



Wake development of wind turbines in off-shore neutral ABL

Dr Shanying Zhang

Dr Philip Hancock

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University of Surrey



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 - Atmospheric boundary layer
 - Wake flow development
- Instrumentation
 - EnFlo Wind tunnel
 - Wind turbine models
 - Measurement methods
- Development of wake flow
- Summary



Introduction

- Offshore boundary layer
 - From wave to 1km
 - From 50km off the land
 - Neutral, stable and unstable stratified ABL
- Characteristics
 - High wind speed
 - Low turbulence
 - Wake development and interactions



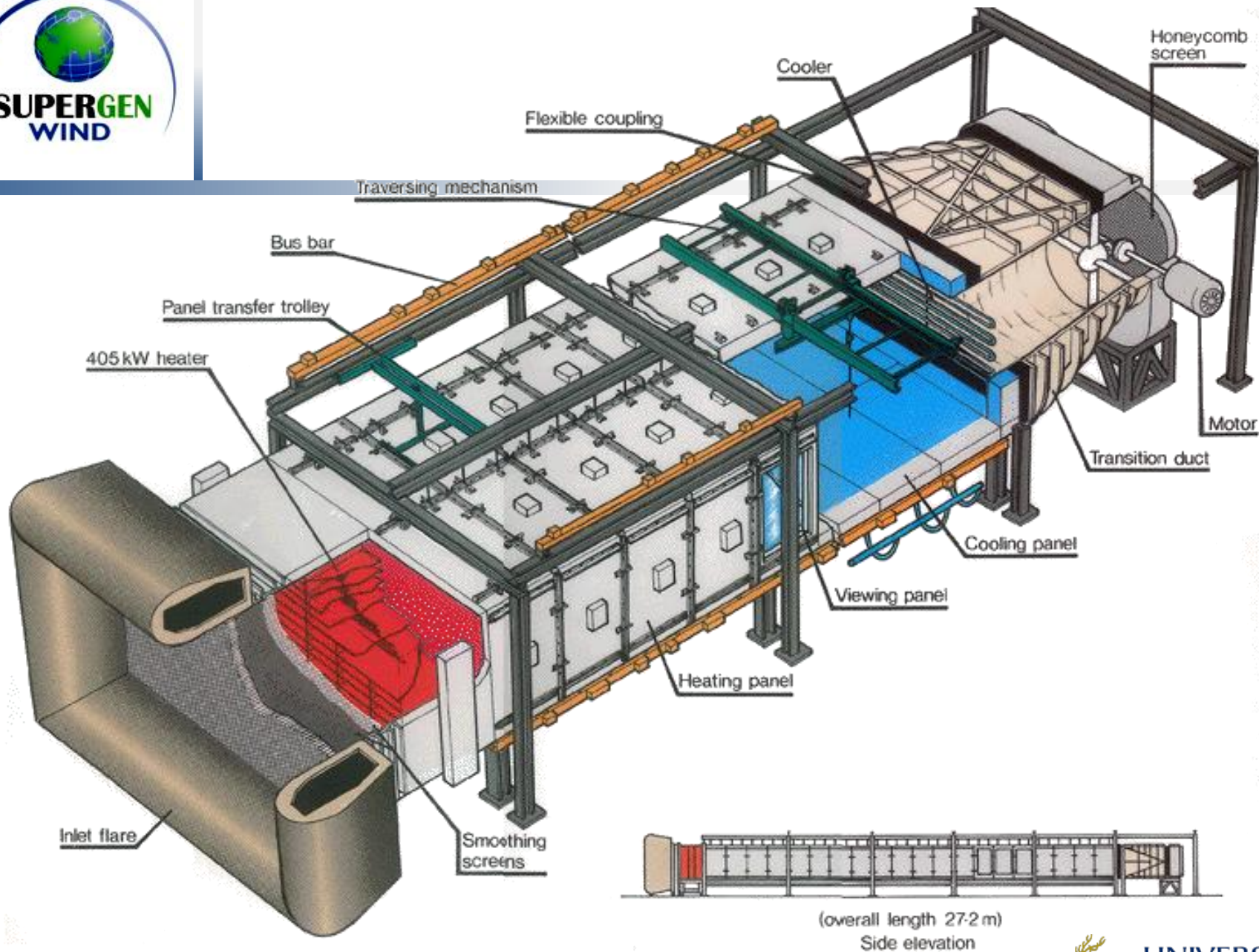
Wind tunnel simulation

- Onsite experiments are expensive and flow conditions are complex
- Computational simulation
 - Top down simulation
 - Bottom up simulation
- Wind tunnel simulation
 - Specific flow conditions



Experimental arrangement

- EnFlo metreology wind tunnel
- Wind turbine models
- Measurement techniques
 - Two-component laser Doppler anemometry (LDA)
 - Force moment balance
 - Thermal methods



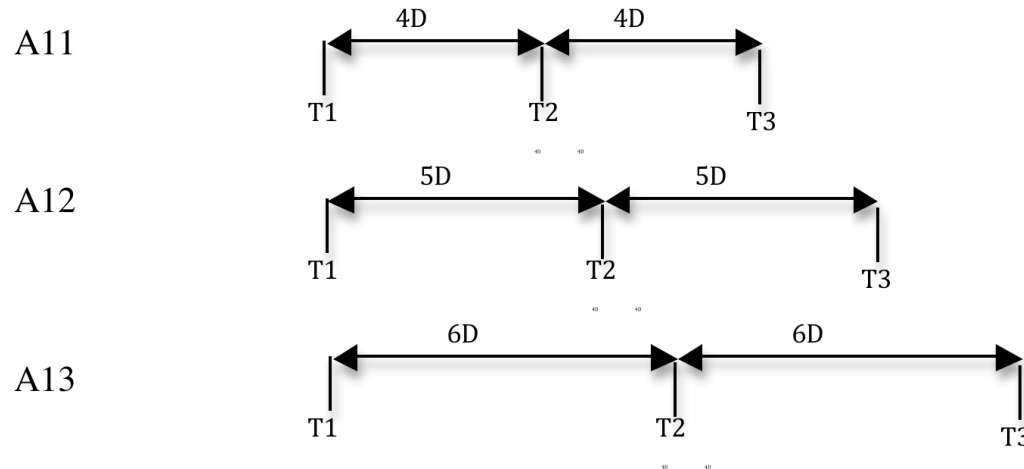
Wind turbine models

- 300:1 scale-down models
 - Hub height 300mm
 - Blade radius 208mm
- Thin blade theory
 - Blade 1 (constant taper)
 - Blade 2 (constant circulation)
- Micro motor with a gear box



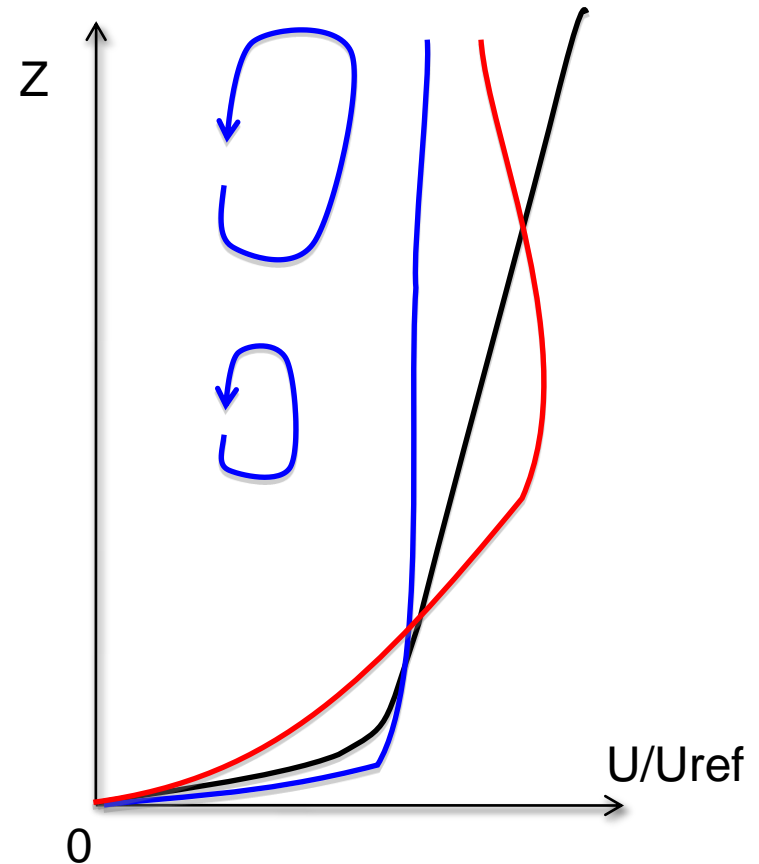
Laser Doppler anemometry

- Two-component LDA
- Typical data rate 200 Hz
- Typical time for each point : 3 minutes
- Statistic parameters were produced



Atmospheric boundary layer

- Neutral ABL
 - Strong wind
- Stable ABL
 - Code night
- Unstable ABL
 - Hot surface



