Center for Wind Turbine Aerodynamics and Atmospheric Turbulence

Projektstatus task 2 og 3

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Overview of tasks:

Task 1. Rotor/ABL Aerodynamics (NNS)

Task 2. Wind Turbine Wakes and Clusters (JNS)

Task 3. Wind Farms (JNS)

Task 4. Siting in Forested and Complex Terrain (JM)

Task 5. Atmospheric Boundary Layers (JM)

Objectives

Task 2: Wind Turbine Wakes and Clusters

Analyse and simulate turbulent wakes and turbine to turbine interaction subject to

- Wind shear
- Turbulent inflow
- Different wind directions
- Wind veer

Overall goals:

- Understanding of wake aerodynamics
- Development of turbulent wake model

Milestones Task 2

- **M7:** Parabolized stand-alone N-S park model. **Month 14. Completed.**
- **M8:** Validation of N-S model for wake behind a single wind turbine. **Month 24. Completed.**
- **M9**: Refined far wake model. **Month 24. Pending.**
- **M10**: Parametric study of wake interaction. **Month 36. Pending.**
- **M11:** Parametric study of wake stability. **Month 36. Completed.**
- **M12:** Refined Dynamic Wake model. **Month 48. Pending.**

Objectives

Task 3: Wind Farms

Analyse and simulate wind farms and farm to farm interaction subject to

- Wind shear/stratification
- Turbulent inflow
- Different wind directions
- Wind veer

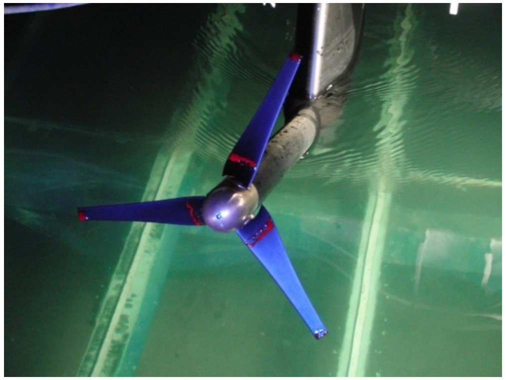
Overall goals:

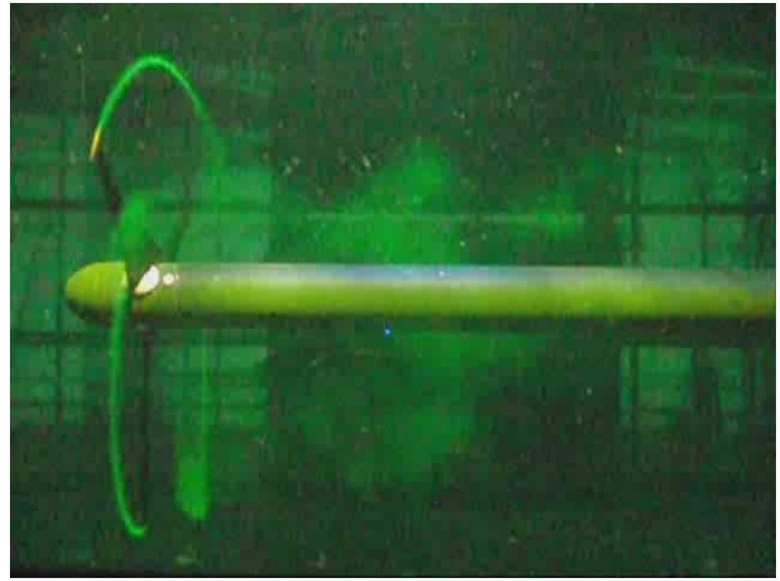
- Understanding of flows in wind farms
- Development of optimization tools for farm siting

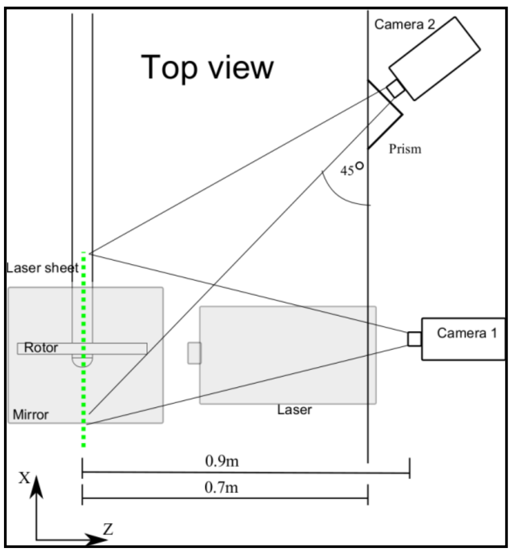
Milestones Task 3

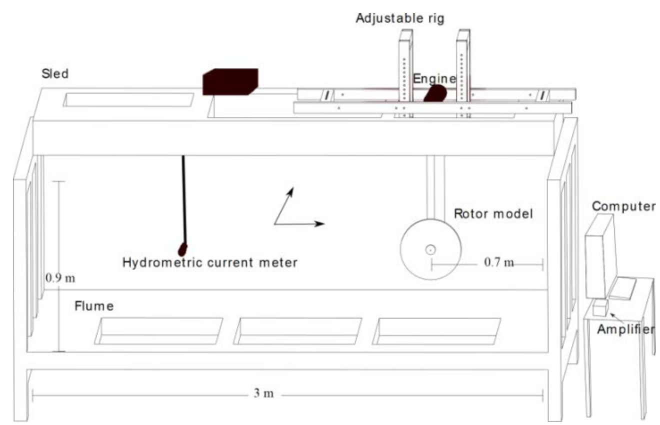
- **M13**: LES simulations of wind farms; Comparisons to experiments. **Month 24. Completed.**
- **M14:** Low-dimensional turbulence model for wind farms. **Month 36. Completed.**
- **M15:** LES simulations subject to neutrally stable ABL . **Month 36. Pending.**
- **M16**: Simulation of influence of stratification on wind farm performance. **Month 48. Pending.**
- **M17:** Simulation of mutual influence between two wind farms. **Month 60. Not yet started.**

