Rotor and wind farm modelling with distributed momentum sources

DTU Wind Energy
Technical University of Denmark

Linné FLOW Centre
KTH Mechanics

Gotland University

Robert Mikkelsen

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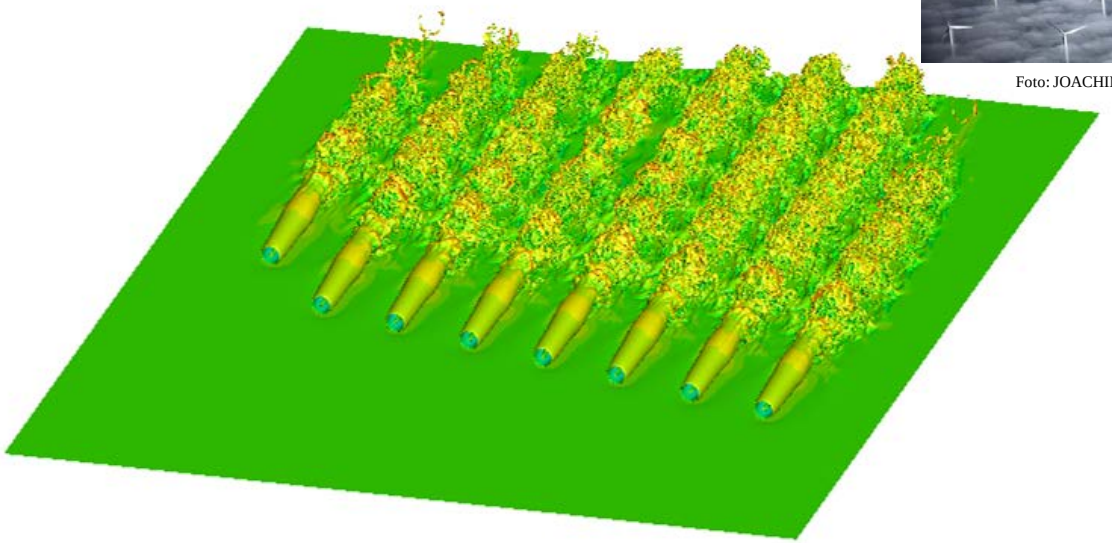

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Wind farm modelling with distributed momentum sources

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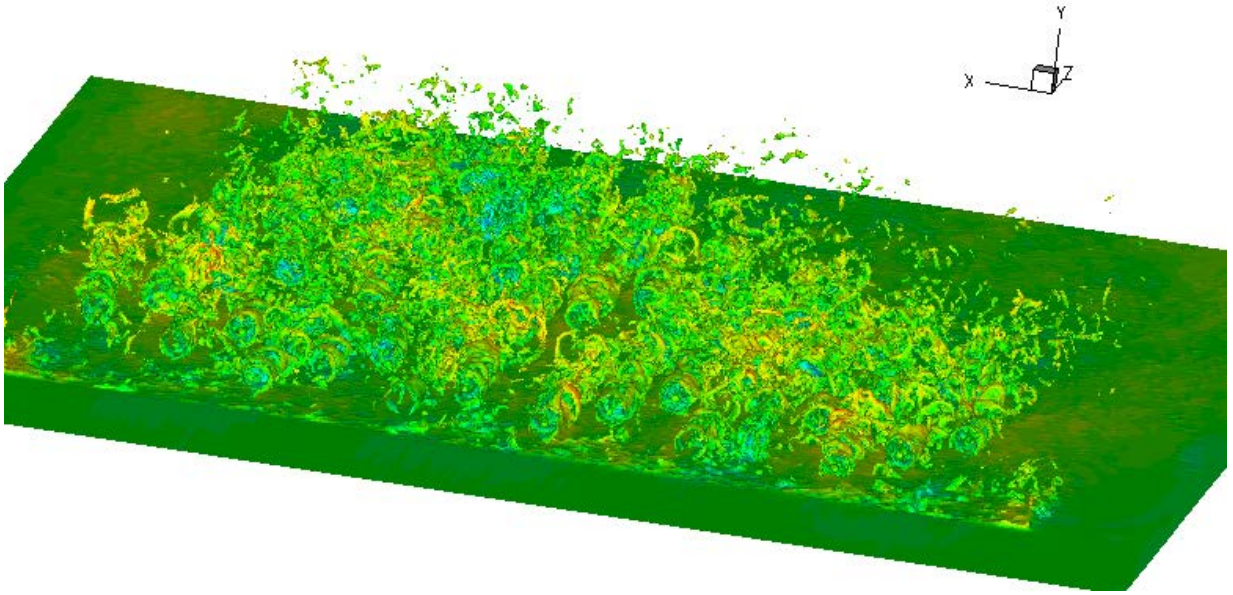
- Momentum sources in CFD for rotor and wind farm modeling
- Flow cases:
  - Blind comparison: Two turbines inline, Actuator line
  - Wind farm: Lillgrund, 3D Actuator Disc
- Summary



Momentum sources in CFD for rotor and wind farm modelling

Governing Equations

$$\frac{\partial u_i}{\partial t}+\frac{\partial u_i u_j}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}[(\upsilon+\upsilon_t)(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i})]+f_{body,i}$$

$$\frac{\partial u_i}{\partial x_i}=0$$

- Actuator Line/Surface/Disc (AL/AS/AD)
- Resolved turbulence (Underresolved LES)
- Wind Shear (Imposed)

EllipSys

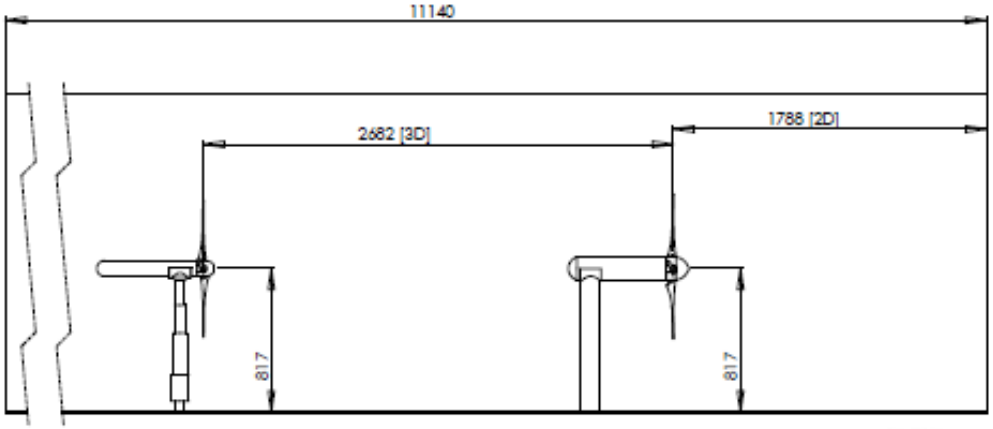
Blind comparison, experimental setup

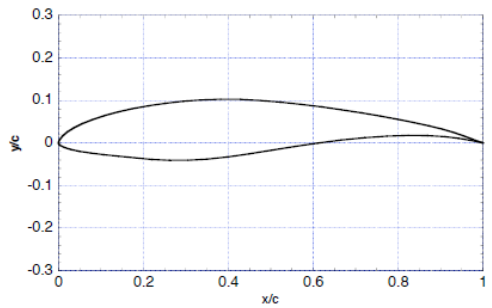
BT1: Single turbine, D=894mm

BT2: Two turbines, D_1=944mm, D_2=894mm

Wind tunnel, NTNU : 2.0m x 2.7m

V=10m/s

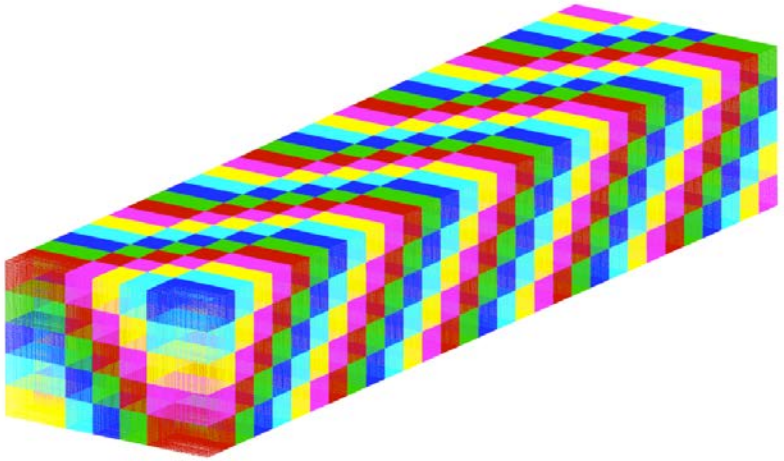




CFD: EllipSys - FLEX5 Actuator line

Computational domain

- Multi-blocks Cartesian grid
- 750 blocks (each block 32^3 grid points)
- 42.46 millions grid points
- Each AL blade is divided into 43 segments



Boundary conditions

- Constant inflow velocity
- Convective outflow
- Walls are included using slip boundary conditions
- Mann turbulence box is added at 1.5*D* upstream of the first wind turbine

Time step

- The movement of the blade tip during one time step should not exceed one grid spacing
- **CFL<0.2**

Turbine(s)

- Stiff turbine, constant rpm
- Effects of tower and nacelle are not considered in the present simulations