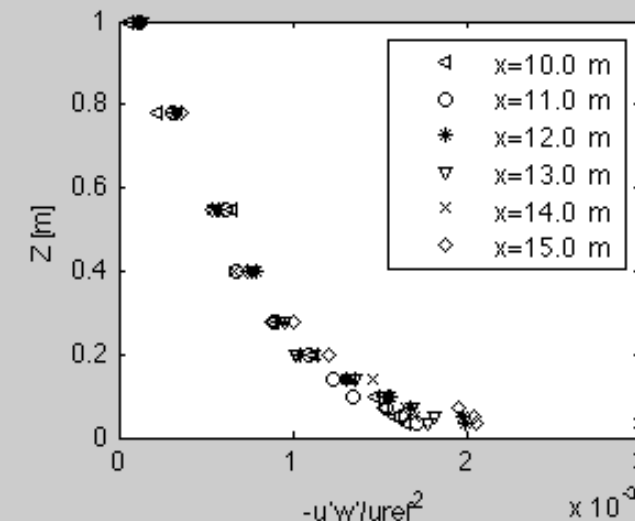
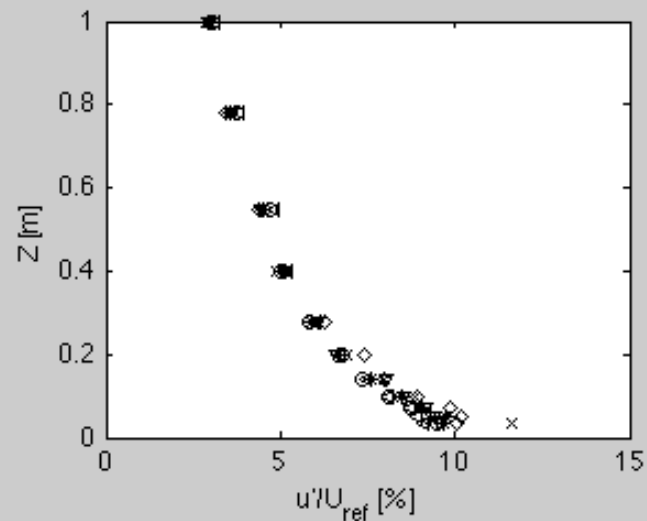
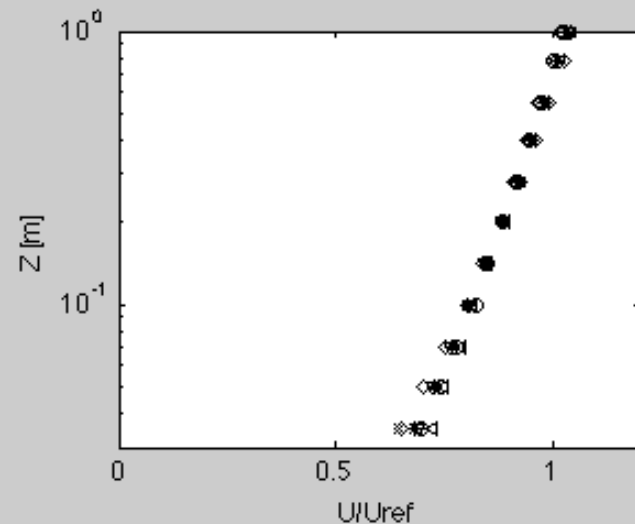
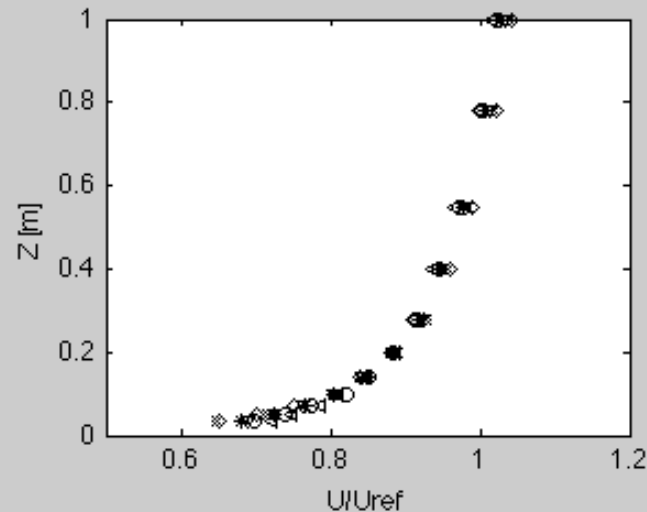
Neutral ABL

- Log law

$$\bar{U}(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right)$$

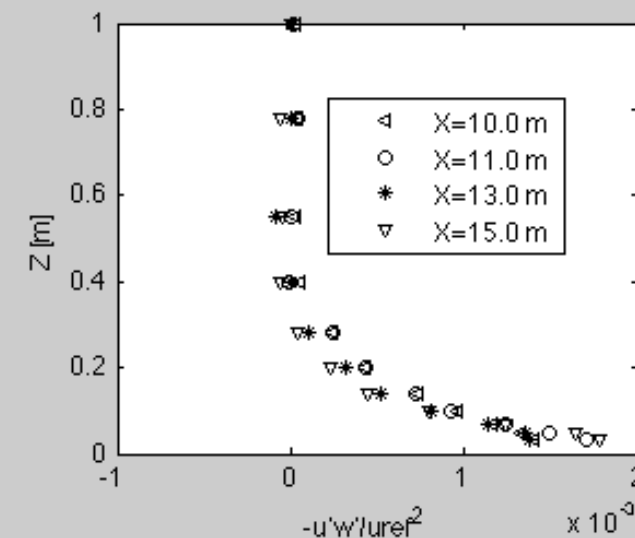
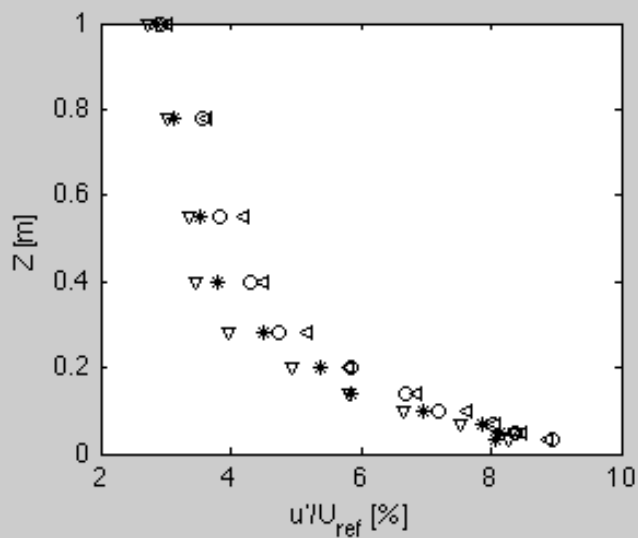
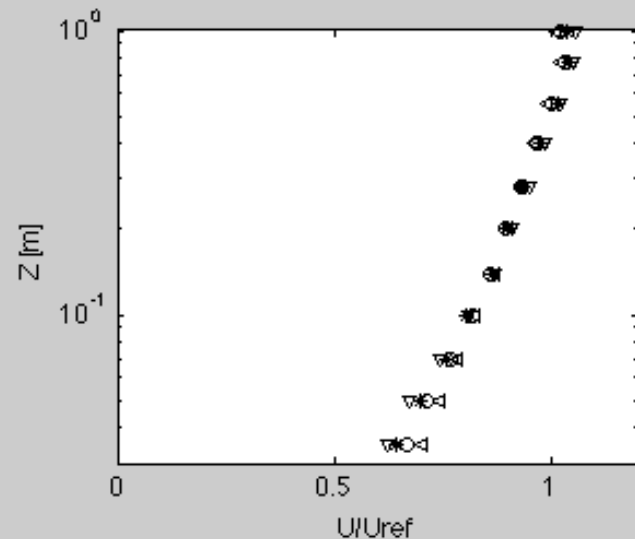
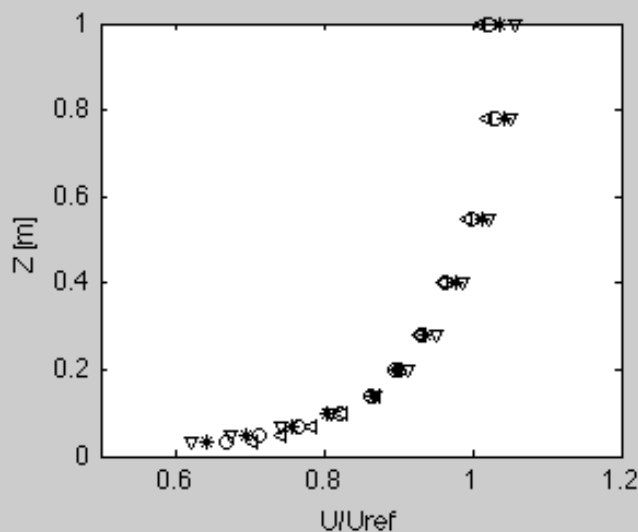
- Power fit

