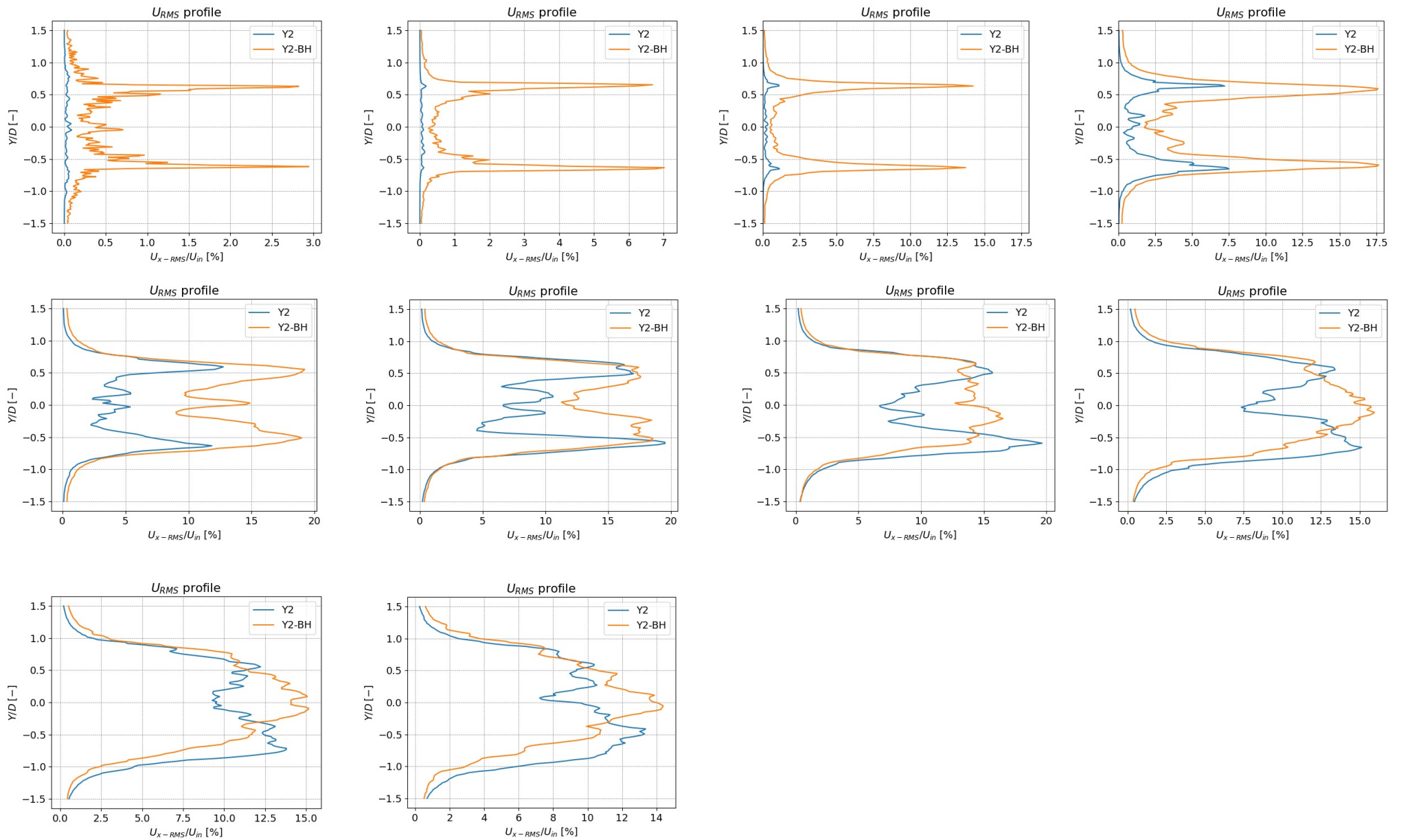


- [1] Benard P. et al. (2018) 'Large-Eddy Simulation of wind turbines wakes including geometrical effects', *Computer and Fluids*, 173, 133.
- [2] Breton S-P. et al. (2017) 'A survey of modelling methods for high-fidelity wind farm simulations using large eddy simulation', *Philosophical Transactions of the Royal Society A* 375.
- [3] Moureau, V., Domingo, P. and Vervisch, L. (2011) 'Design of a massively parallel CFD code for complex geometries', *Comptes Rendus Mécanique*, 339(2–3).
- [4] Rubak, R. and Petersen, J. T. (2005) 'Monopile as part of aeroelastic wind turbine simulation code', *Proceedings of Copenhagen Offshore Wind*, 20.