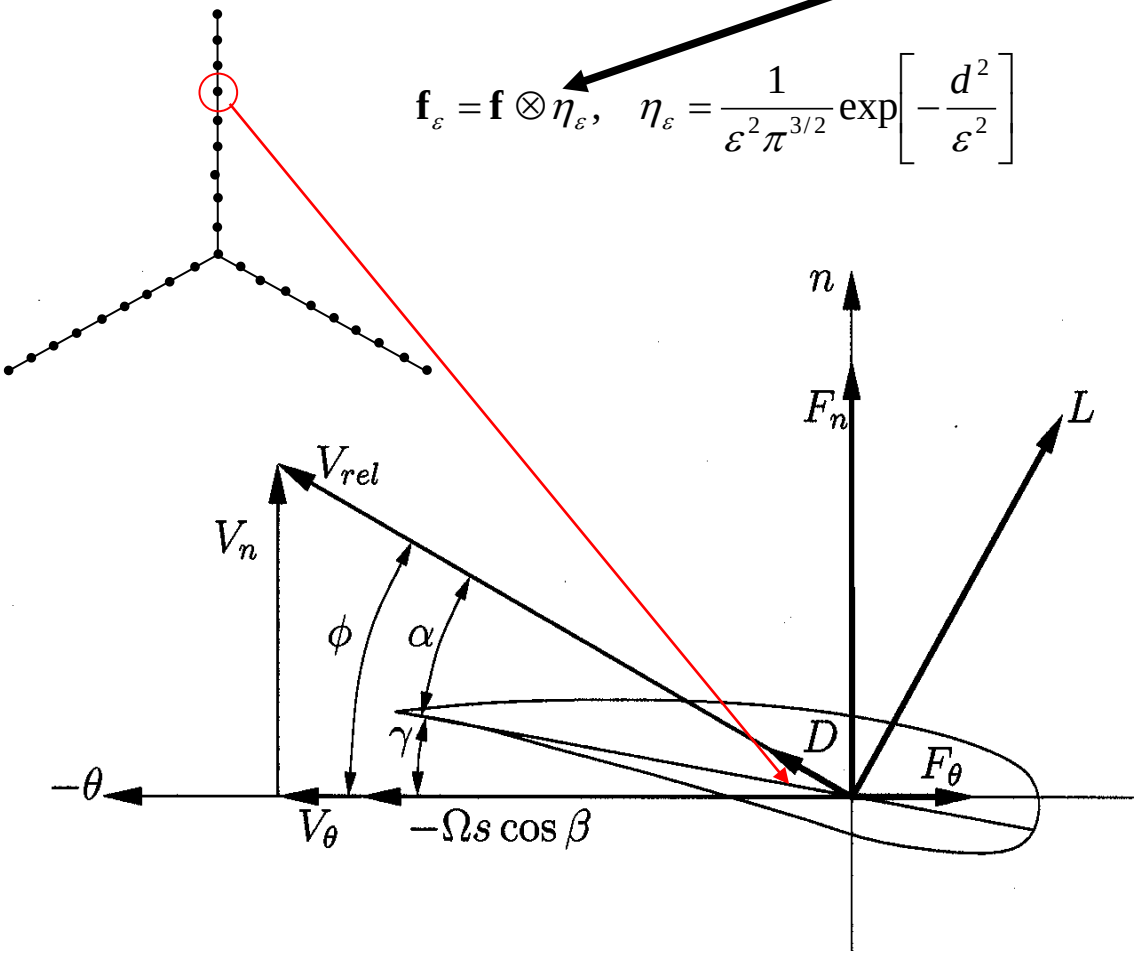
Computing resources

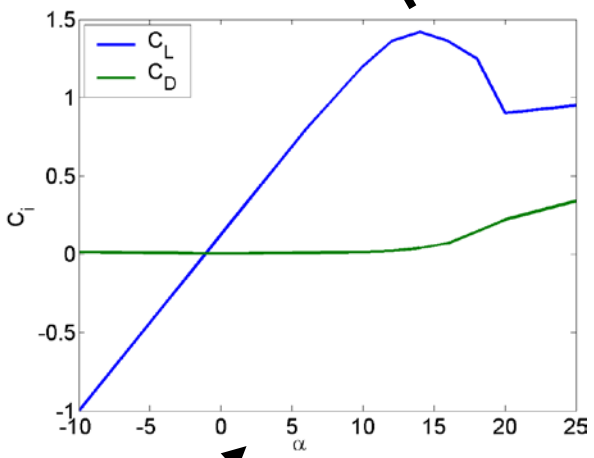
- Lindgren, CRAY XE6 system 1.516 nodes x 24 cores = 36.384
- 750 cores – 12h simulation for one case

AL[1], Blade loads – BEM approach

$$f_{2D} = (L, D) = \tfrac{1}{2}\rho V_{rel}^2 c(C_L \mathbf{e}_L, C_D \mathbf{e}_D)$$

$$\mathbf{f}_\varepsilon = \mathbf{f} \otimes \eta_\varepsilon, \quad \eta_\varepsilon = \frac{1}{\varepsilon^2 \pi^{3/2}} \exp\left[-\frac{d^2}{\varepsilon^2}\right]$$





$$\alpha = \varphi - \gamma$$

$$\varphi = \tan^{-1}\left(\frac{V_n}{\Omega r - V_\theta}\right)$$

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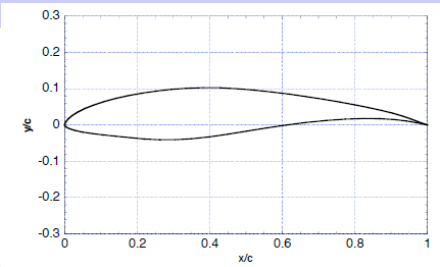
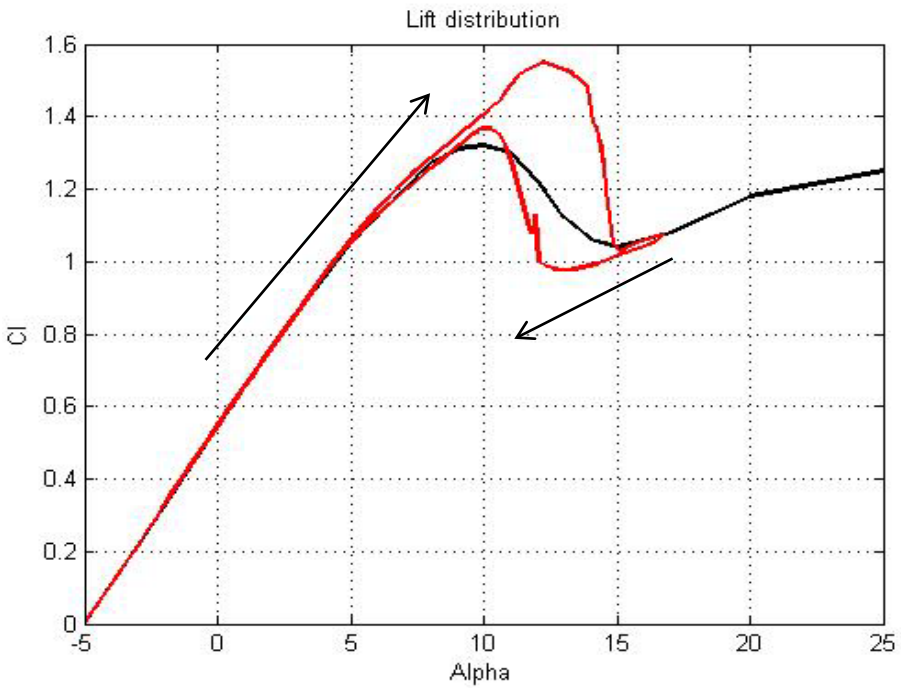
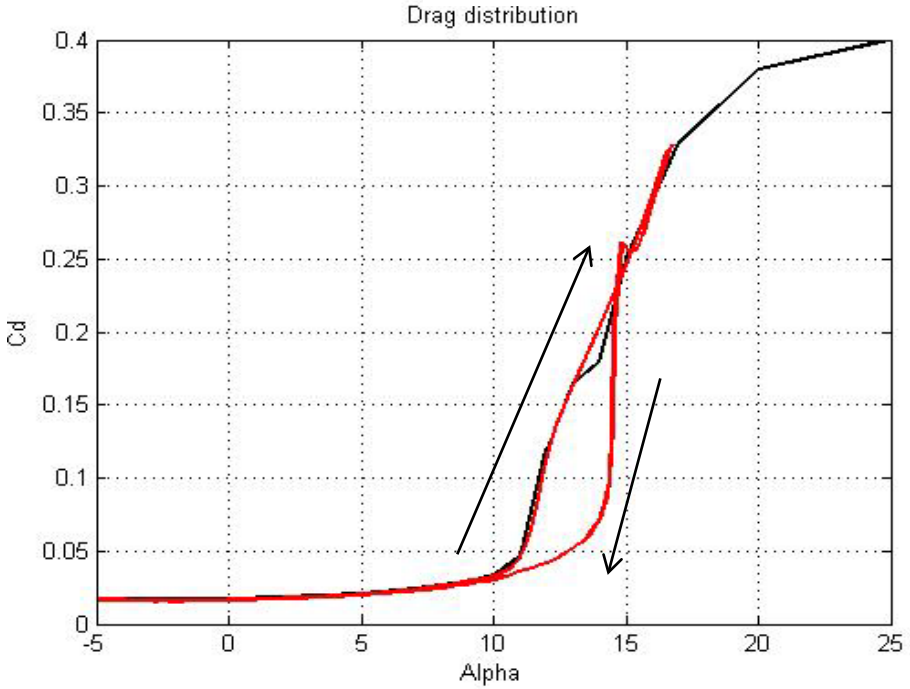
[1]JN Sørensen, WZ Shen. Numerical modeling of wind turbine wakes. *J. Fluid Eng.*, 124, 2002

S826 aerofoil, Re=10^5

***Q*^{3}*uic*^{1}*:* Panel code with viscous/inviscid boundary layer modeling including rotational effects**







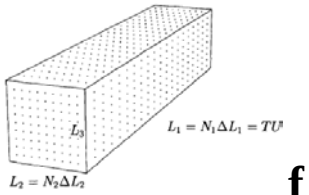
Airfoil (S826) at experimental Reynolds number is subjected to static stall hysteresis

Increasing incidences ⟶ Higher lift and drag coefficients

Decreasing incidences ⟶ Lower lift and drag coefficients.