Experimental investigation of wakes



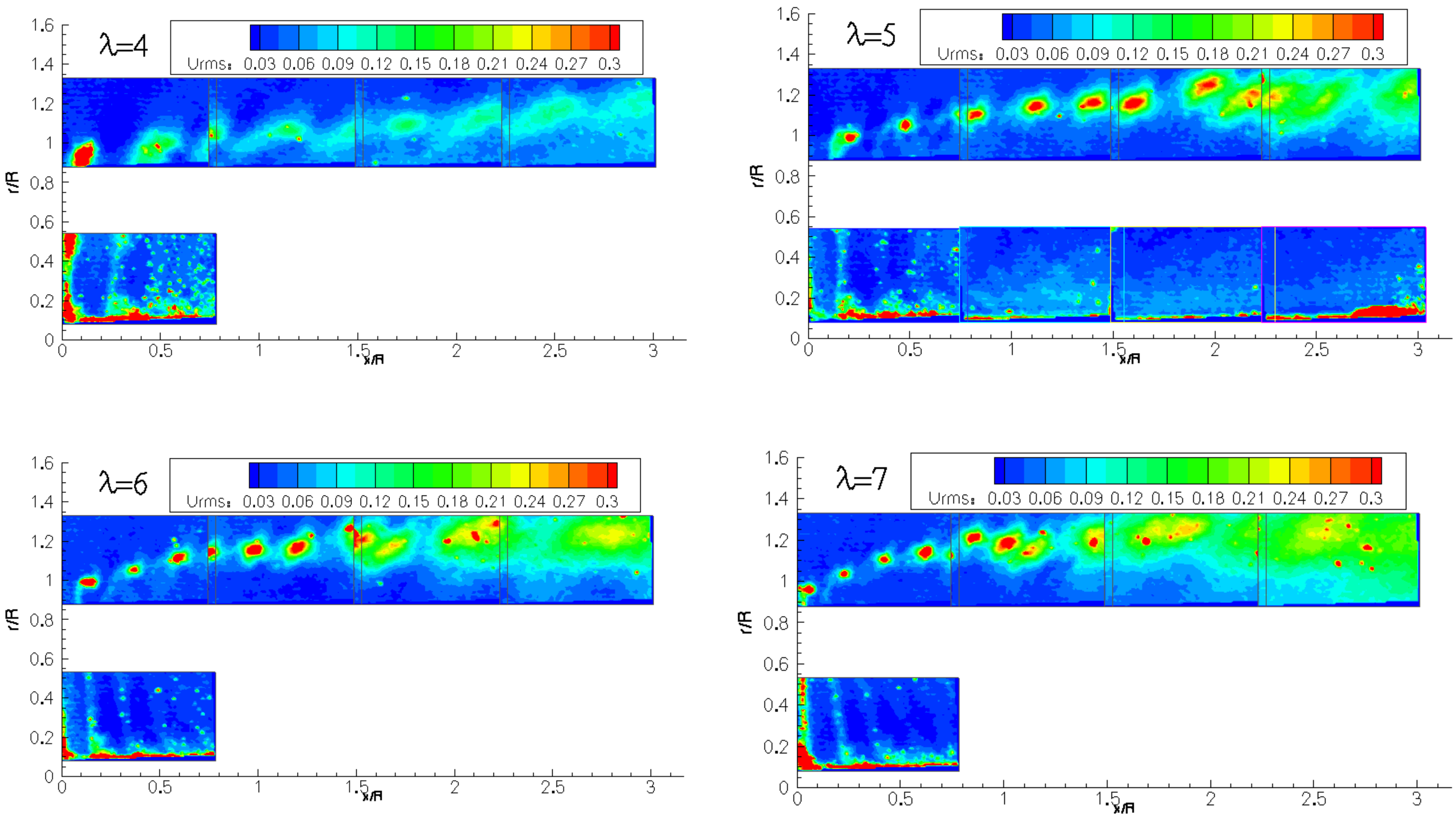




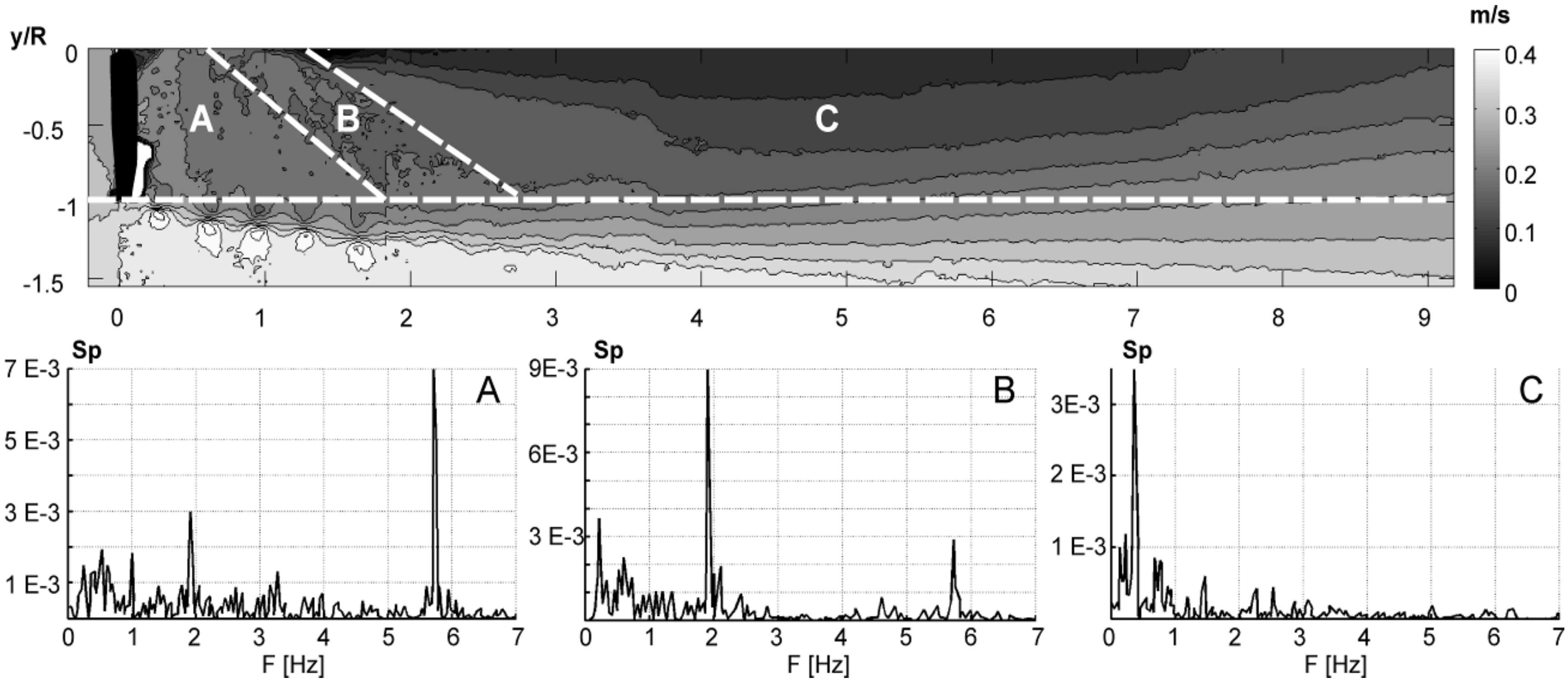


PIV measurements and visualizations of model rotor in water flume

PIV, Phase ave., U-rms, TSR 4-7

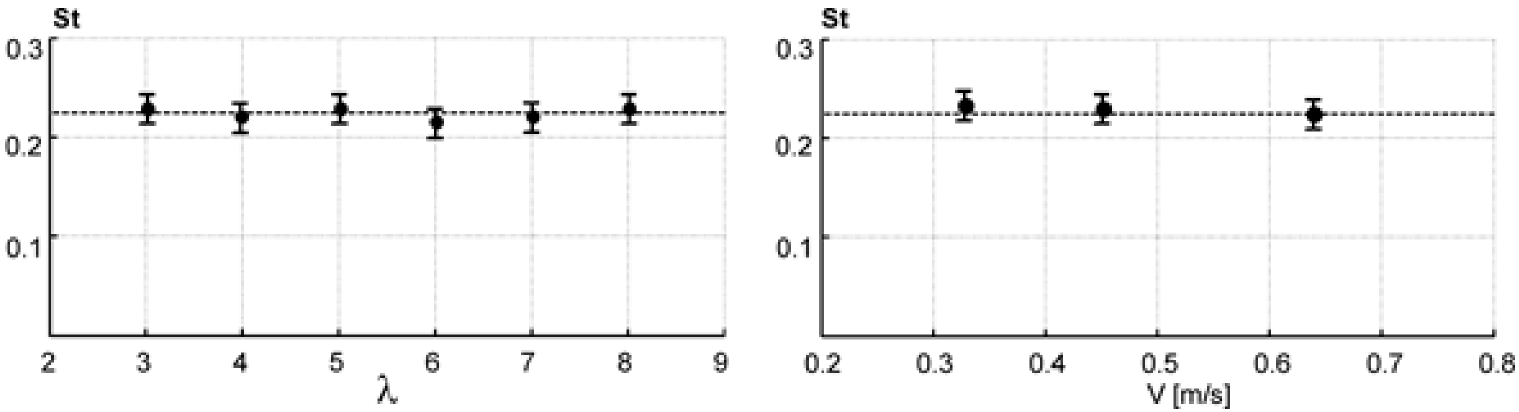


Averaged flow structure and main frequencies

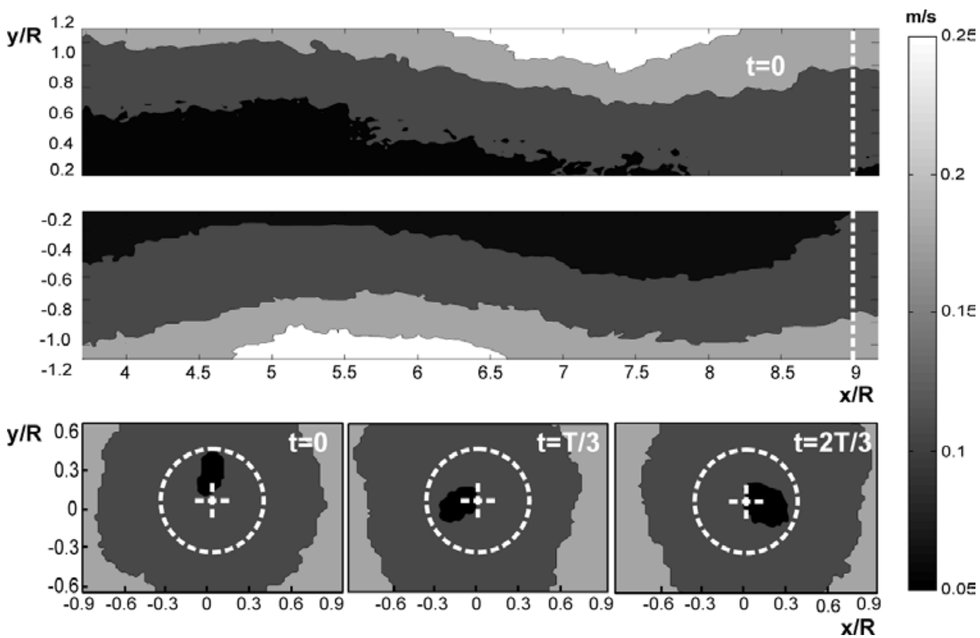


Zones showing main frequencies of the oscillations in the rotor wake

Averaged flow structure and main frequencies



Strouhal number - St=fD/U - as function of (a) tip speed ratio and (b) inflow speed