$$\bar{U}(z) = U_{ref} \times \left(\frac{z}{z_{ref}}\right)^\alpha$$



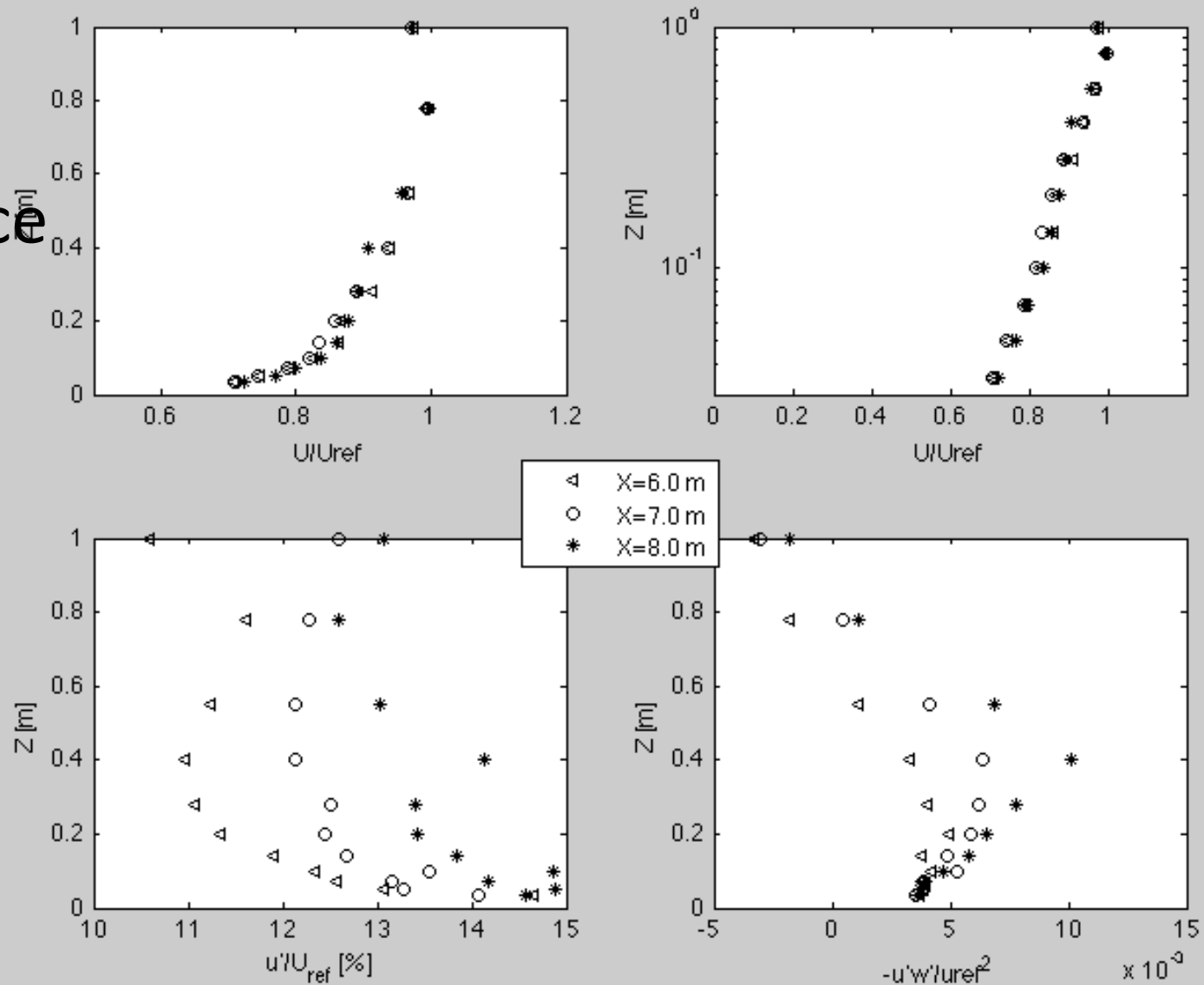
Stable stratified ABL

high shear
low turbulence

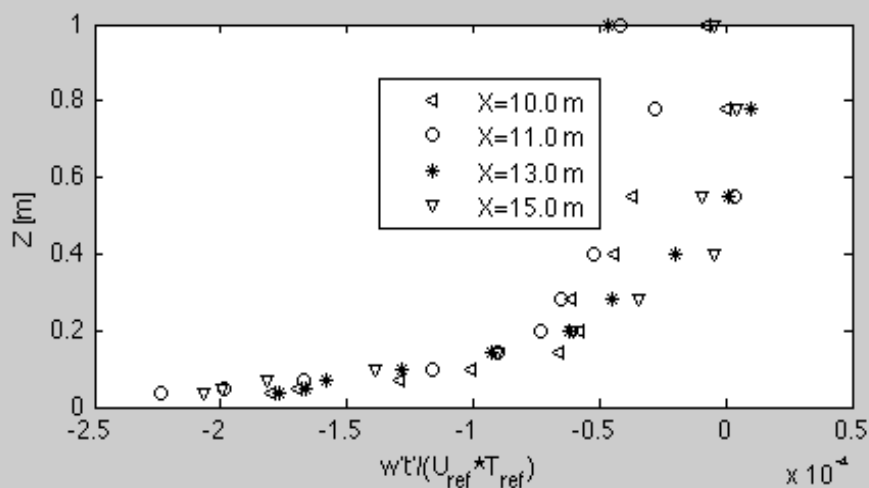
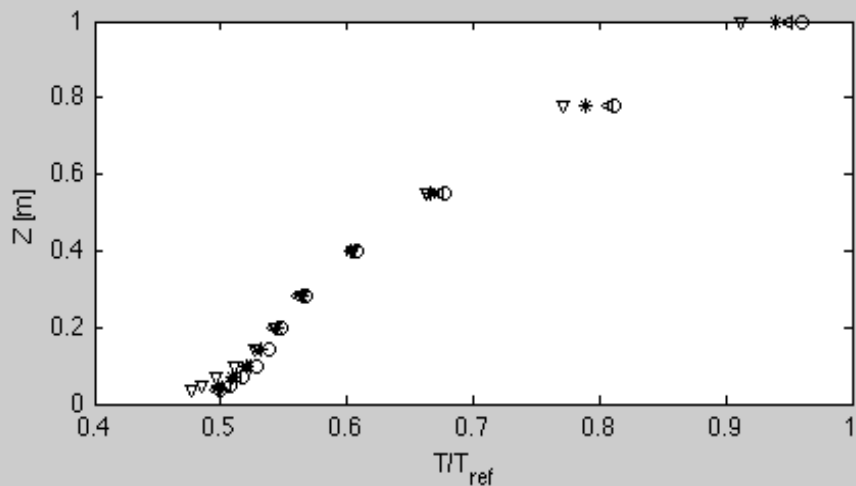


Unstable stratified ABL

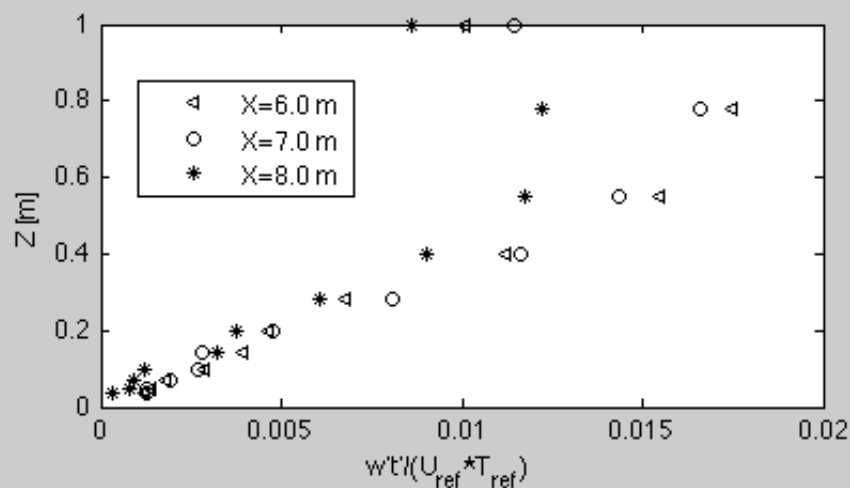
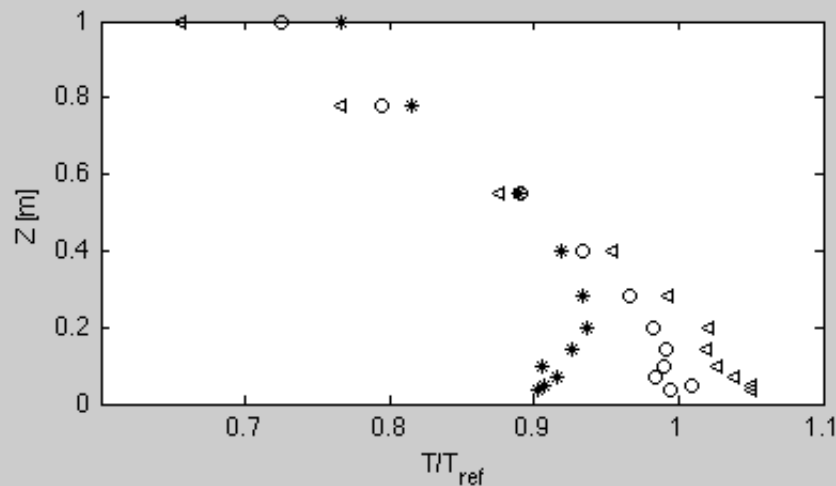
Low shear
High turbulence