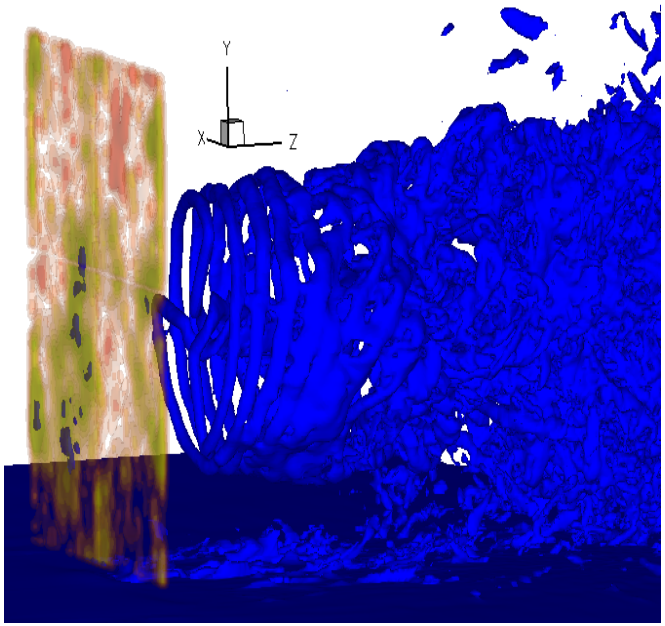
ABL - atmospheric turbulence

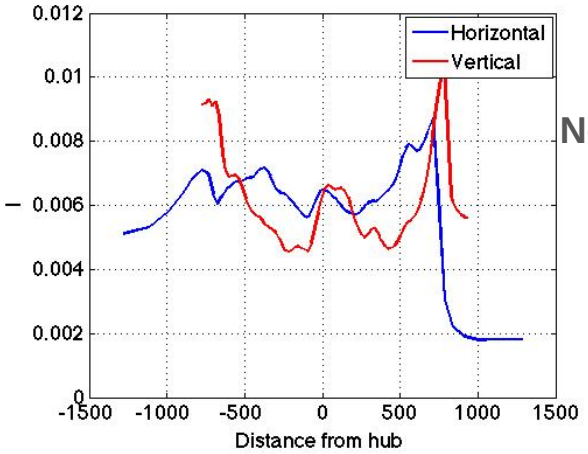
- Atmospheric boundary layer modelling consists of two parts:
  - Ambient turbulence by Mann[1] method
  - Imposed like actuator disc



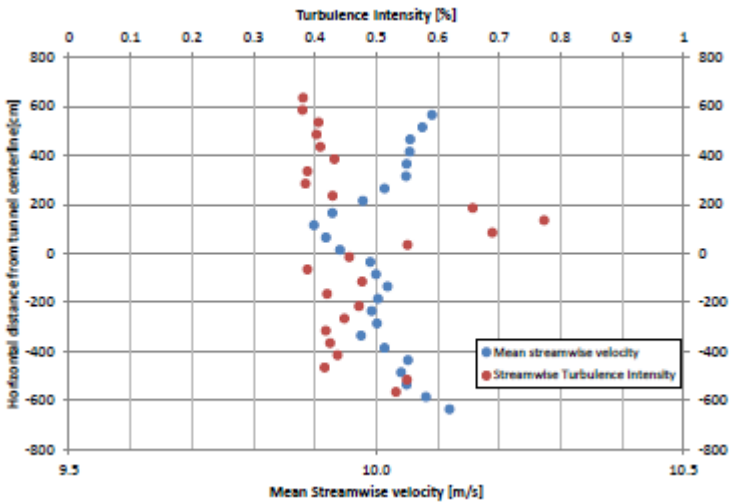
$$\mathbf{f} = \dot{m}\mathbf{u} + \rho\varepsilon\frac{\partial \mathbf{u}}{\partial t}$$

$$\mathbf{f}_\varepsilon = \mathbf{f} \otimes \eta_\varepsilon, \quad \eta_\varepsilon(d) = \frac{1}{\varepsilon\sqrt{\pi}}\exp\left(-\left(\frac{d}{\varepsilon}\right)^2\right)$$





No turbines



Exp

[1]J. Mann. Wind field simulation (1998)