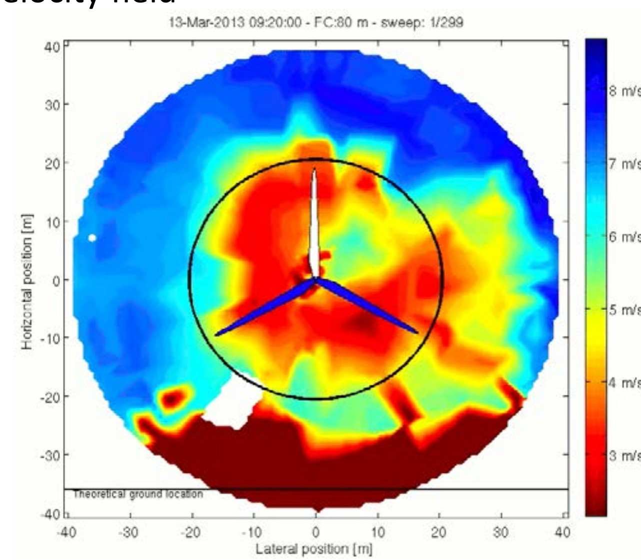
Oscillation of the helical vortex structure in the rotor far wake

PhD on Multiple Turbine Wakes (1/2)

- **Full scale merged wake experiment**: mutual validation of CFD LES-ACL/AD models with lidar based experiments on merged wake characteristics:
  - organized flow structure of the merged wake (deficit, attenuation, expansion)
  - turbulent part of the flow structure (stream wise Reynolds stress component, added wake turbulence)
- Set up involving **3 lidars:** 2 cross sectional wakes scanning and one conical forward scanning.

Nordtank turbine in the wake of the Tellus turbine

Corresponding cross sectional merged wake velocity field



* high spatial and time resolution

PhD on Multiple Turbine Wakes (2/2)

Current activities

- Measurement phase completed in May 2013.
- Post processing program developed.
- Data analyzing in progress. Selection of merged wake case.
- EllipSyS3D LES-ACL /ACS simulations of merged wake.

Future activities

- CFD model benchmark: DTU Wind Energy / NREL.
- Condensing experimental work and high fidelity CFD into a simple engineering model for wake interaction.
- Integration of engineering model into the DWM framework in HAWC2 for power and load calculations in wind farms.

Validation of the actuator line technique

- **NextMex project**
- **Krogstad experiment**
- **WakeBench**

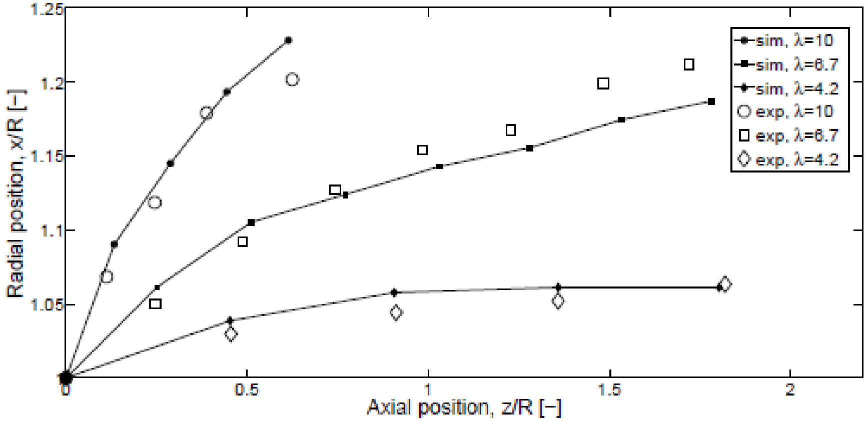


Figure 10. The spatial wake expansion, i.e., the wake trajectory. Lines represent simulations and markers represent measurements.

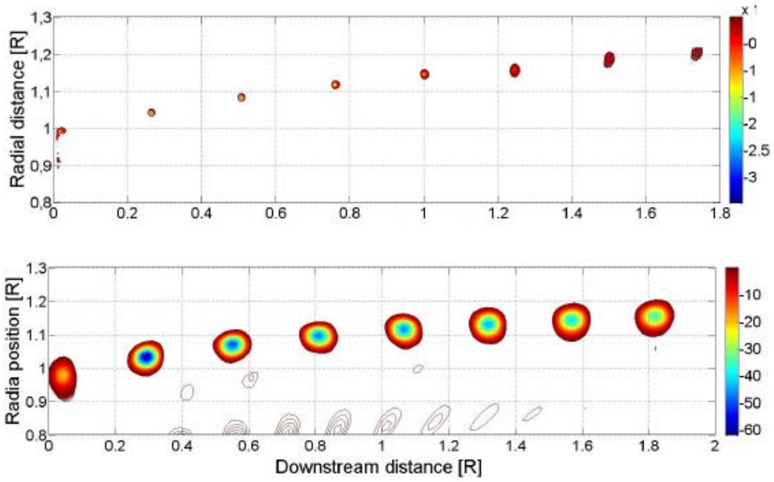
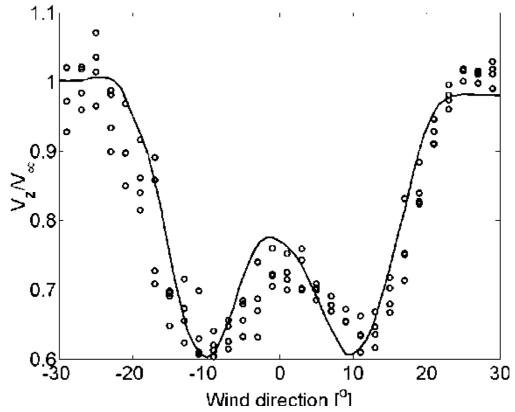
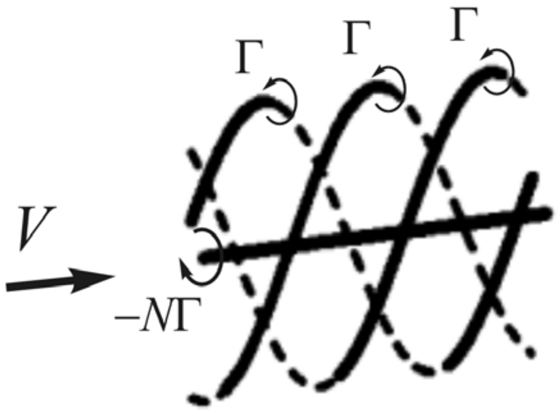


Figure 1: The tip vortices identified by λ_2.

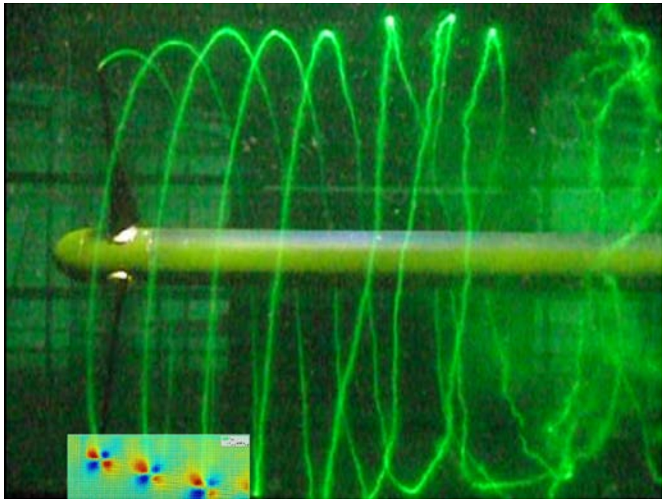


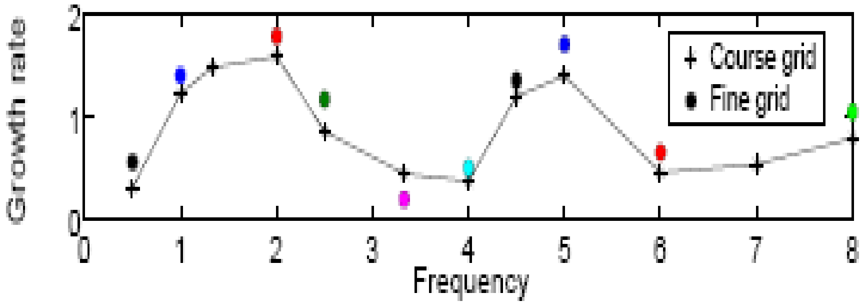
Comparison between computated and measured wake structures

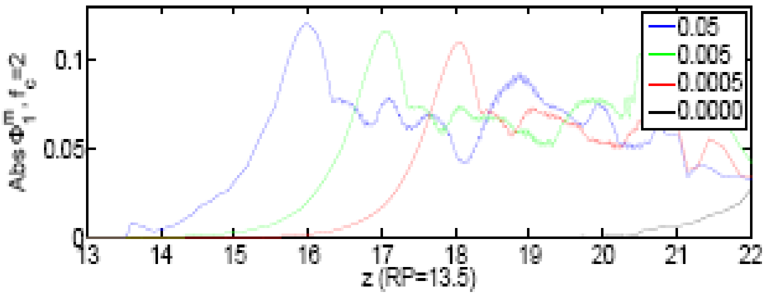
Stability of wakes



Model of Okulov and Sørensen (JFM, 2007)