Temperature and heat flux



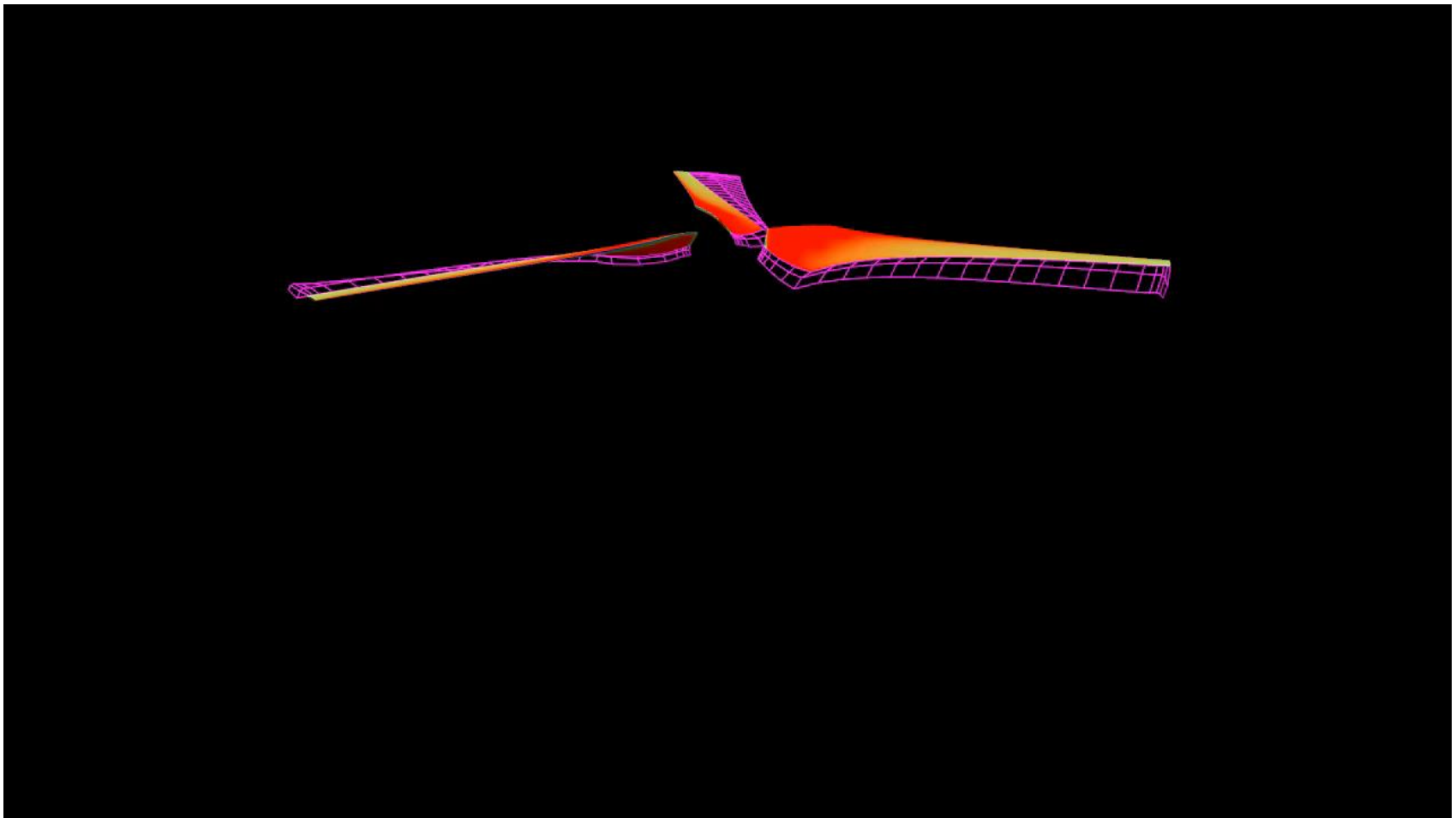
Stable ABL



Unstable ABL 



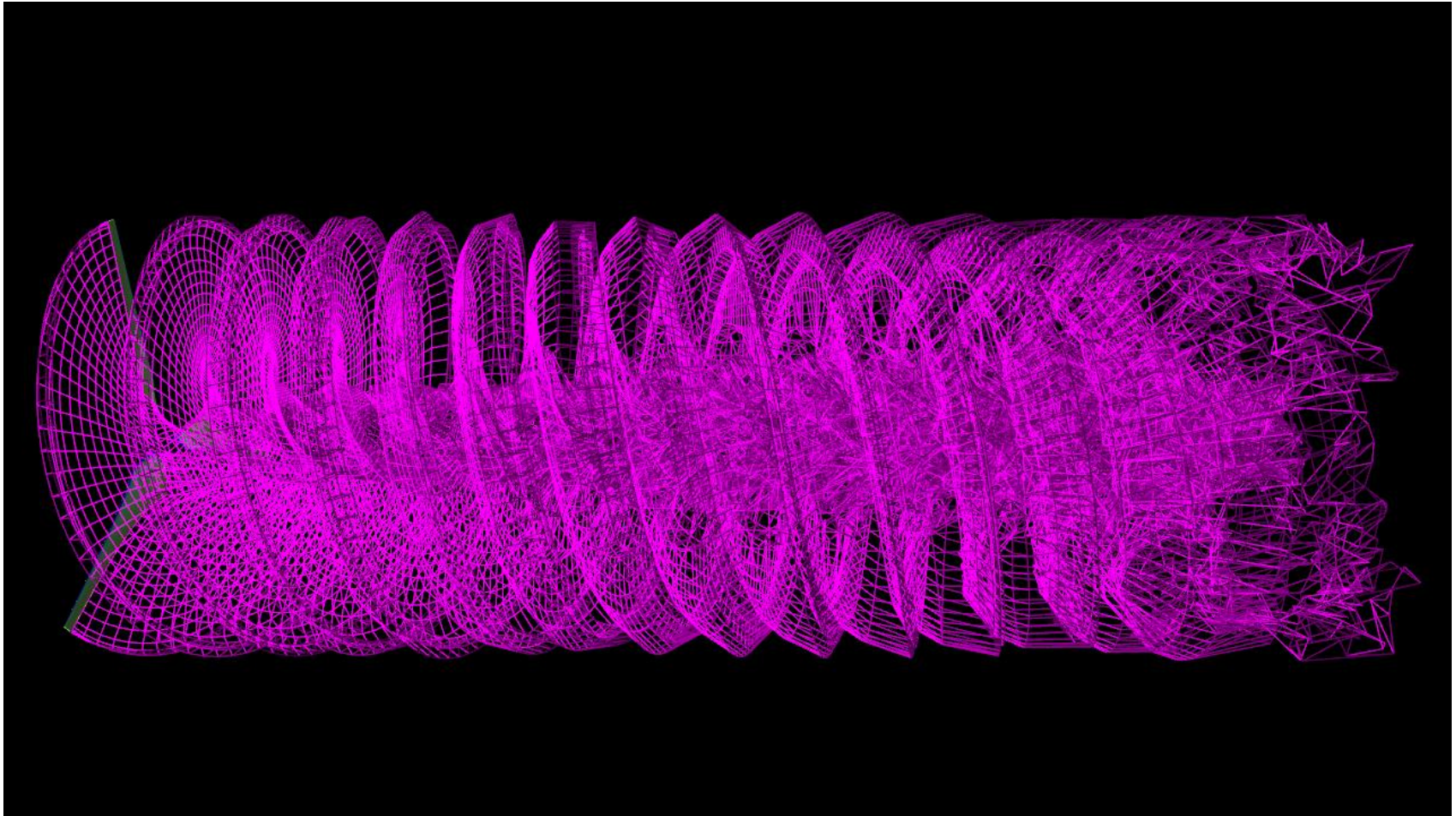
Video of wake development



(Produced by Paul Nathan at Surrey University)



Vortex Lattice Method

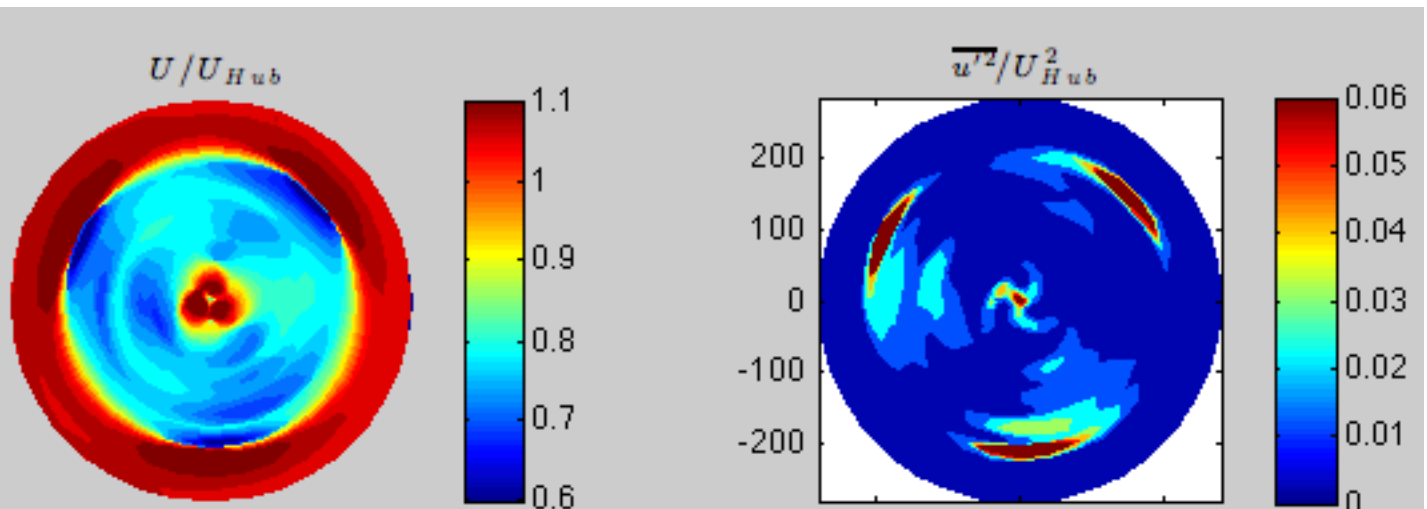


(Produced by Paul Nathan at Surrey University)