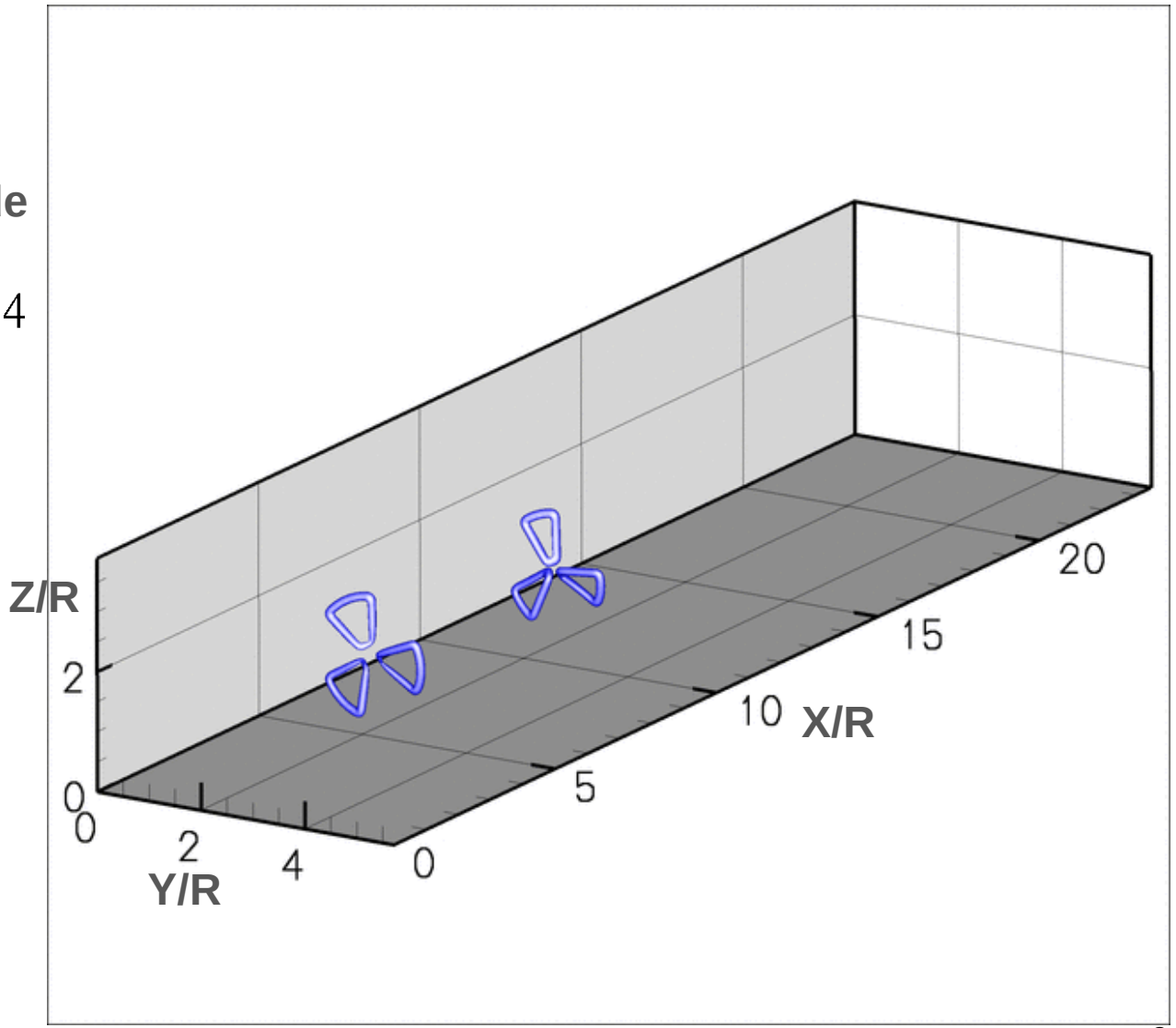
Numerical

Two turbines, AL

Vorticity magnitude

V=10m/s

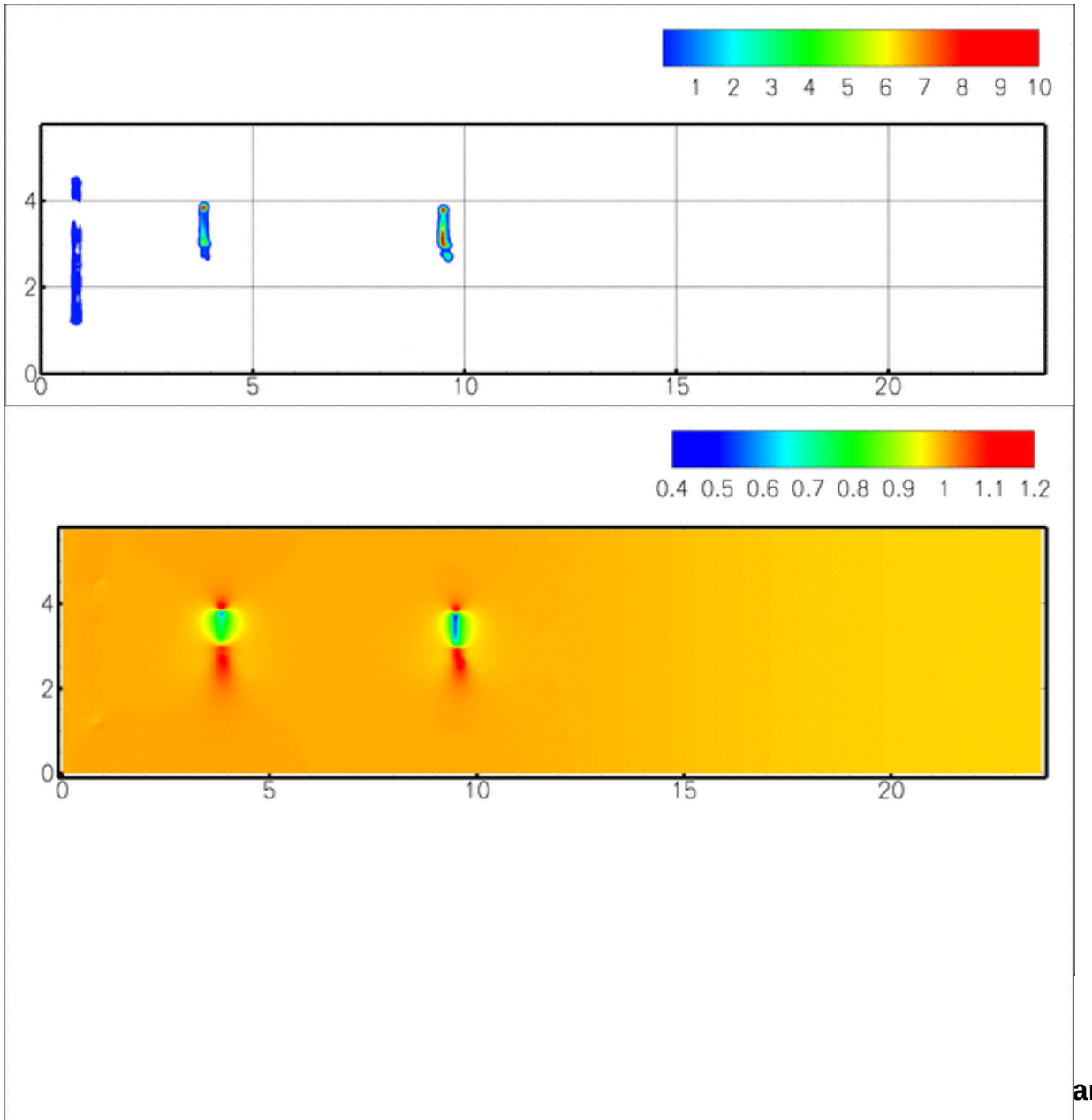
$$\lambda_1 = 6, \lambda_2 = 4$$



Resolved turbulence in wind tunnel

V=10m/s

$\lambda_1 = 6, \lambda_2 = 4$

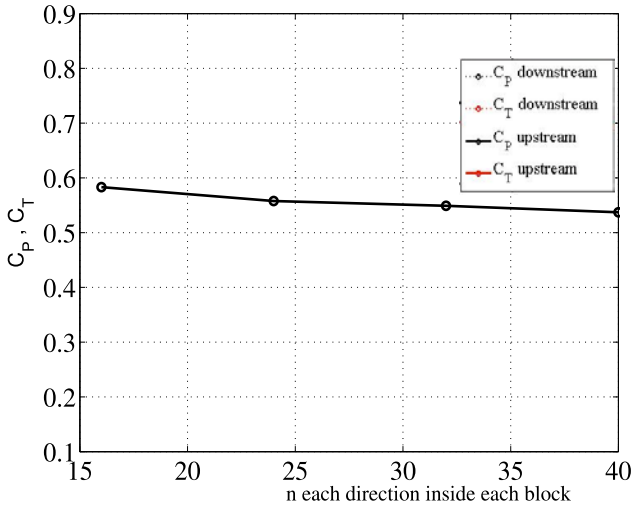


Grid sensitivity

Similar number of blocks but different number of grid points

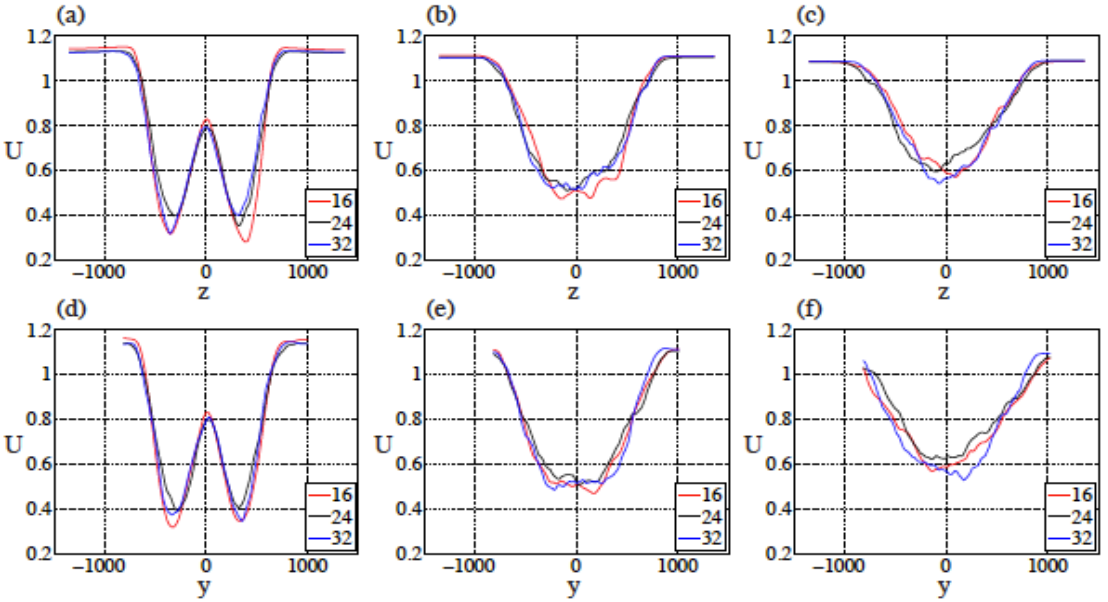
$$R_1 = R_2 = 0.447, \lambda_1 = \lambda_2 = 6$$

The solutions always exhibit a dependency on grid resolution but the relative error committed is rather small