- [5] Sorensen, J. N. et al. (2002) 'Numerical Modeling of Wind Turbine Wakes', *Journal of Fluids Engineering*, 124(2), p. 393.
- [6] Veers, P. et al. (2019) 'Grand challenges in the science of wind energy', *Science*, 366(6464).
- [7] H. Meng et al. (2017) 'Elastic actuator line modelling for wake-induced fatigue analysis of horizontal axis wind turbine blade', *Renewable Energy* 116
- [8] Z. Yu et al. (2018) 'Study on Actuator Line Modeling of Two NREL 5-MW Wind Turbine Wakes', *Applied Sciences*

Mean Velocity Profile

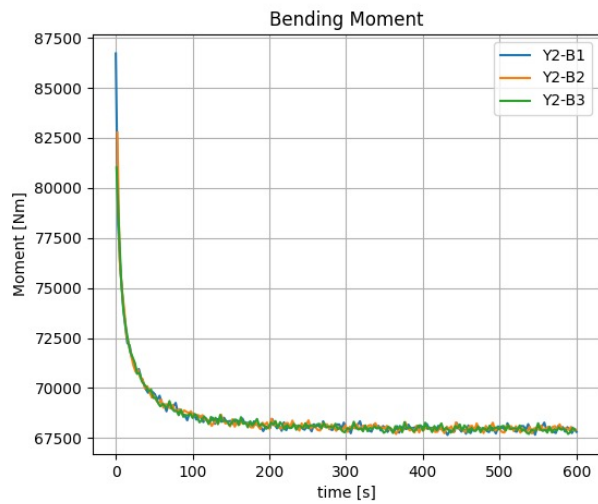


Velocit RMS



$$TSR = \frac{\omega R}{U_{in}}$$

Blade Root Bending Moment

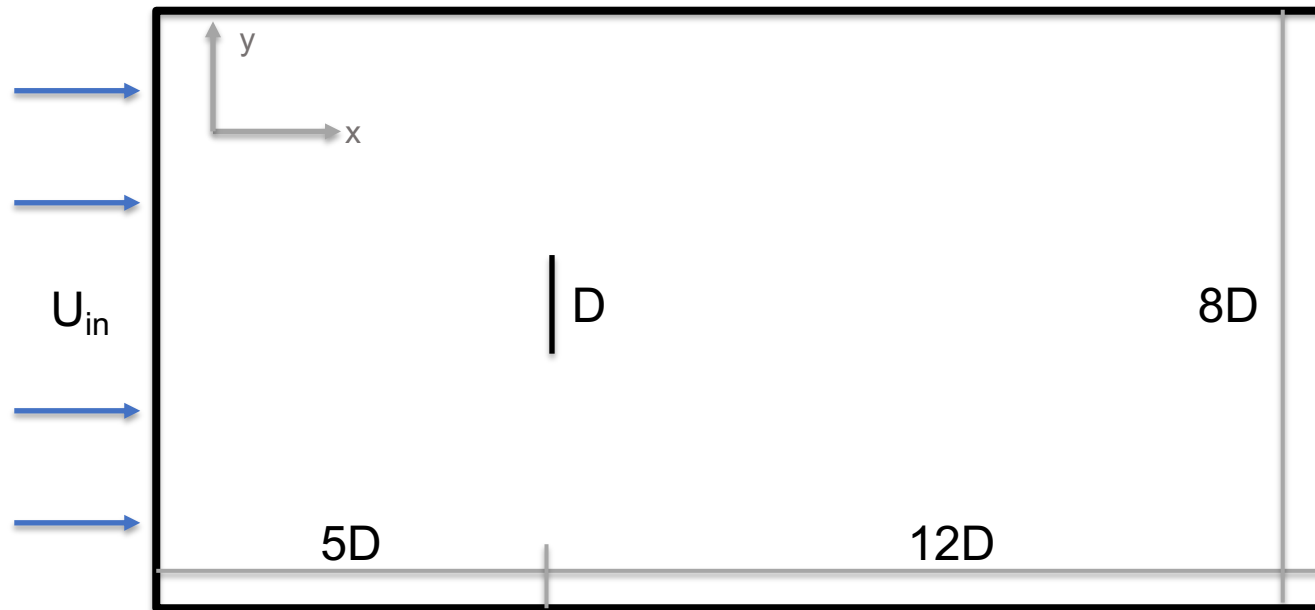


Y2

Y2-BH

Blending Moment standalone simulation
Comments on the deformations
Meilleure évaluation des forces