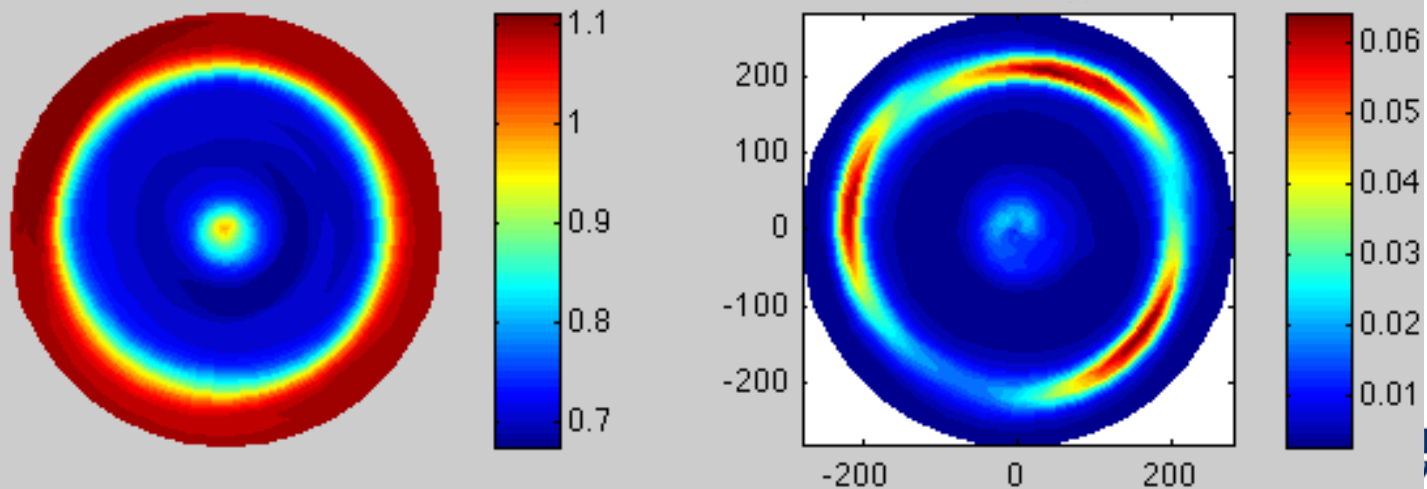
Uniformed upstream flow

(Phase-locked HW data)

$x/D=0.2$



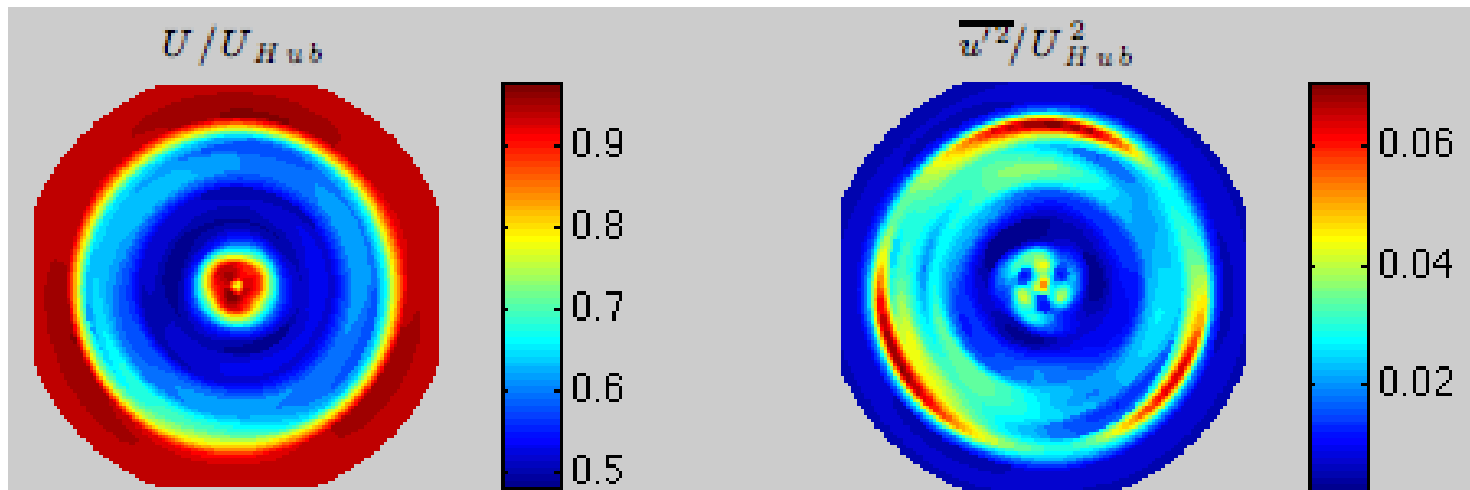
$x/D=1$



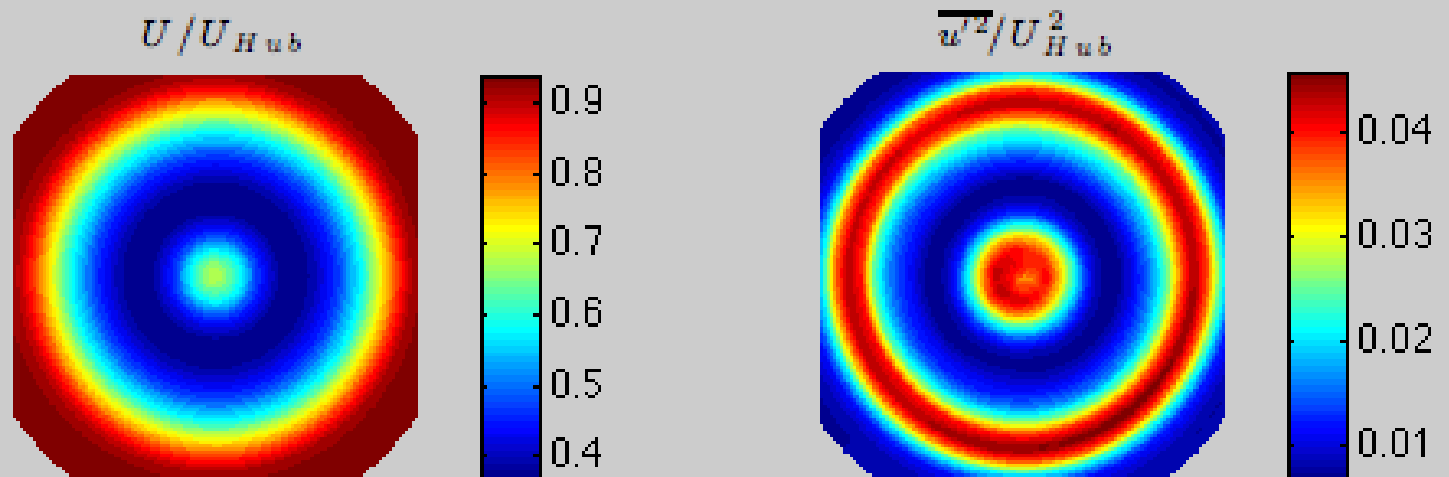
Neutral stratified ABL

(Phase-locked HW data)