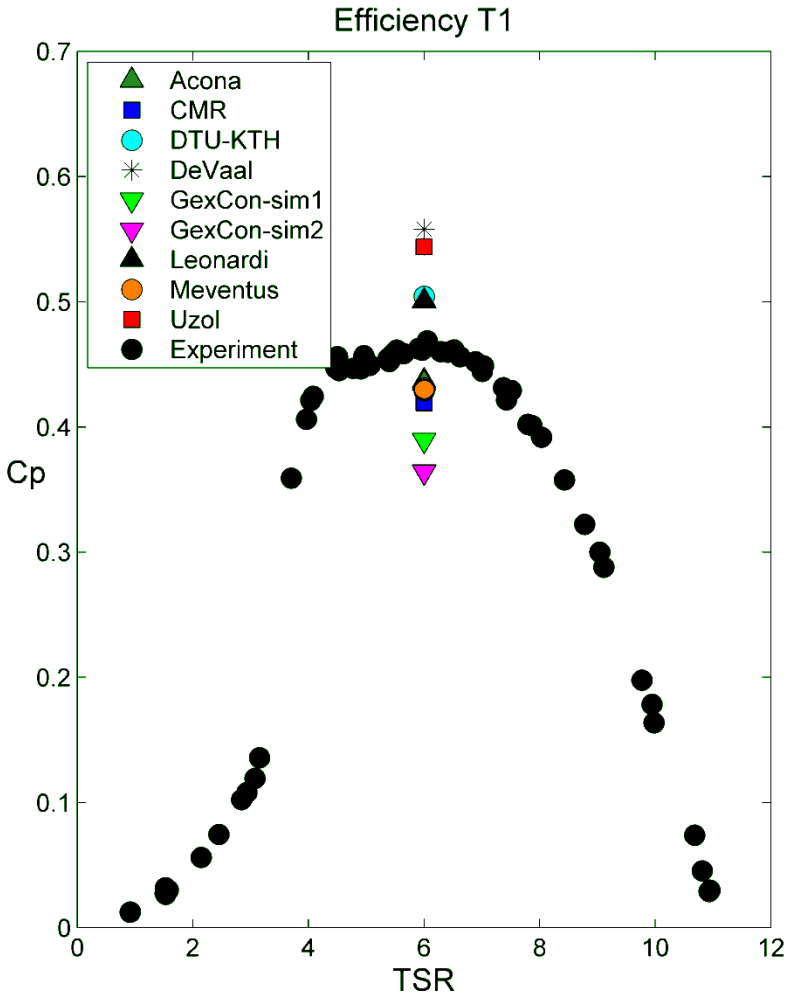
Horizontal

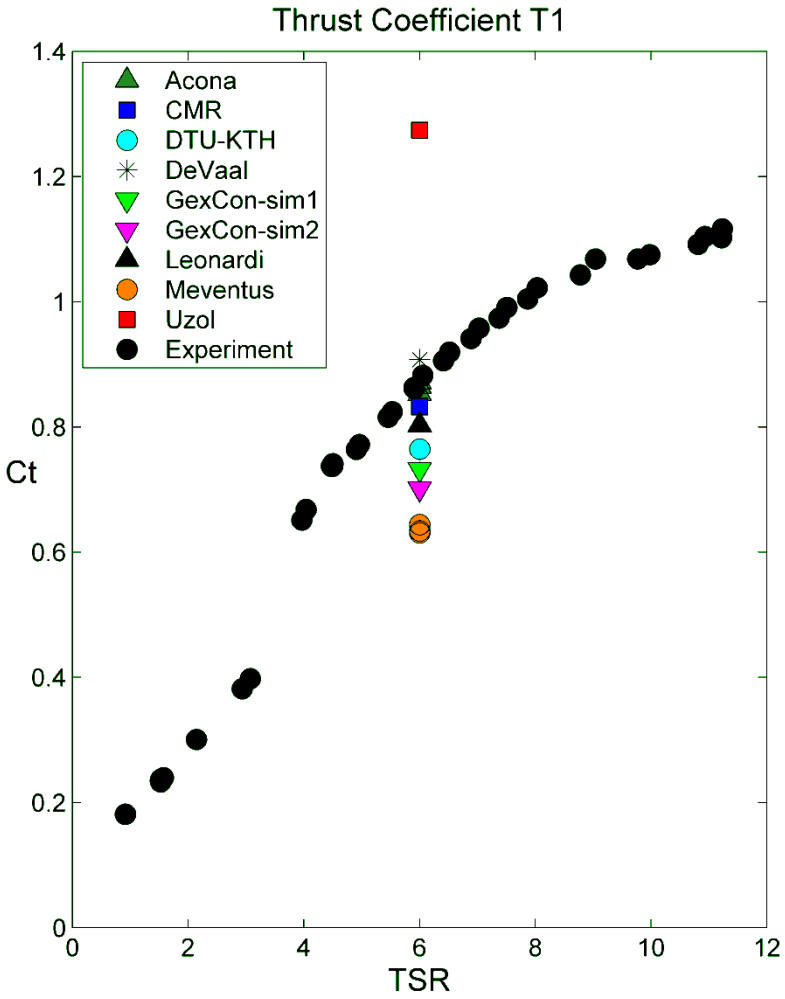
Vertical



Blind comparison: C_P,C_T

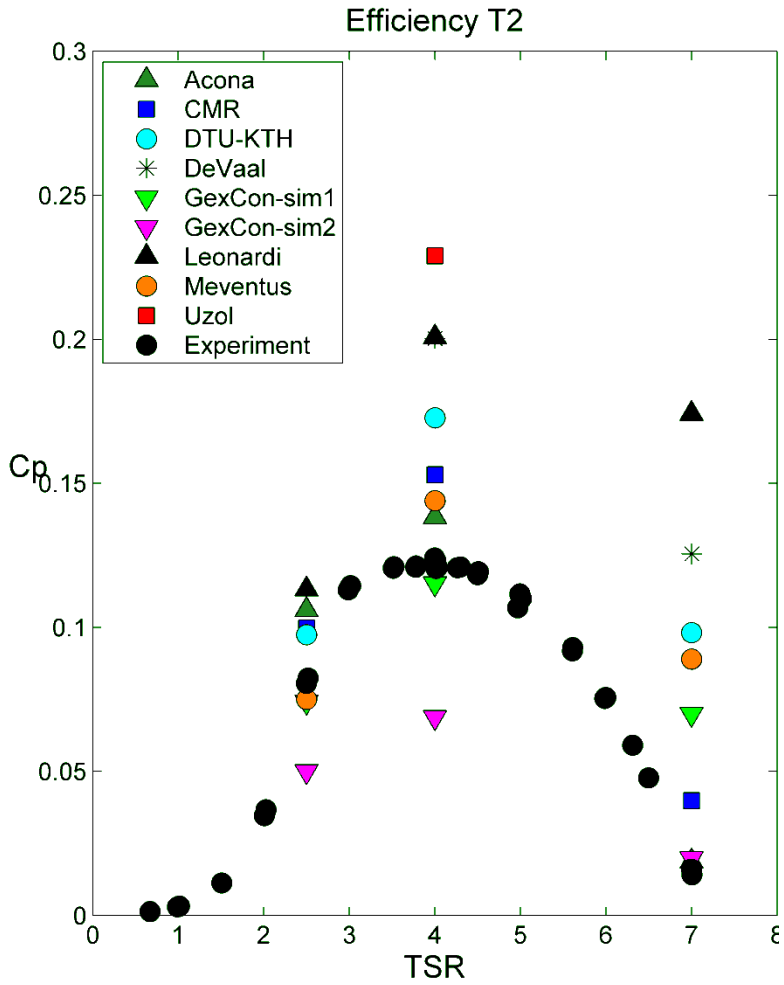
Turbine 1

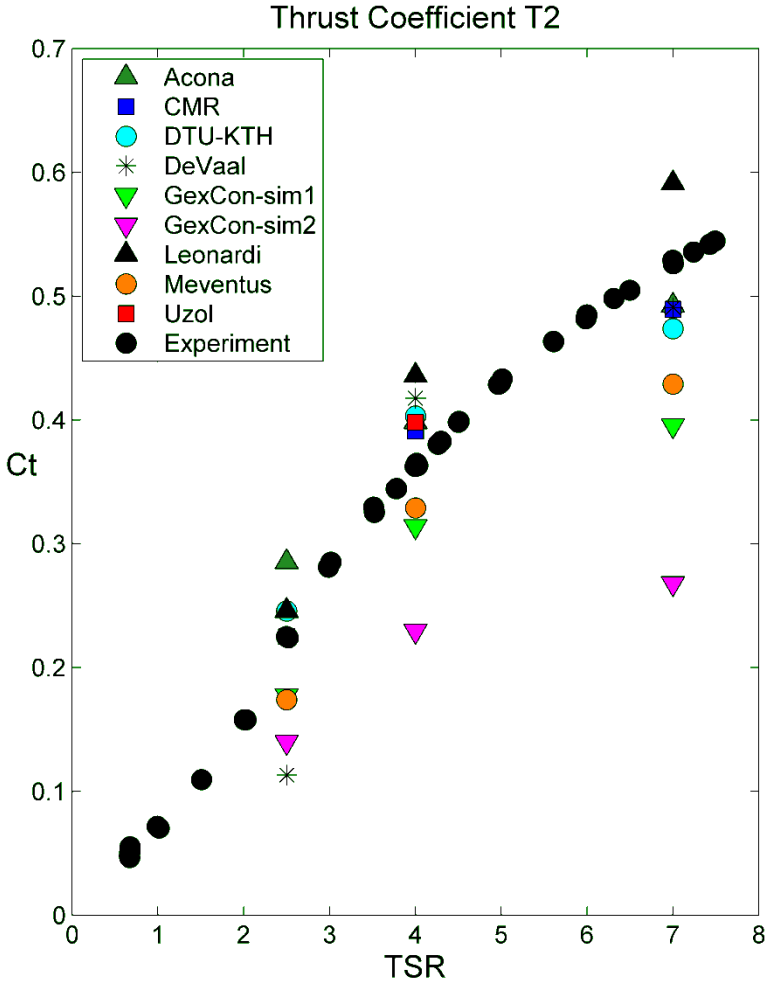




Blind comparison : C_P,C_T

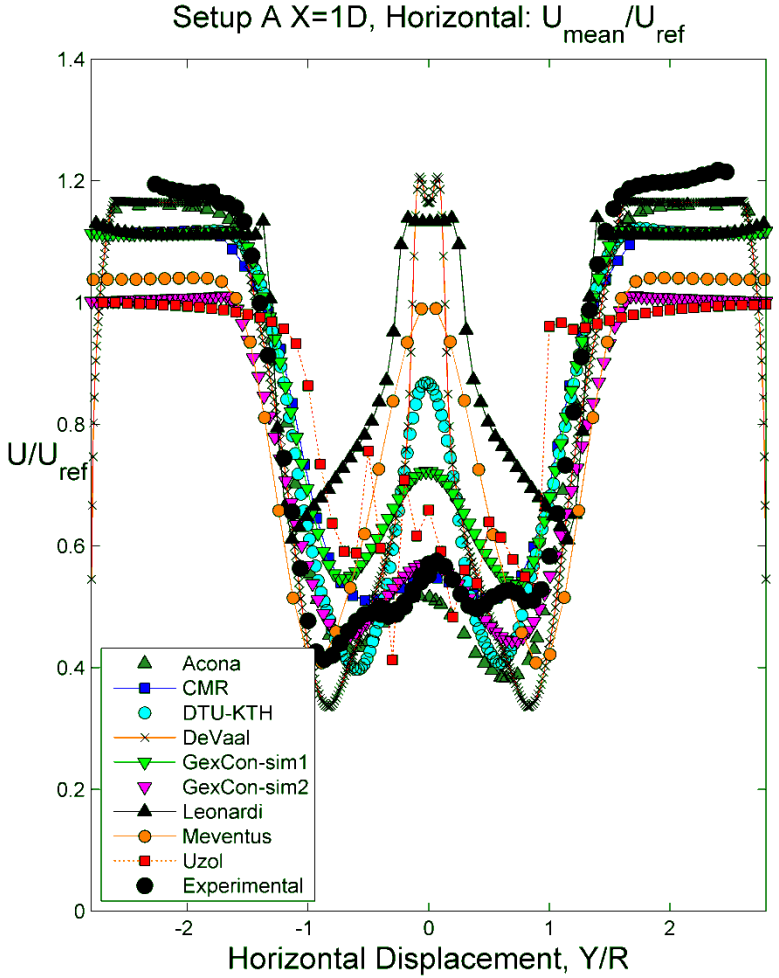
Turbine 2

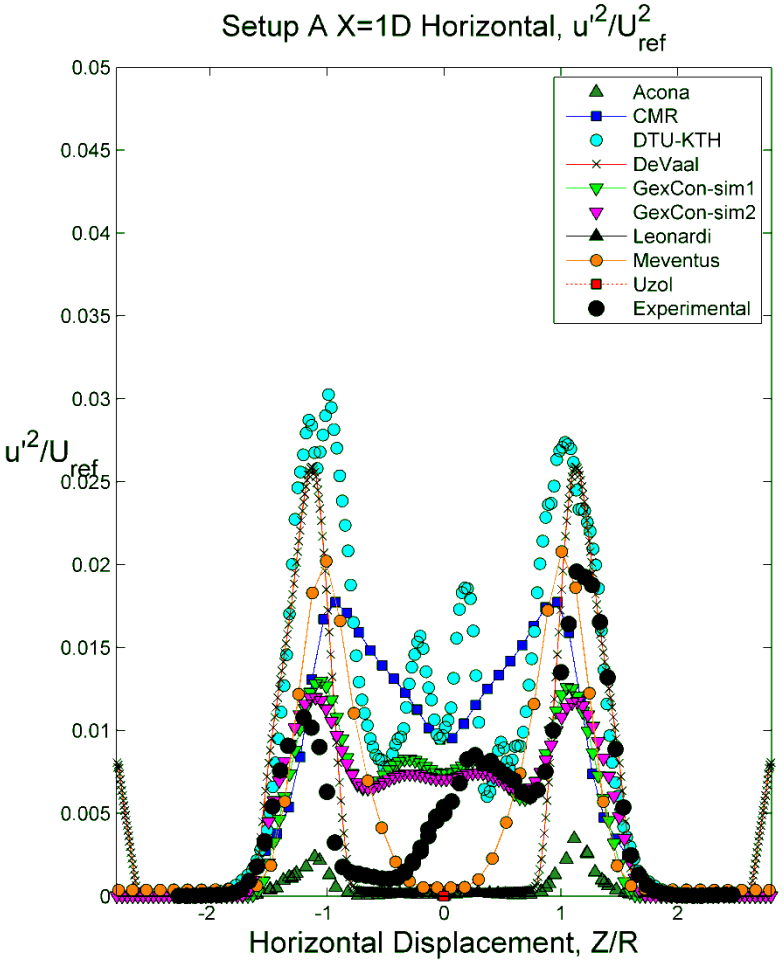




Wake, 1D

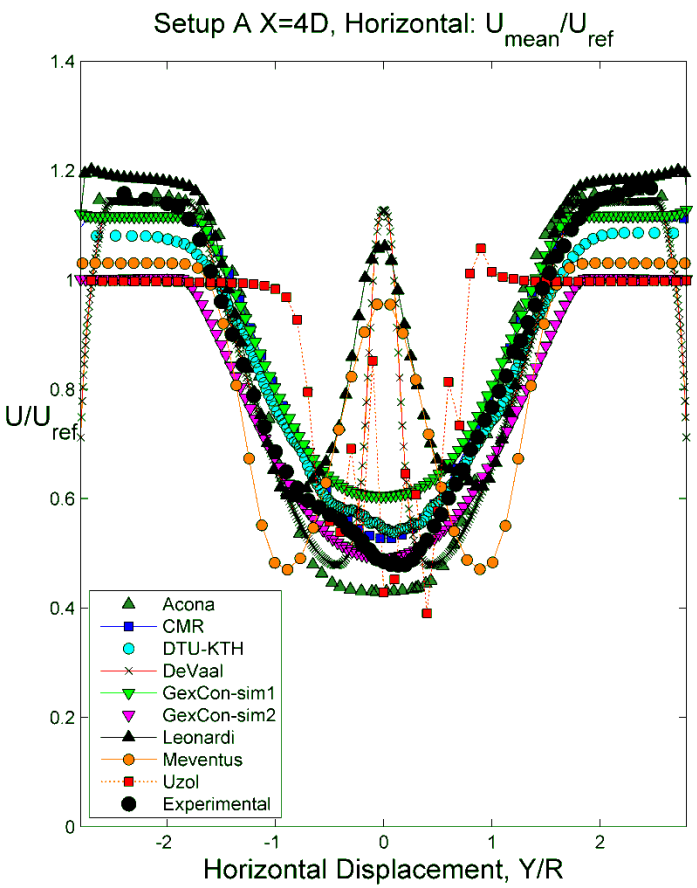
1D behind T2, Horizonthal

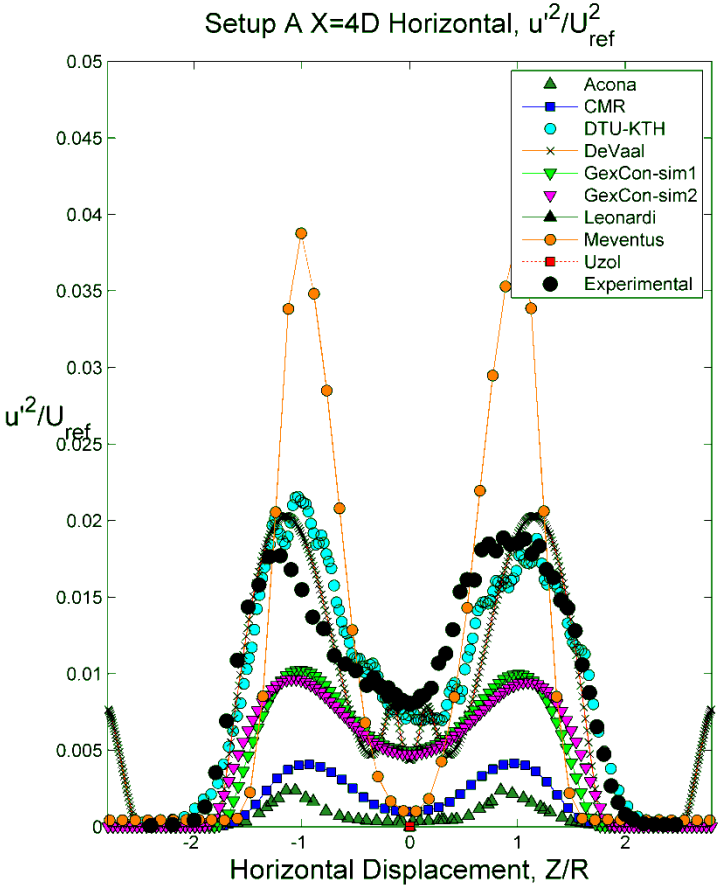




Wake, 4D

4D behind T2, Horizontal

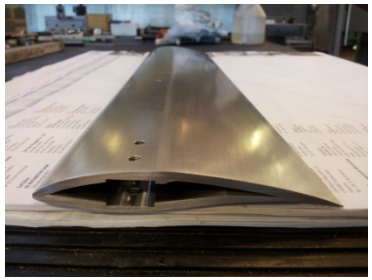




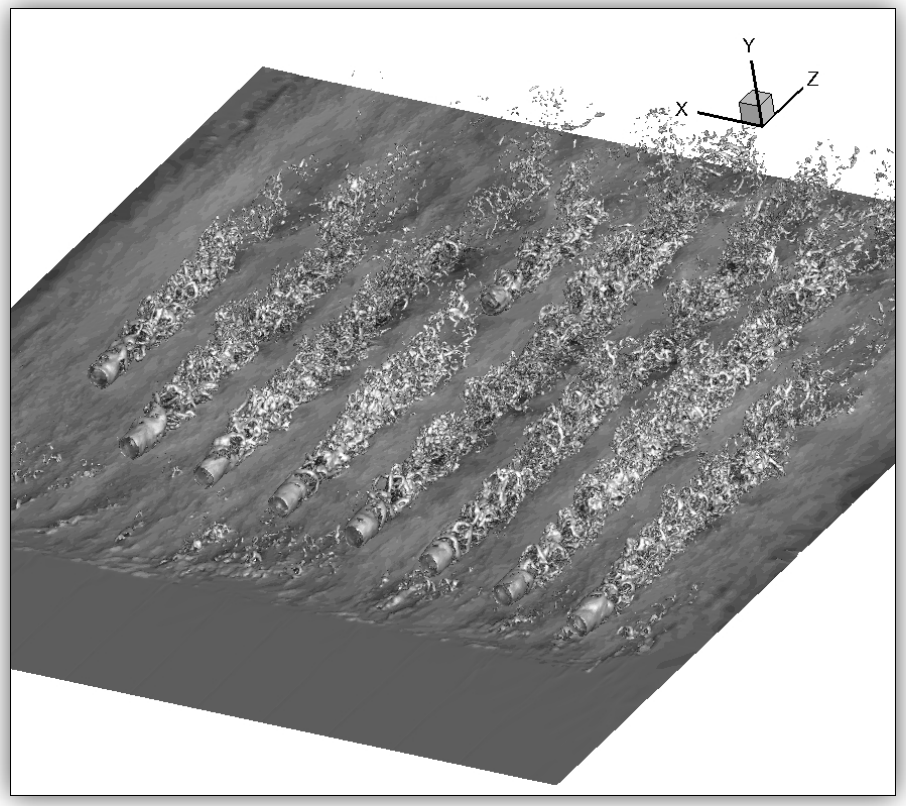
Conclusion

- LES –Actuator line modeling of two turbines in a row performed
  - Good prediction for the T1, too high for T2, improvements are needed
  - Near wake at 1D looks Ok, but could be better, good prediction at 4D