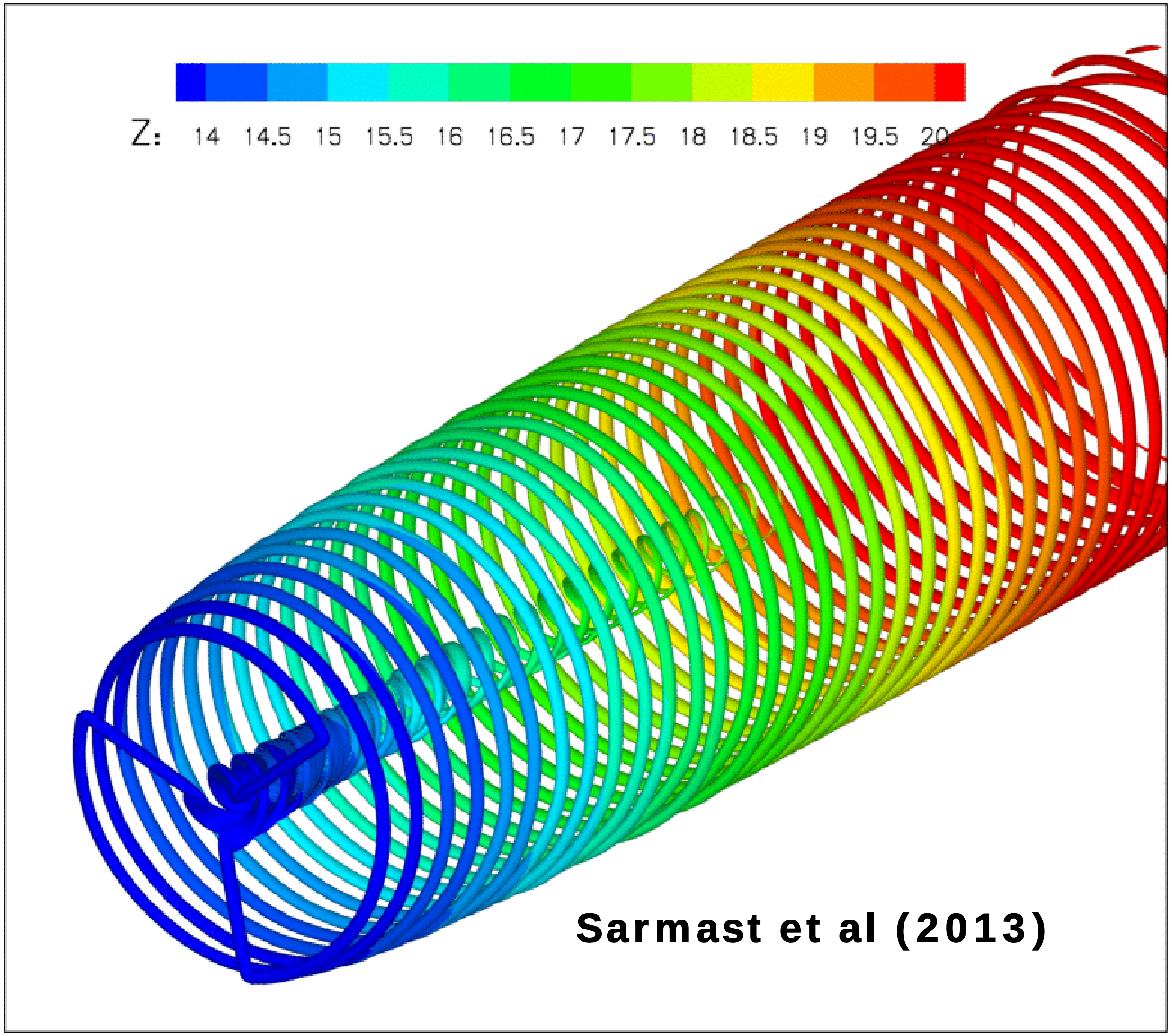




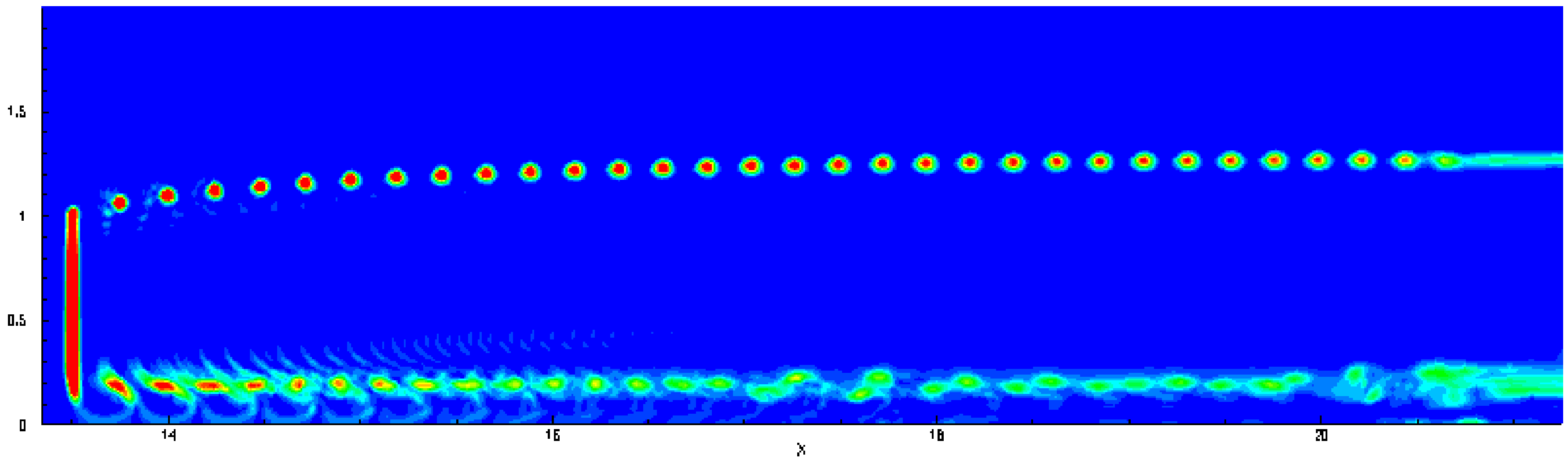


Amplification of perturbations for various frequencies

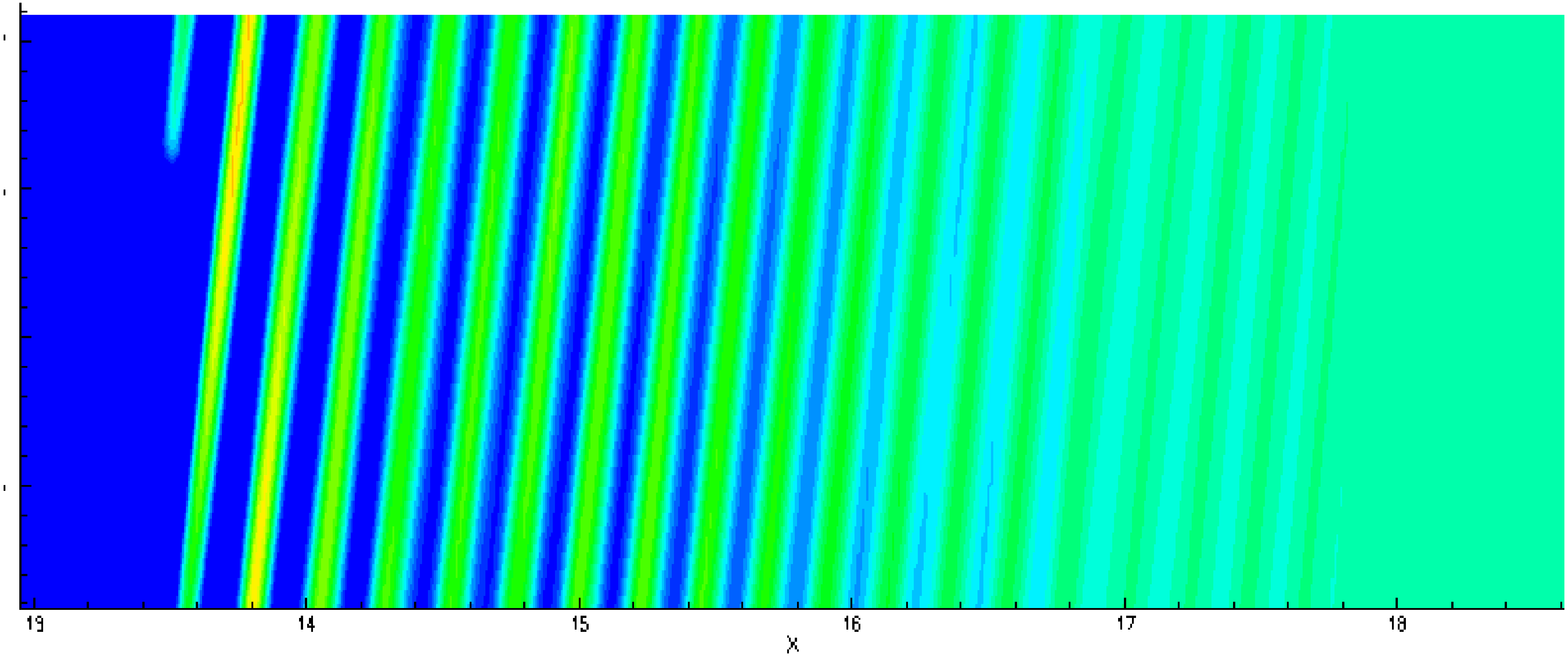
Wake breakdown due to presence of low upstream amplitude excitation