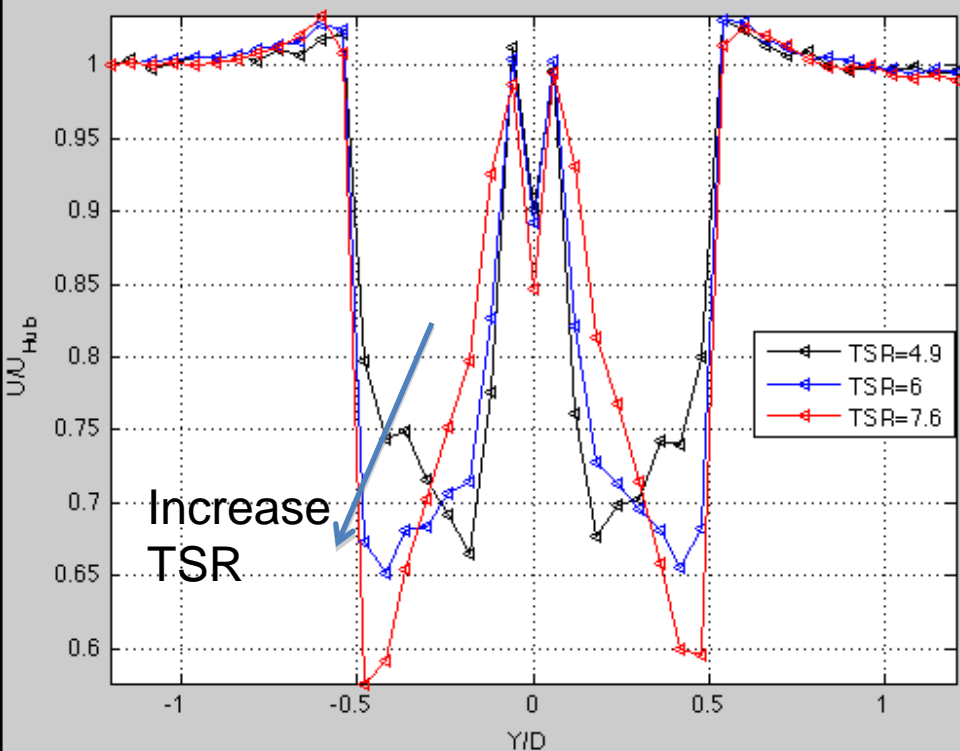
$x/D=0.2$



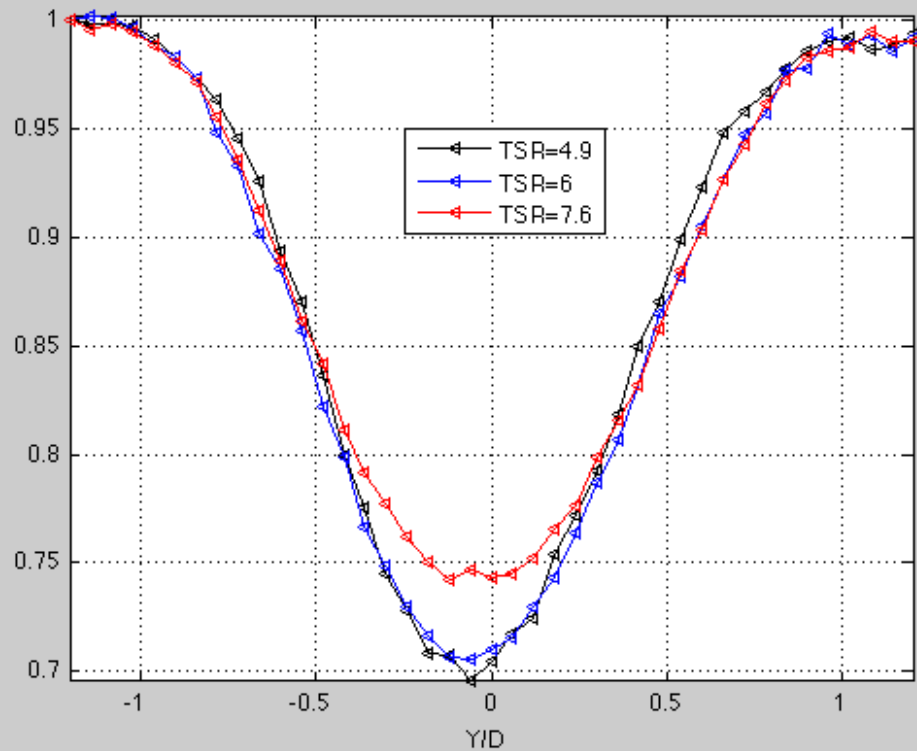
$x/D=1$



Effect of tip speed ratio



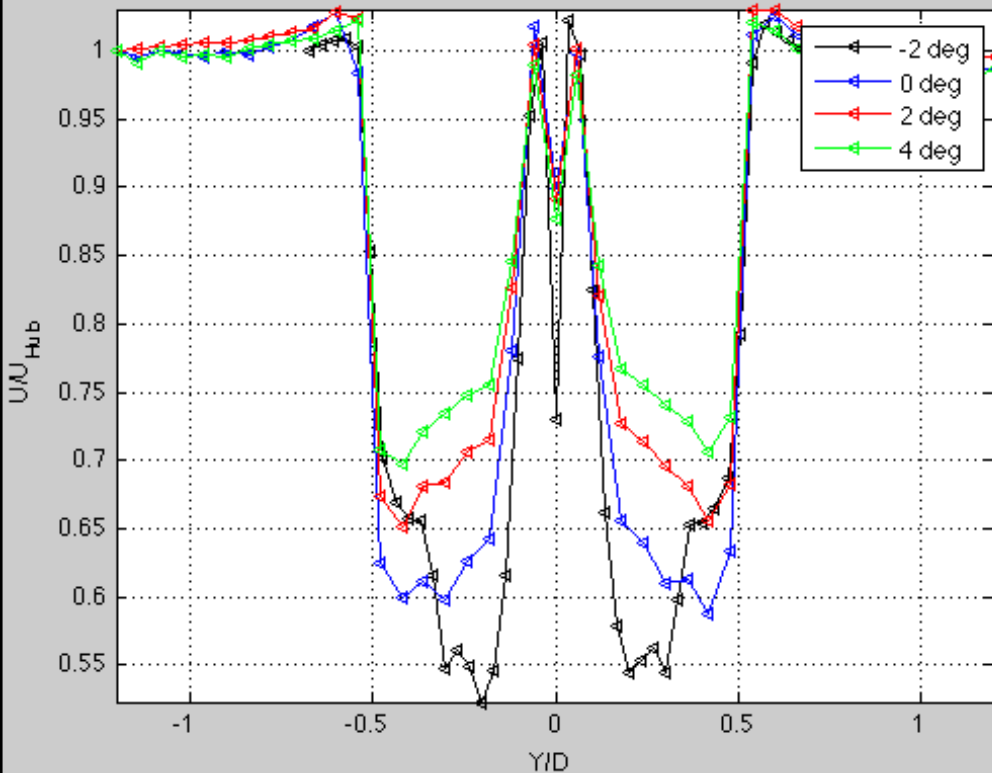
$x/D=0.2$



Pitch angle
2 deg at the tip

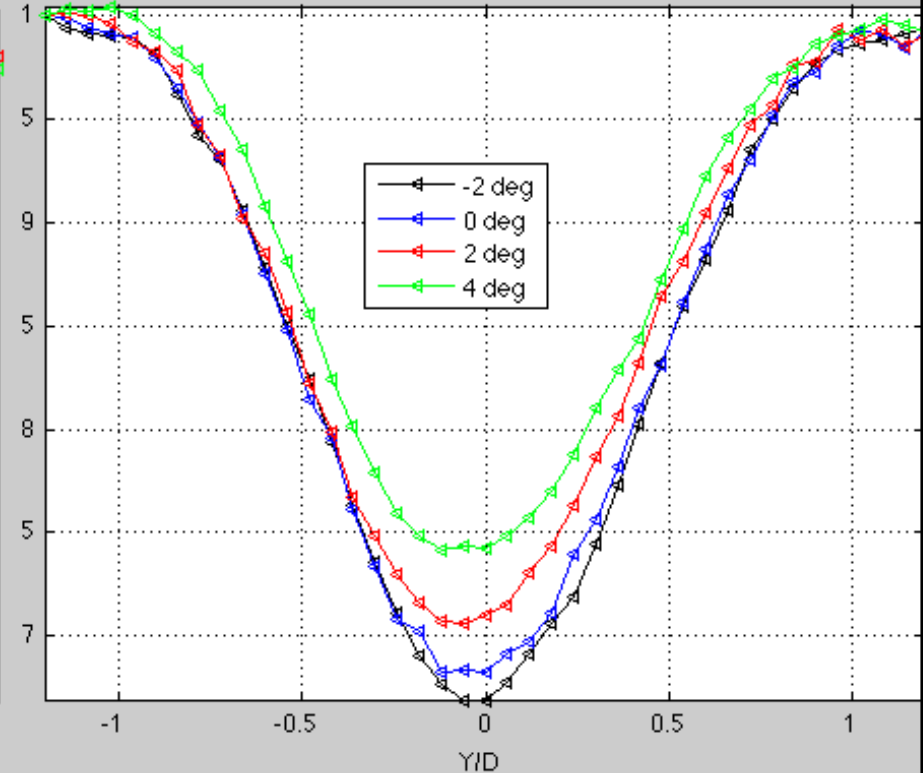
$x/D=6$

Effect of different pitch angle



$x/D=0.2$

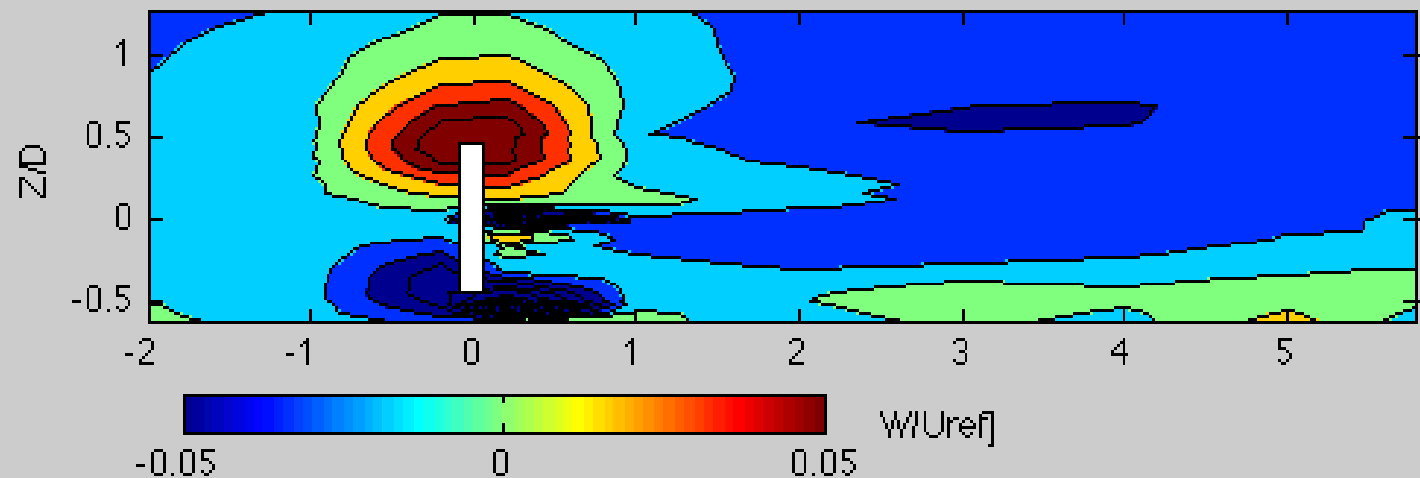
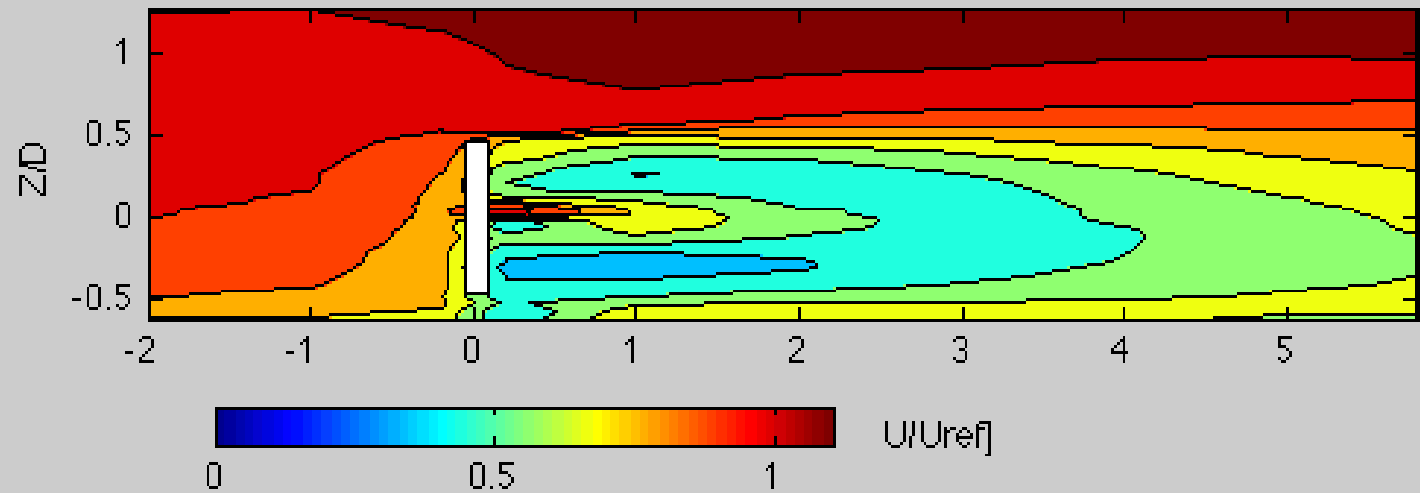
TSR = 6.2