  - Thrust OK
  - Cp: not to good for T2, (more drag needed?)

- Improvements
  - Better aerofoil data 2D, measured



Wind Farm modelling : Lillgrund

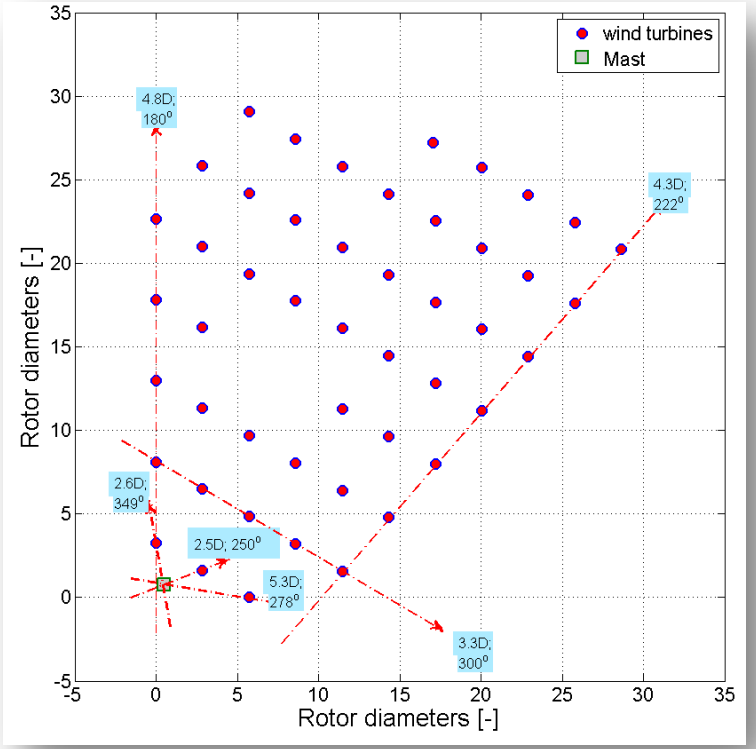


Wind Farm Study

- Aim of study:
  - Wind farm simulation using LES/AD
  - Evaluated method
  - Investigate simple farm optimization by de-rating front row (pitch)

- One inflow sector is investigated (120±2.5º)
- One wind speed is considered (8m/s)

- Evaluation
  - Sensitivity to turbulence intensity
  - Comparison with the measured data
  - De-rated case, i.e. front row pitching

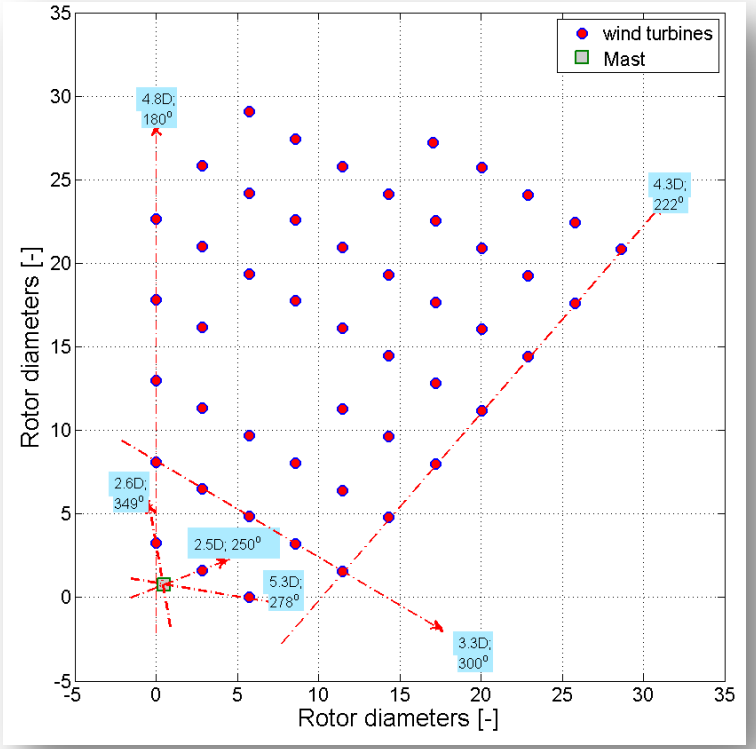


Lillgrund Wind Farm

- The Lillgrund wind farm:
  - Located offshore between Malmö and Copenhagen
  - 48 turbines, Siemens SWT-93-2.3MW, variable speed - pitch controlled
  - Turbine spacing: 3.3D – 4.3D