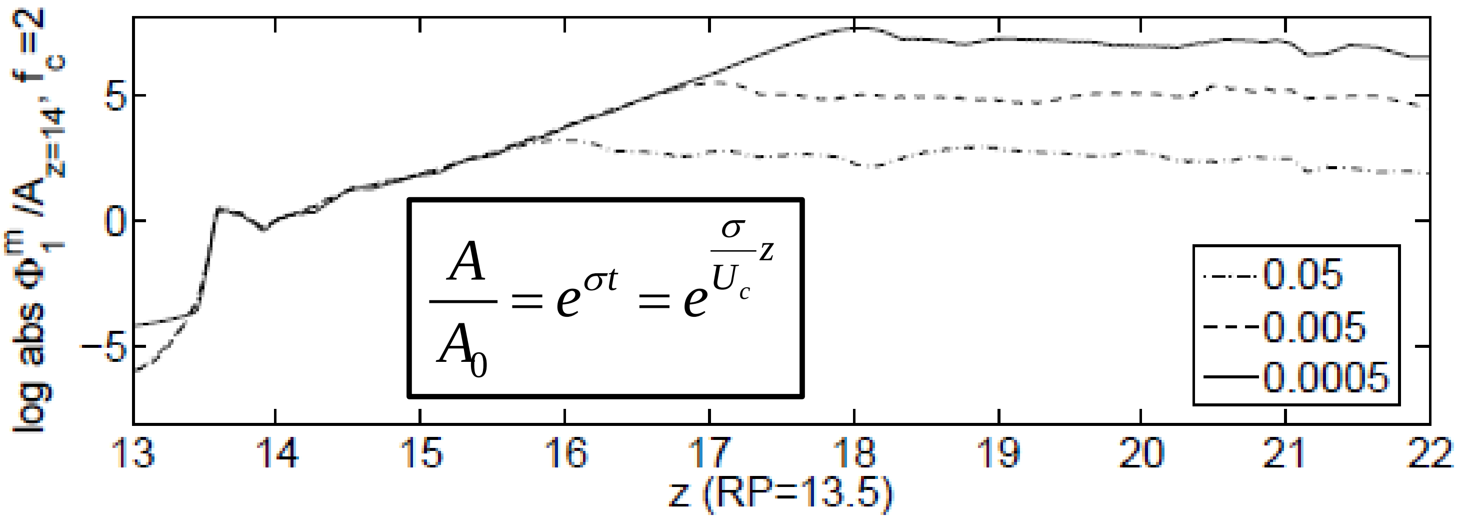
Mutual inductance instability of tip vortices



Mutual inductance instability of tip vortices



Mutual inductance instability of tip vortices



Amplification: $$\frac{\sigma \cdot 2h^2}{\Gamma} = \frac{\pi}{2}$$ (Lamb, 1932)

h : Distance between vortices

U_c: Convective velocity

Γ : Circulation

Relations between wake and rotor charateristics

Geometry of of wake: $$\frac{N_b h}{2\pi R} = \frac{U_c}{\Omega R} \Rightarrow h = \frac{2\pi R U_c}{N_b \lambda U_o}$$

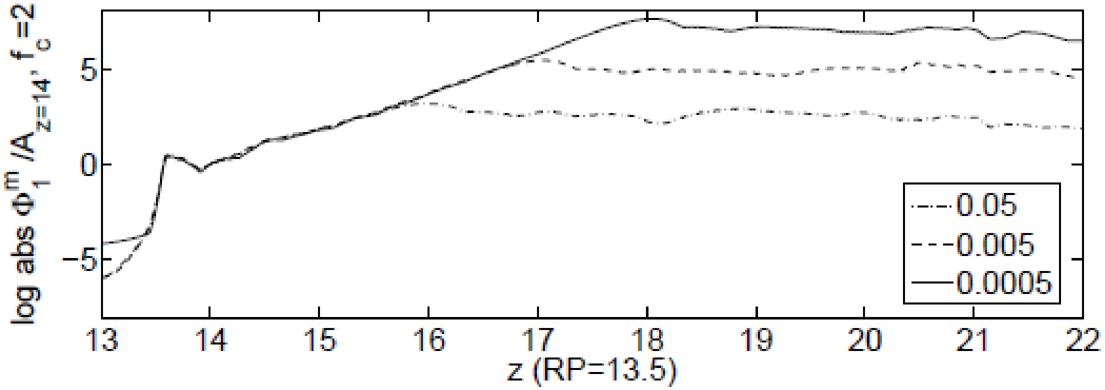
Assuming constant loading: $$\Gamma = \frac{\pi U_o^2 C_T}{N_b \Omega}$$

Roller bearing analogy: $$U_c = C_1 \cdot \frac{1}{2}\left(U_o + U_{wake}\right) + \left(1 - C_1\right) \cdot U_o$$

From 1-D Momentum theory: $$U_{wake} = U_o \sqrt{1 - C_T}$$

Combining: $$\boxed{\frac{\sigma R}{U_c} = \frac{N_b \lambda C_T}{16\left[1 + \frac{1}{2} C_1 \left(\sqrt{1 - C_T} - 1\right)\right]^3}}$$

Expression for length of near wake



Amplitude amplification:

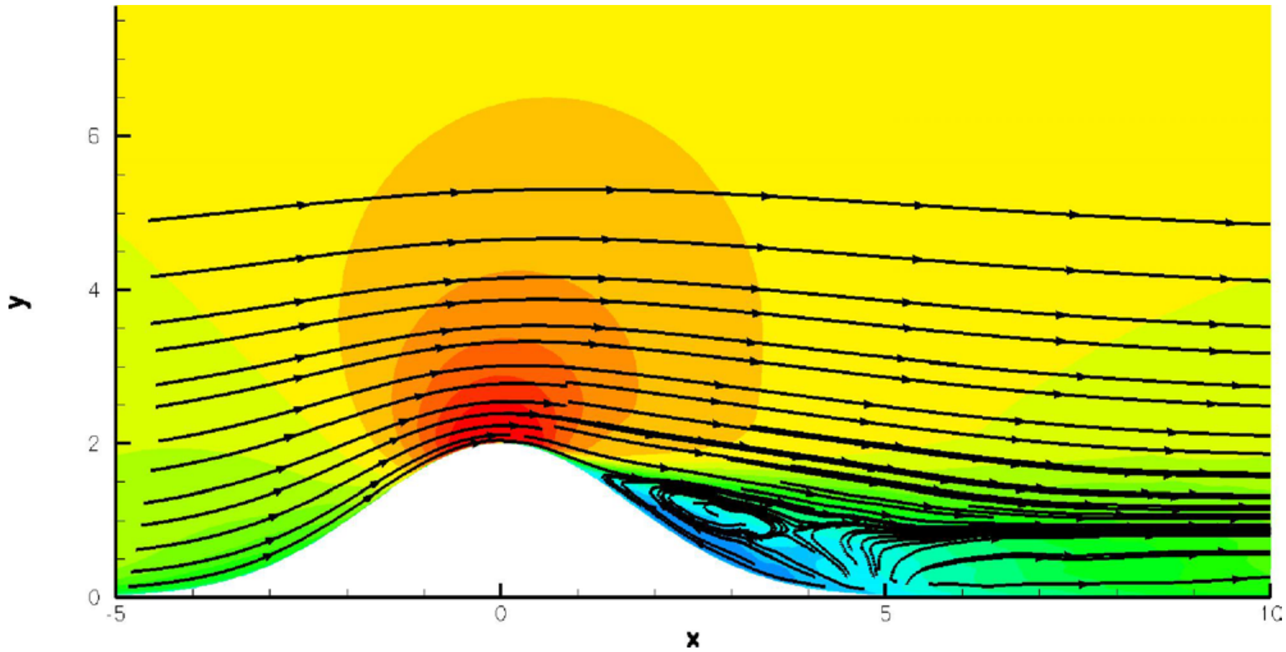
$$\ln\left(\frac{A_{\max}(t)}{A_o}\right) \simeq -\ln\left(\frac{u'}{U_o}\right)$$