$x/D=6$

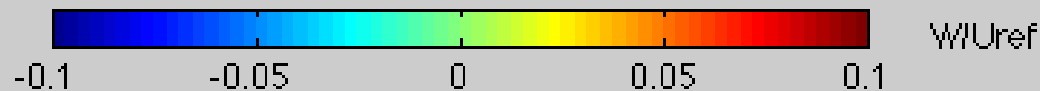
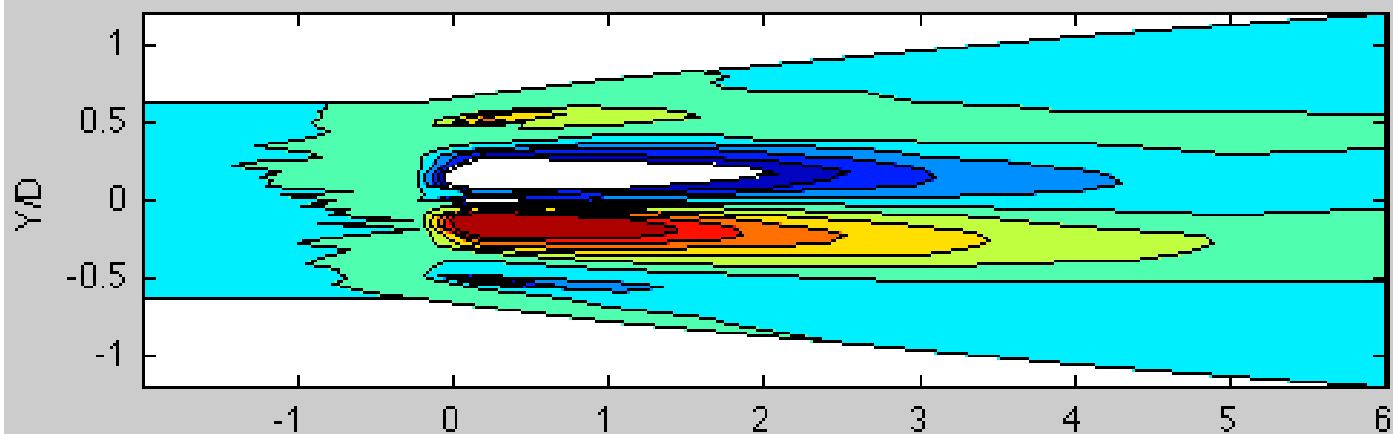
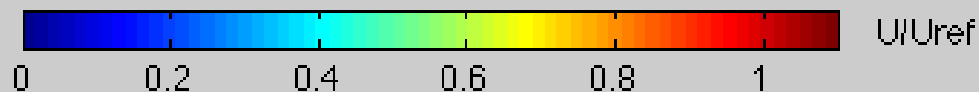
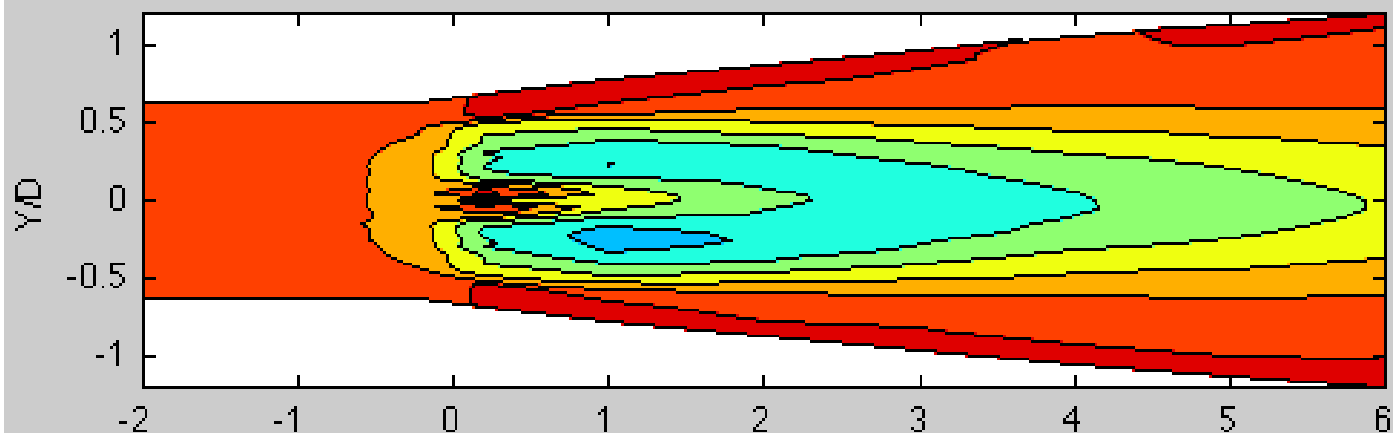
Single Wind turbine

- Vertical plane

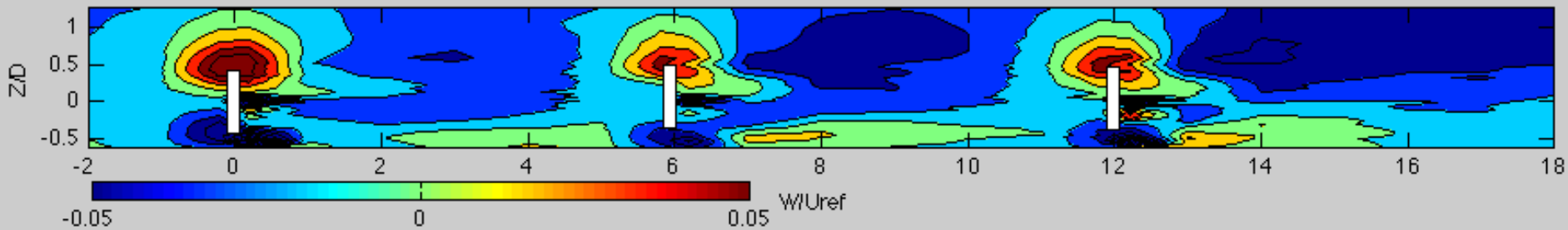
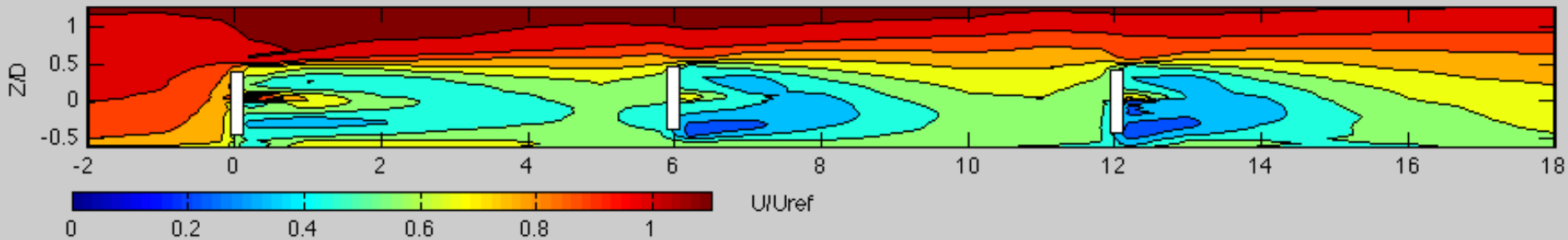