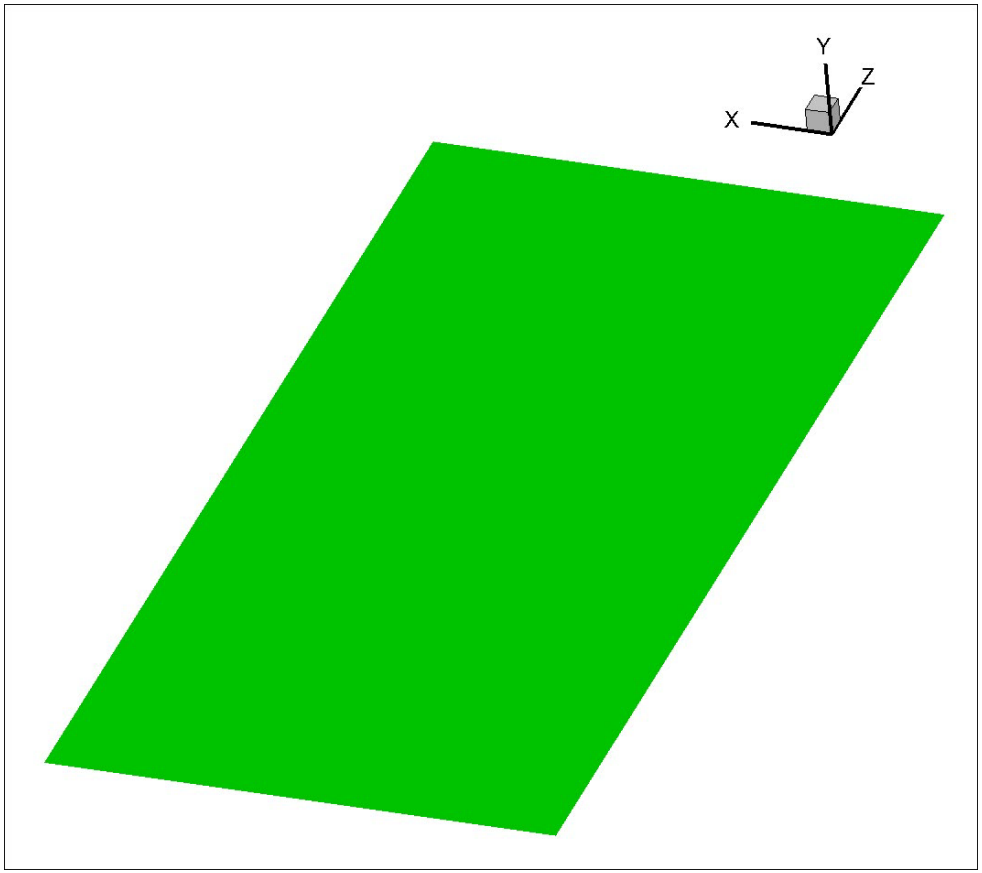
- Measured data for comparison
  - Production
  - Atmospheric conditions

- Farm efficiency : ≈ 75%

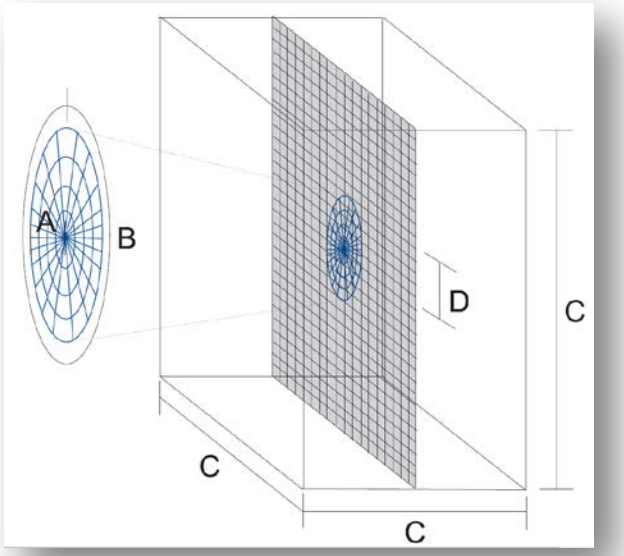


Actuator disc

One row, 4 turbines



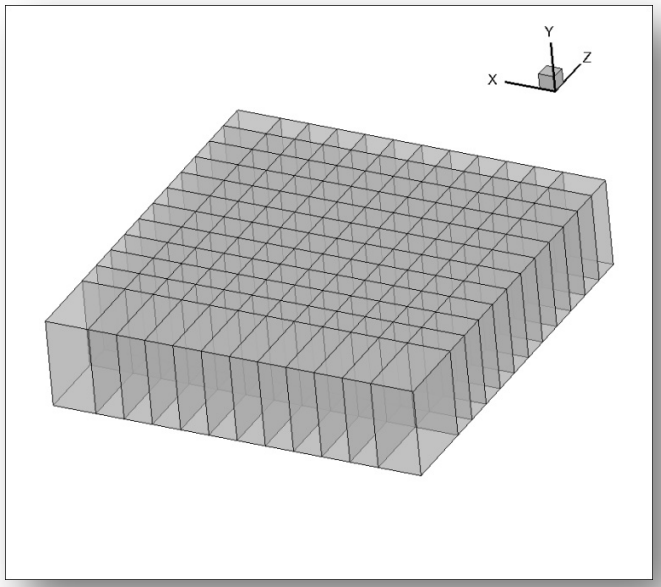
- 3D AD -> Many AL fixed in space
- Loads using aerofoil data locally
- Faster than AL
  - Lager timestep
  - Lower resolution



Numerical setup

Grid – Cartesian type

- 144 block, 64^3
- 84R x 82R x 20R (R=46.5m)
- Fine resolution, 0.1R
- Stretching away from fine region



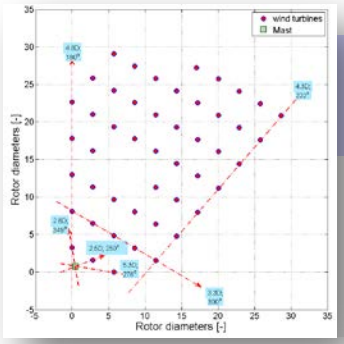
Turbine:

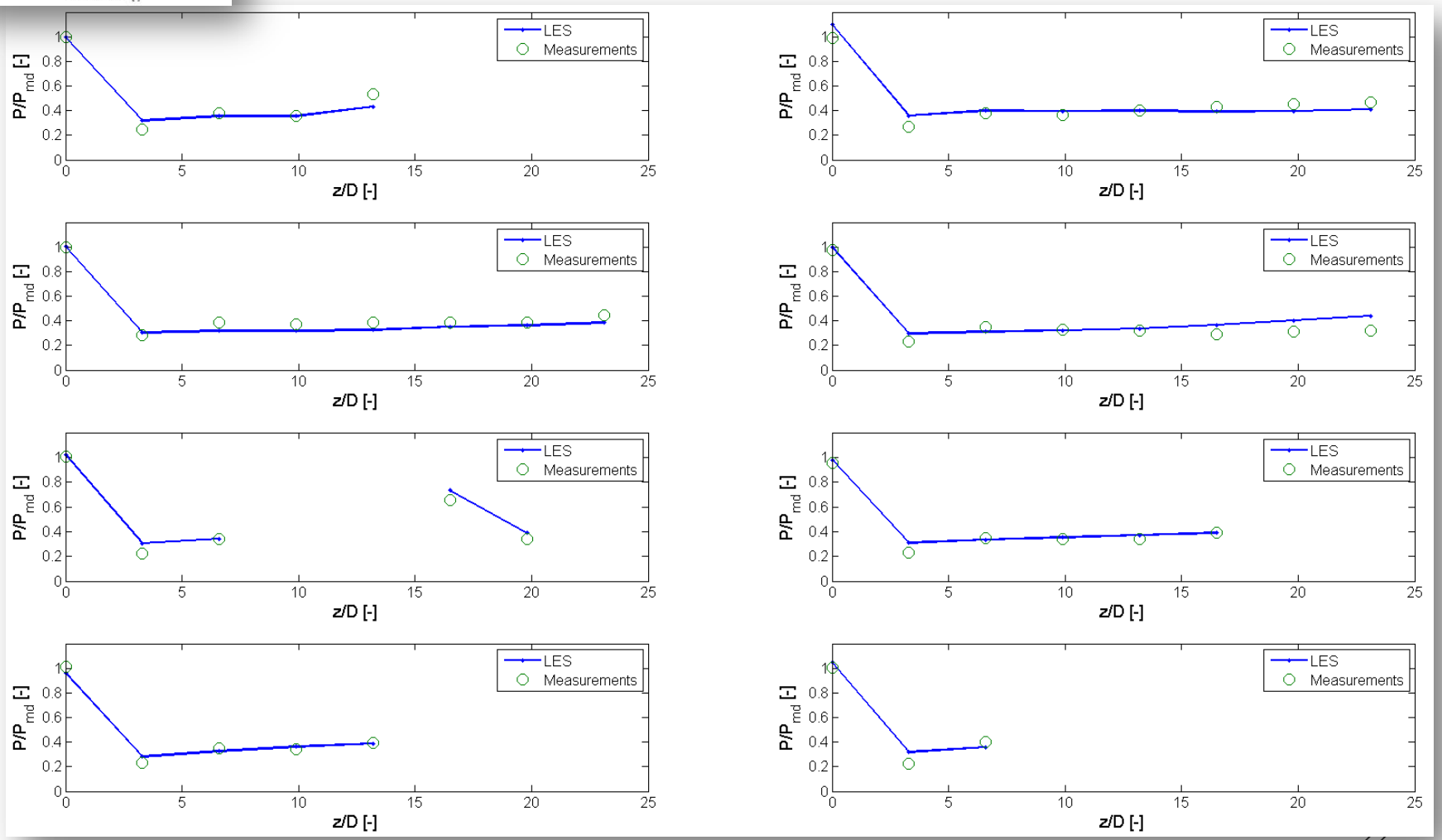
- Downscaled NREL 5MW
- R=46.5m
- Rated power 2.3MW