Assuming that: $\frac{u'}{U_o} = C_2 \cdot Ti$

We get the following expression for the length of the near wake (defined as the stable wake of the tip vortices):

$$\frac{l}{R} \simeq -\frac{16\left[1+\frac{1}{2}C_1\left(\sqrt{1-C_T}-1\right)\right]^3}{N_b C_T \lambda}\ln(C_2 \cdot Ti)$$

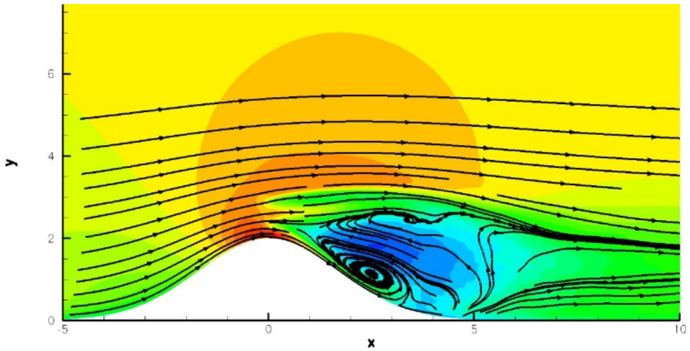
Wake behind a turbine on a hill



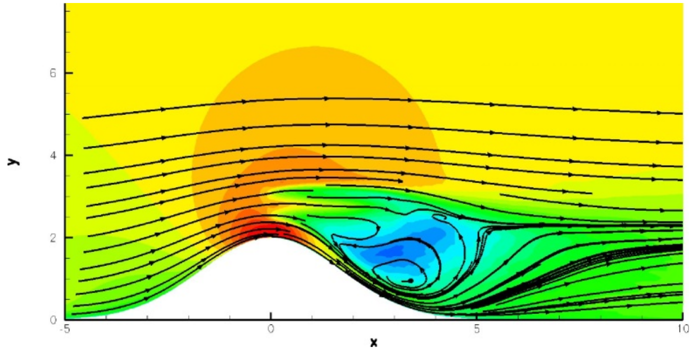
Time averaged plot on a computational mesh of 48x64^3=12.6x10^6. The turbine diameter is 80 m. The hill has a height of 200 m and a slope of 45^o.