Computational Setup



Number of cells: $\sim 64e6$
 Mesh size at the rotor: 2 m

Flow condition: $U_{in} = 8$ m/s

Industrial wind turbine spec:

- $D_{rotor} = 154$ m
- $P_{rate} = 7$ MW
- $L_{blade} = 75$ m
- $TSR = 9.3$
- Realistic aero description

Y2 standalone simulation

- Constrained rotation speed
- Simplified geometry (straight blade)
- Rigid blade

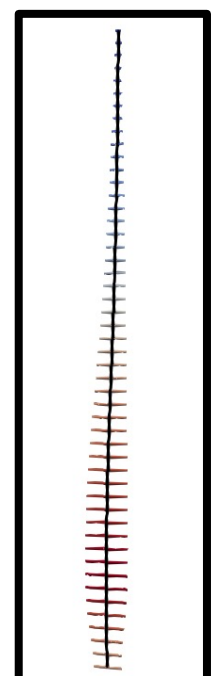
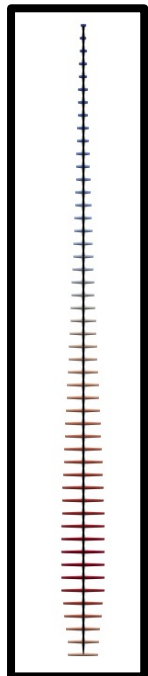
Y2-BH coupled simulation

- Rotation speed: controller
- Realistic geometry (sweep + prebend)
- Flexible blade

BEM Blade Element Momentum:

- Same as Y2-BH

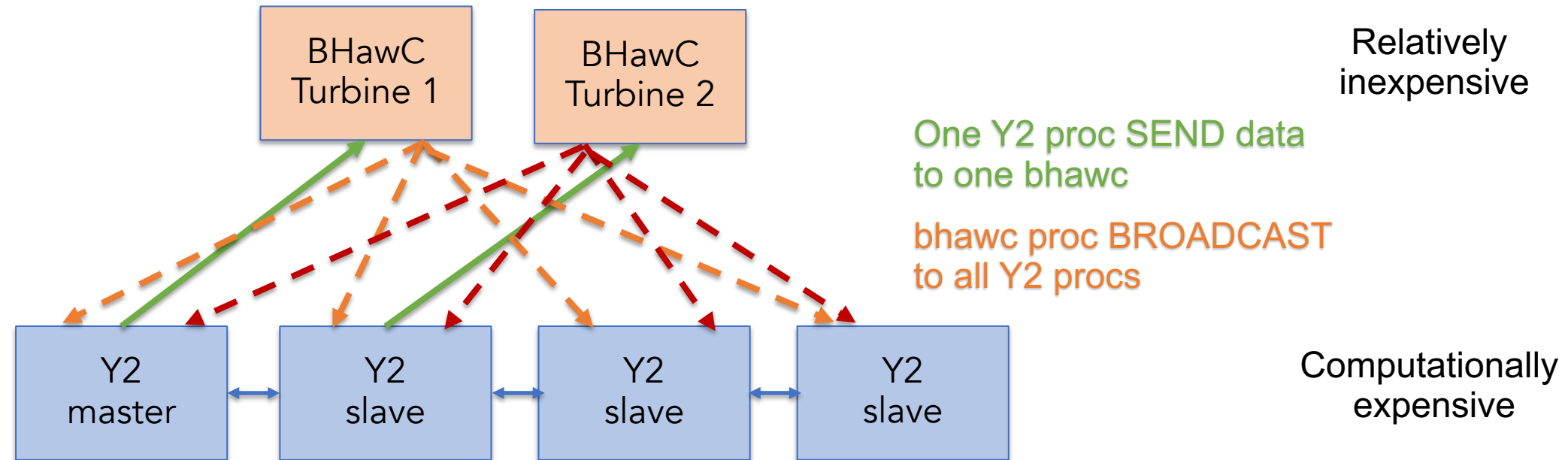
Results used as reference: validated with experimental data



Parallel Implementation YALES2-BHawC Coupling

Message Passing Interface (MPI) handles communications between processors:

- Implementation of communicators in external DLL for more flexibility
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- Yales2 workload distributed on several processors



Implementation:

- handles arbitrary number of turbines
- efficient for massively parallel simulations

BHawC computational cost smaller than YALES2: waiting time can be neglected for very large simulations