Single wind turbine

Horizontal
plane

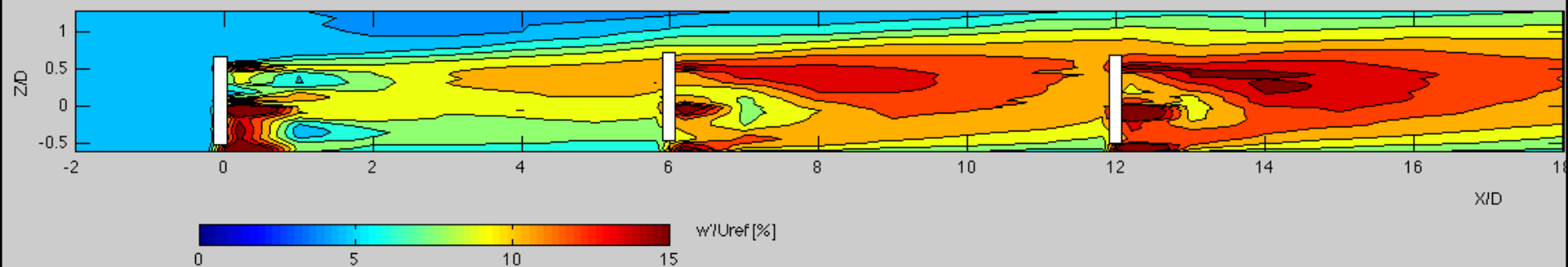
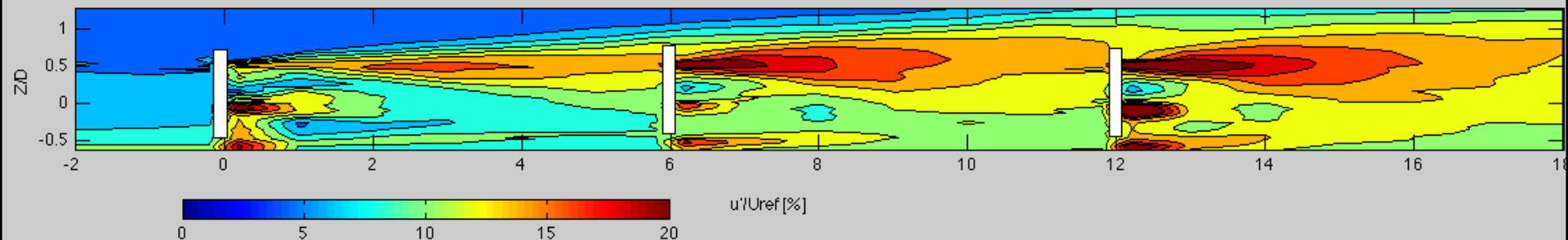
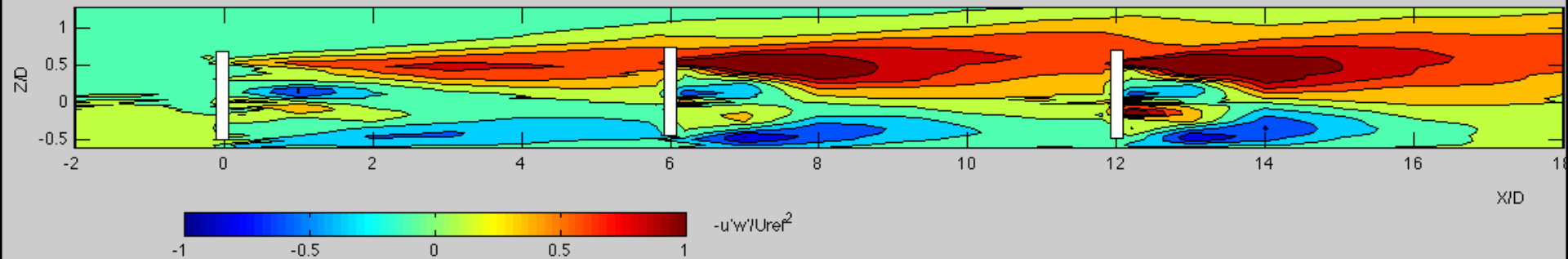


Wind turbine array A13

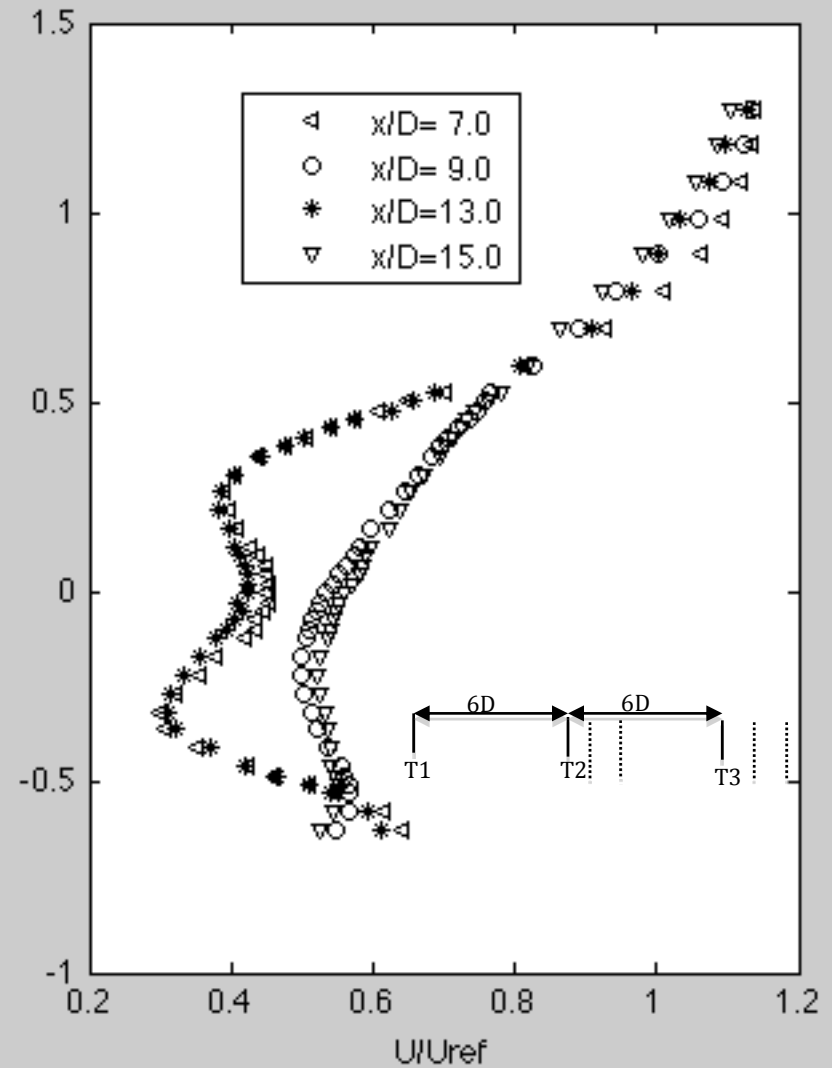
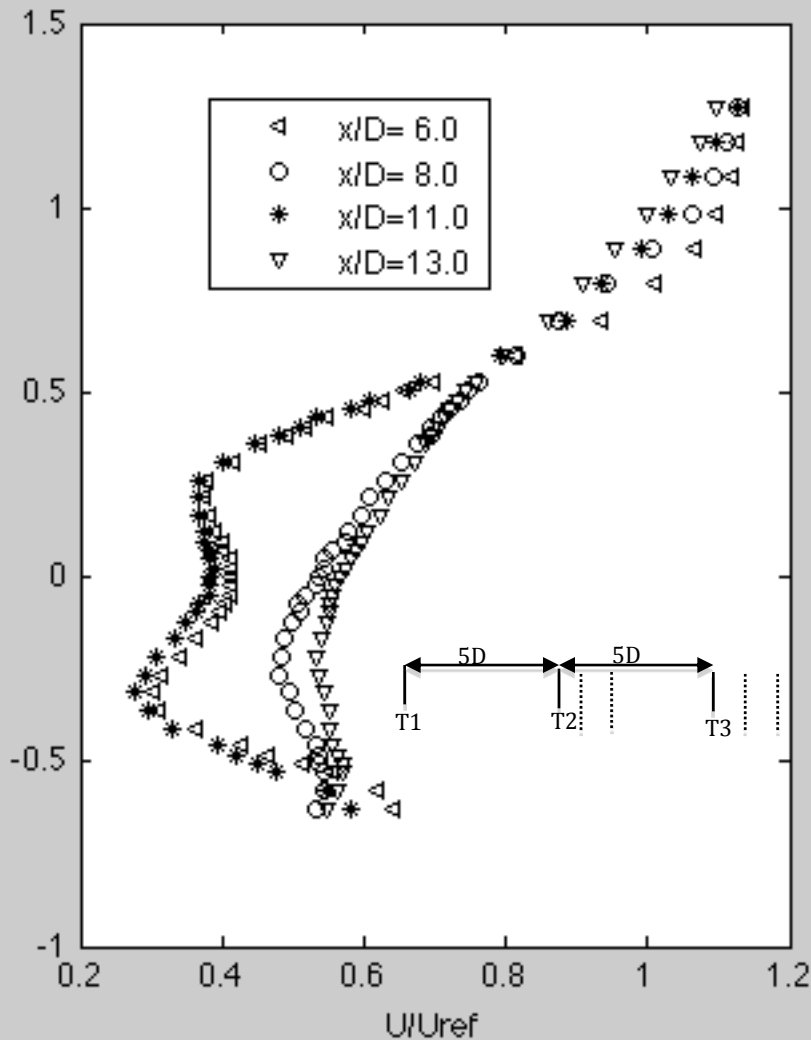


- Spacing $6D$
- TSR=6.8; pitch angle -2 deg

Wind turbine array A13



Similarity of Vertical profiles





Thank You!

Any questions?