Wake behind a turbine on a hill

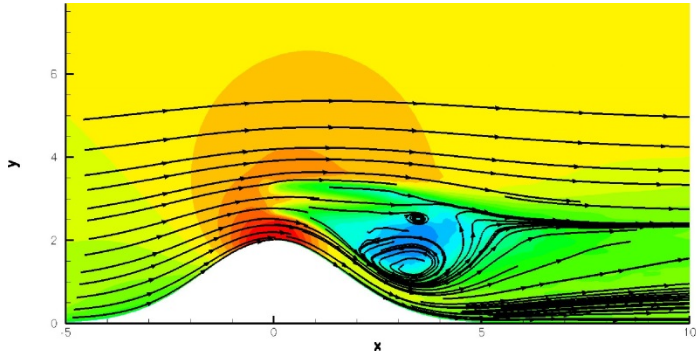
Averaged velocity in z



H = 60 m



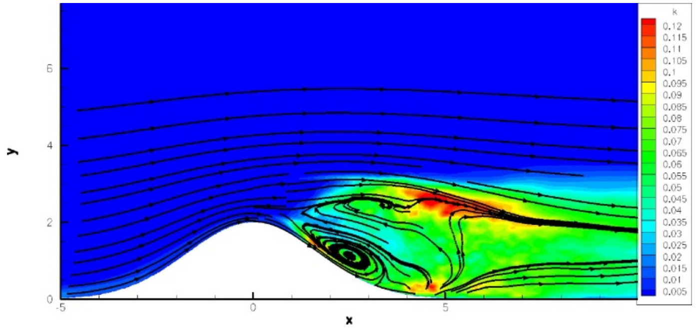
H = 80 m



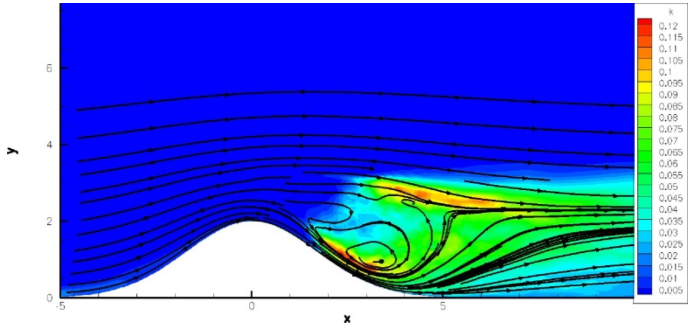
H = 100 m

Wake behind a turbine on a hill

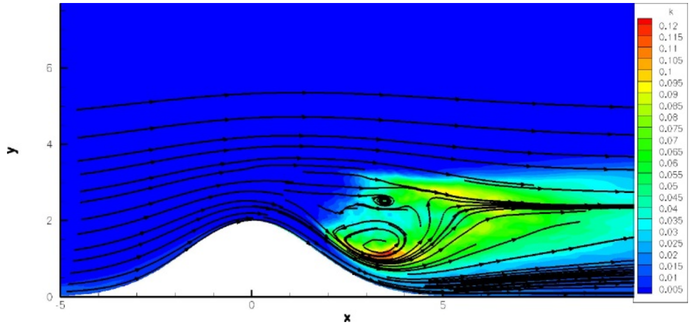
Turbulent kinetic energy



H = 60 m



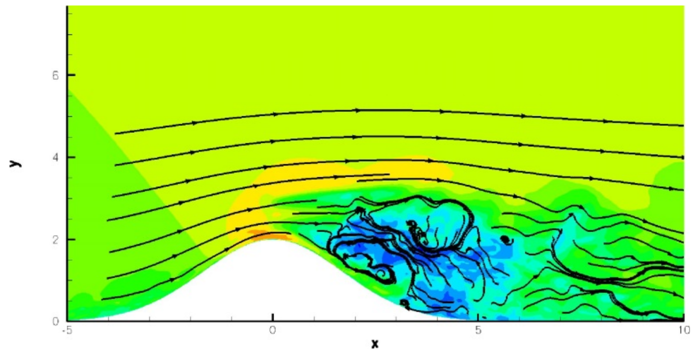
H = 80 m



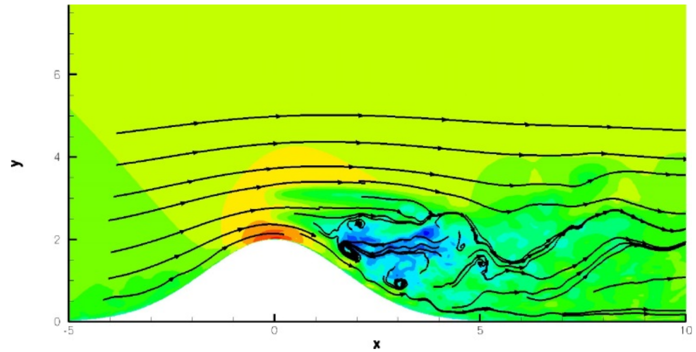
H = 100 m

Wake behind a turbine on a hill

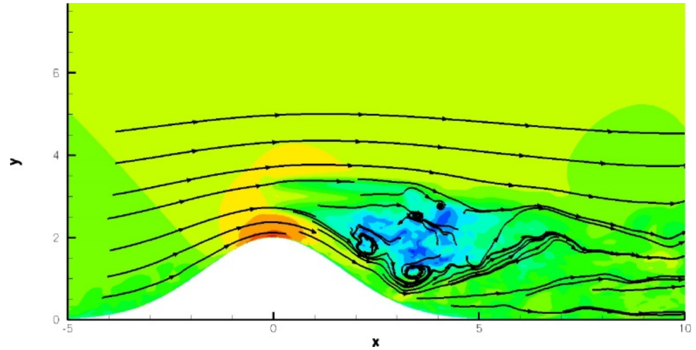
Instantaneous velocity



H = 60 m



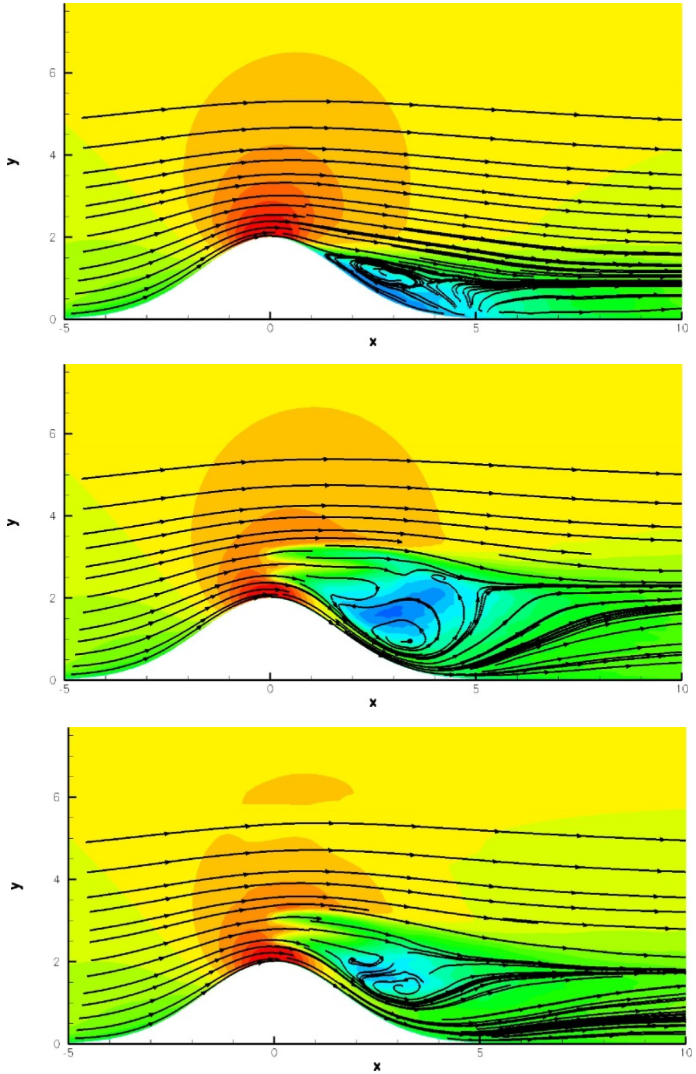
H = 80 m



H = 100 m

Wake behind a turbine on a hill

Averaged velocity



H = 80 m

With turbulence

Refined AD/RANS Model for Wakes

- **Turbulence inflow boundary condition**

❑ In most models[1-3]

The inflow profiles of *k* and ω are given by the relationships:

$$k = \frac{u_*^{\ 2}}{\sqrt{\beta_*}} \qquad \omega = \frac{u_*}{\sqrt{\beta_*} \cdot K \cdot z}$$

where u* is the friction velocity, K is the von Kármán constant.

❑ In present work [4]

$$k = \frac{3}{2}(U \cdot I)^2 \qquad \omega = \frac{k}{\mu}\left(\frac{\mu_t}{\mu}\right)^{-1}$$

where I is the turbulence intensity, μ is the molecular dynamic viscosity.

In our cases, using these two methods, the obtained values for *k* and ω are:

$k_1 = 1.61 \times 10^{-2}$ $\qquad$ $k_2 = 1.50 \times 10^{-2}$

$\omega_1 = 0.513$ $\qquad$ $\omega_2 = 2.33$

- **Rotor modelling**

❑ Actutor disc methods

Decay of turbulence

- Turbulence modelling

- k- ω SST turbulence model

- Decay of turbulence

In the free-stream flow, there is no mean velocity gradient and the variation of turbulence parameters does not exist, so the production term P and the diffusion term D can be neglected.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P - \beta^* \rho k \omega + D_k \qquad \frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t} P - \beta \rho \omega^2 + D_\omega + C_\omega$$

Through solving the left partial differential equations, the decay of turbulence quantities in the free-stream in any downstream positions can be predicted.

$$k = k_{inlet}\left(1 + \frac{\omega_{inlet}\beta x}{U}\right)^{-\frac{\beta^*}{\beta}} \qquad \omega = \omega_{inlet}\left(1 + \frac{\omega_{inlet}\beta x}{U}\right)^{-1}$$

'inlet' means values at inflow boundary

X is the stream-wise distance from the inlet boundary

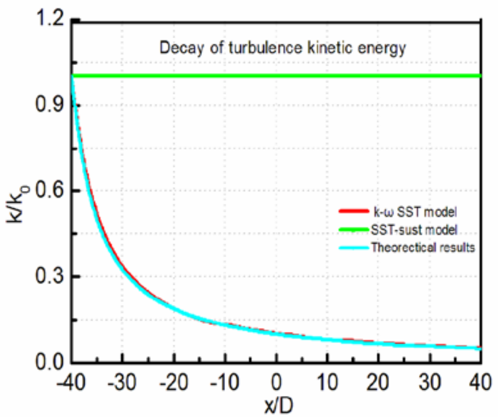
U is local velocity

- Modified turbulence model(SST-sust model)

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P - \beta^* \rho k \omega + D_k + \beta^* \rho k_{amb} \omega_{amb}$$

$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t} P - \beta \rho \omega^2 + D_\omega + C_\omega + \beta \rho \omega_{amb}^2$$

where the subscript 'amb' represents the ambient values.



Modified turbulence models

- Modified turbulence models

❑ SST-const model

According to the measurements in neutral atmospheric flow, Prospathopoulos et al. proposed the corrected set of coefficients of k-ω SST turbulence model:

$\beta^* = 0.033; \quad \beta_1 = 0.025; \quad \gamma_1 = 0.3706$ the original one: $\beta^* = 0.09; \quad \beta_1 = 0.075; \quad \gamma_1 = 0.5532$

➢ Problems

The numerical experiments had shown that the turbulence intensity was still underpredicted by the SST-sust model and SST-const model.

❑ SST-Csust model

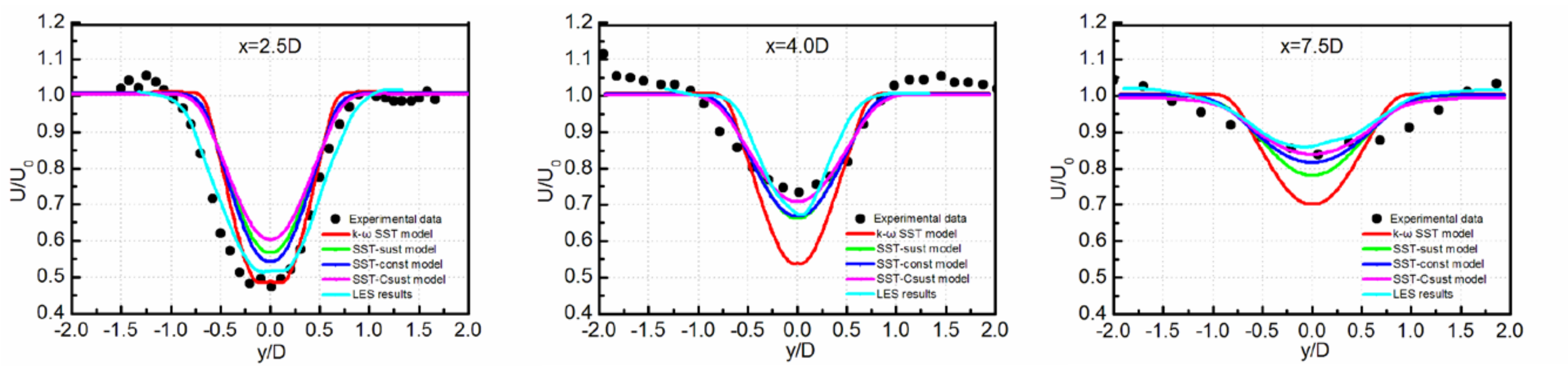
This newly developed model, named the SST-Csust model, is a combination of SST-sust model and SST-const model.

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho u_j k)}{\partial x_j} = P - \beta^* \rho k \omega + D_k + \beta^* \rho k_{amb} \omega_{amb}$$

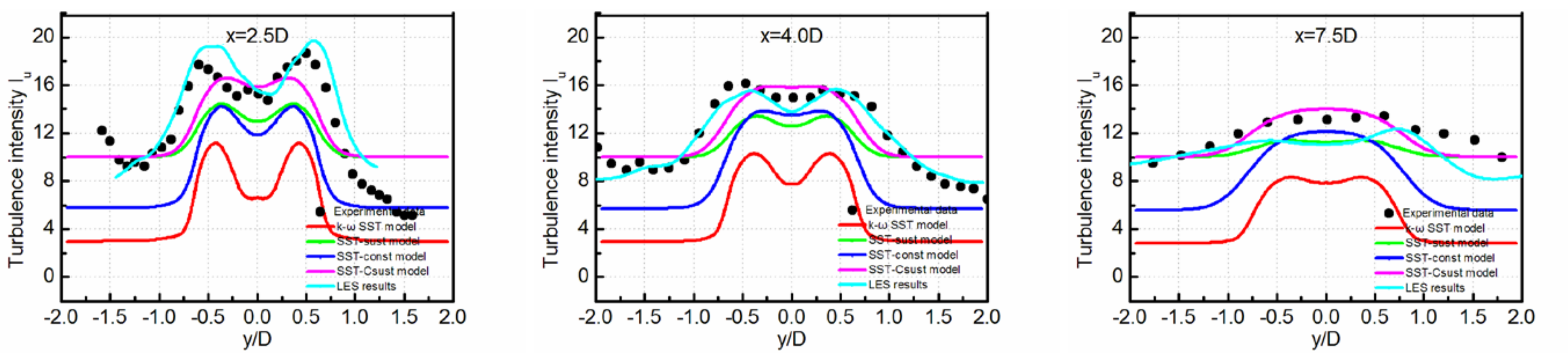
$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho u_j \omega)}{\partial x_j} = \frac{\gamma}{\nu_t} P - \beta \rho \omega^2 + D_\omega + C_\omega + \beta \rho {\omega_{amb}}^2$$