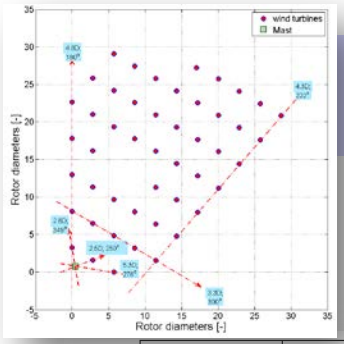
Flow – Neutral stability of ABL assumed

- 8m/s, 120±2.5°
- Shear exponent
- Turbulence, TI=4.7%

Lillegrund: Power

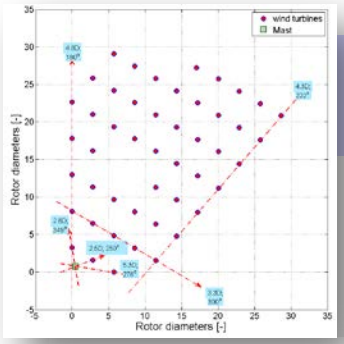


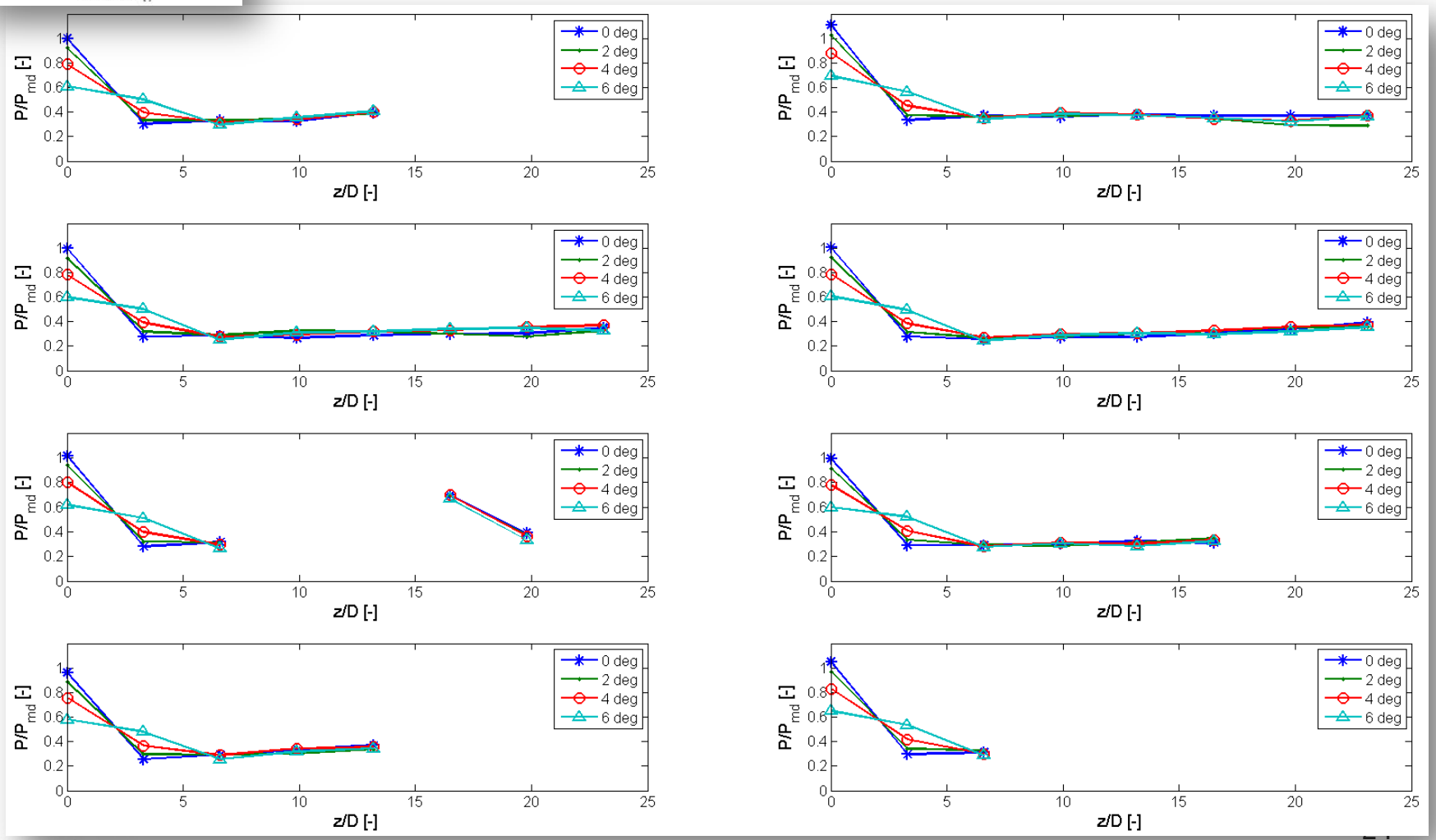




Turbulence: 0% 3.2% 4.7% 6.2%

Front row de-rating, 0,2,4,6deg



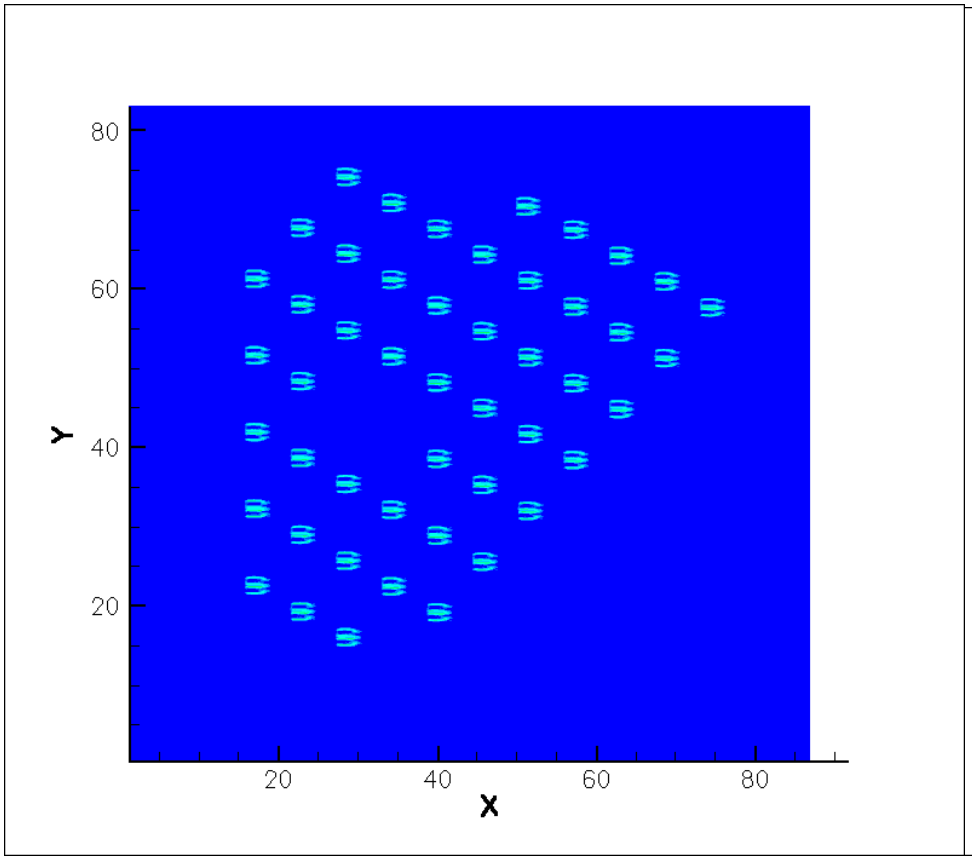


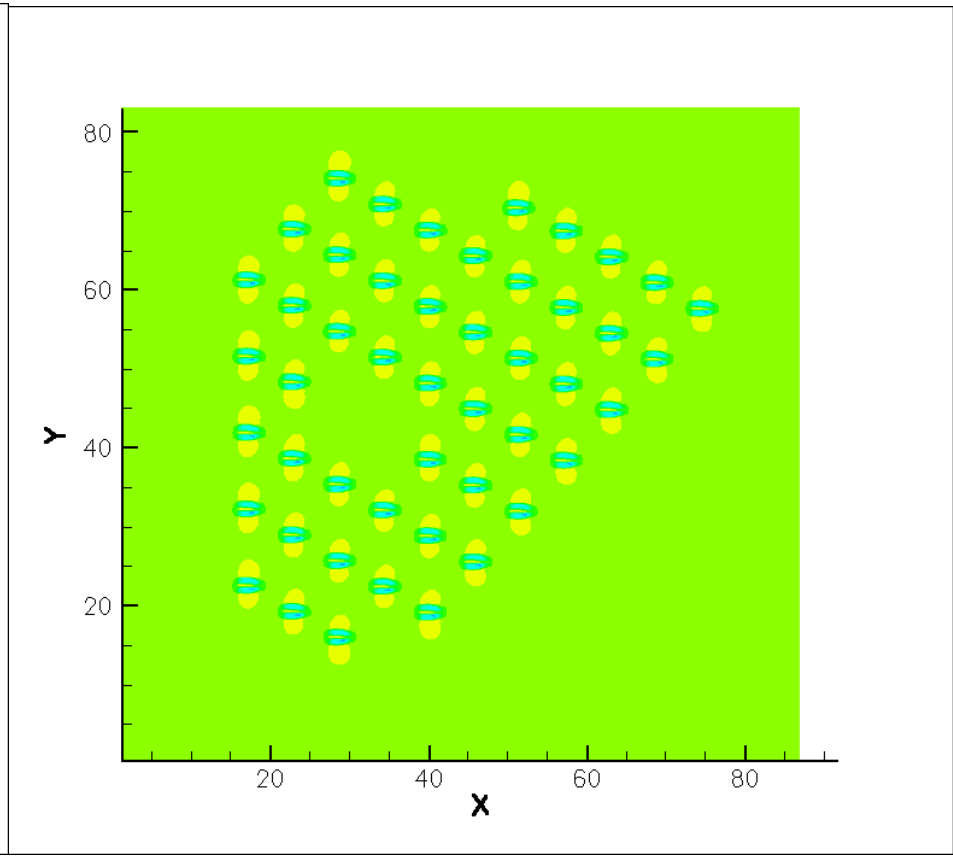
Summary

- LES – AD simulation of power performed and compared to measurements
  - Turbulence sensitivity
  - De-rating

- Good comparison for inflow sector is investigated (120±2.5º)
- No improvement from front row pitch

Thank you!





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