$$\beta^* = 0.033; \quad \beta_1 = 0.025; \quad \gamma_1 = 0.3706$$

Test case 1: single wake

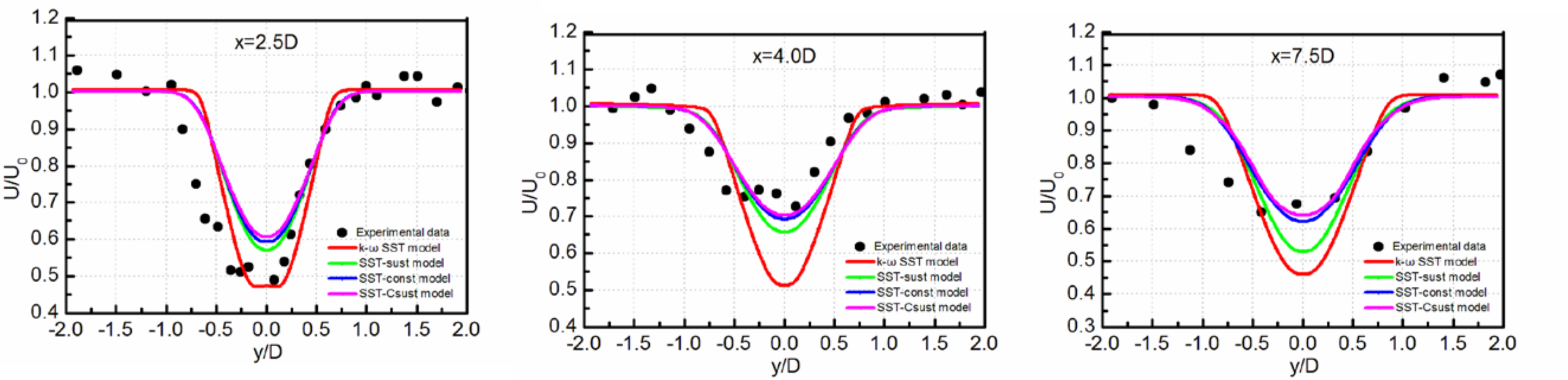


Wind speed ratio in the cross-wind direction at down-stream positions of 2.5D, 4.0D and 7.5D

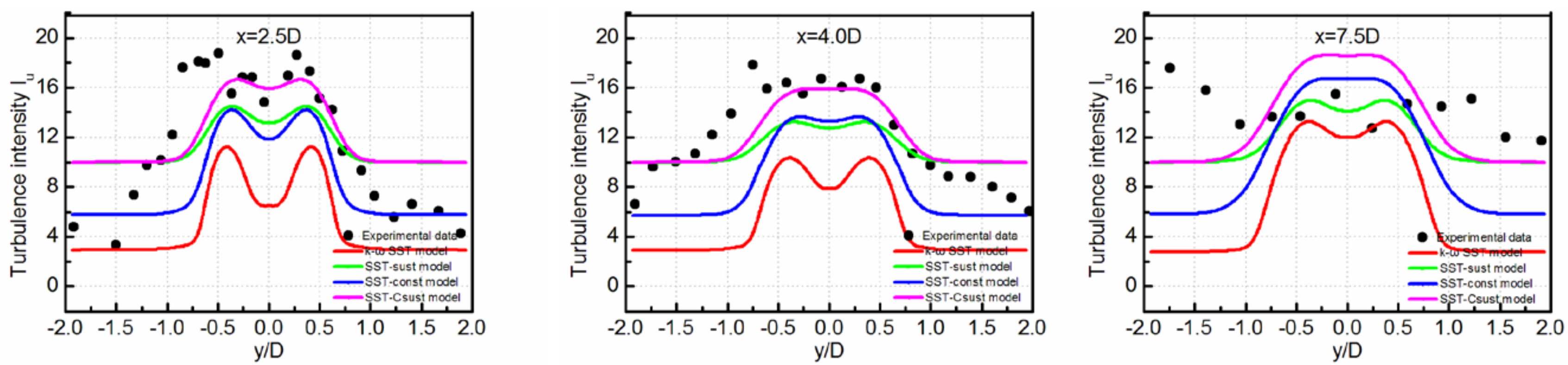


Comparisons of turbulence intensity in the cross-wind direction at down-stream positions of 2.5D, 4.0D and 7.5D

Test case 2: double wakes

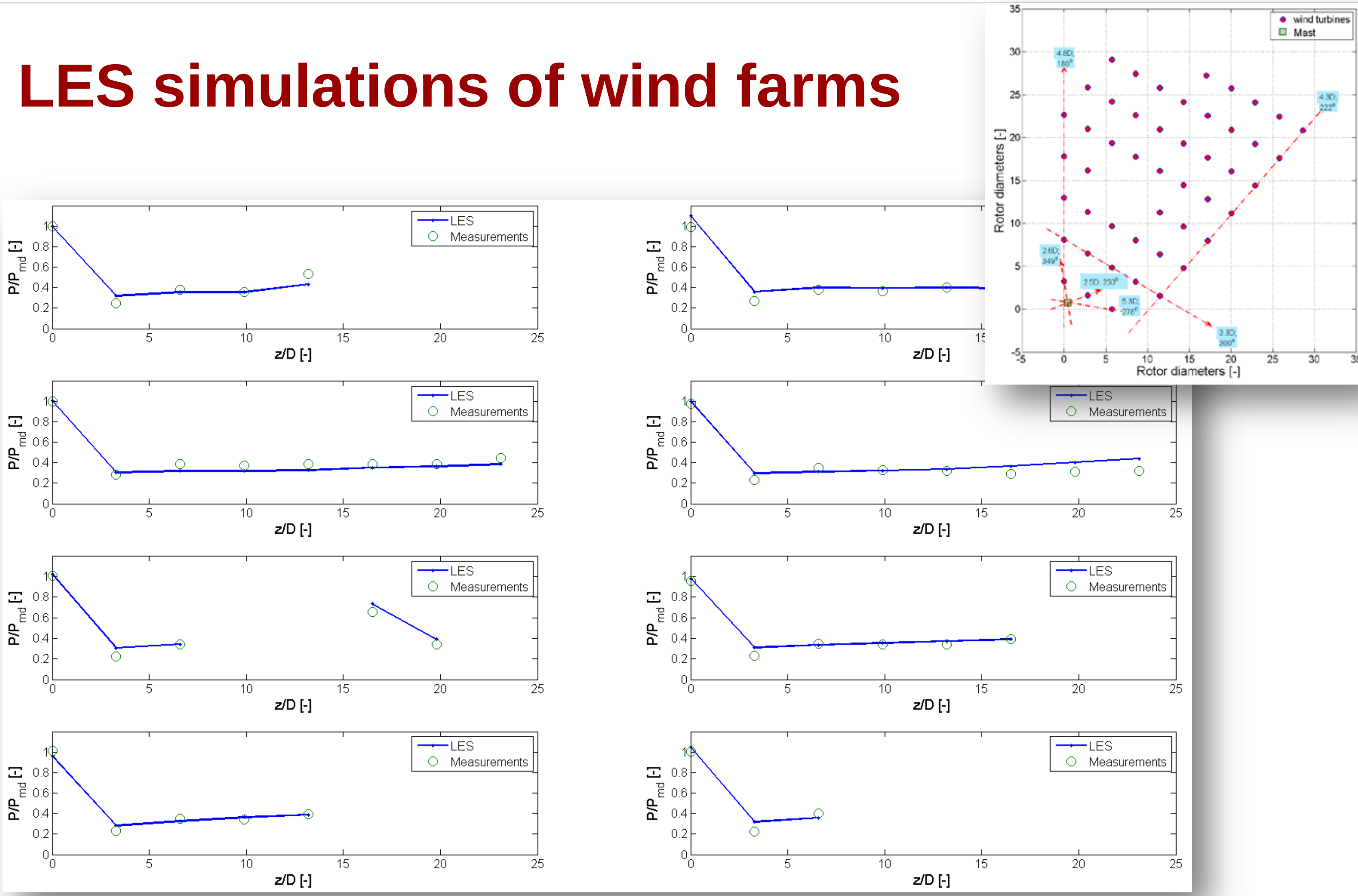


Wind speed ratio in the cross-wind direction at down-stream positions of 2.5D, 4.0D and 7.5D



Comparisons of turbulence intensity in the cross-wind direction at down-stream positions of 2.5D, 4.0D and 7.5D

LES simulations of wind farms



Comparison between computations and experiments of the Lillgrund wind farm