Performance and wake development of vertical axis wind turbines: a LES study using a vortex particle-mesh method

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Introduction

- **Renewed interest in Vertical Axis Wind Turbine (VAWT)**, in particular for large scale off-shore applications and small turbines
  - insensitive to wind direction -> no yaw mechanisms
  - simplified and more accessible drive train
  - but, longer blades and, possibly, supporting arms

- **Less mature aerodynamic prediction tools** than for the established Horizontal Axis Wind Turbine (HAWT) configuration

- Wind turbine aerodynamics : **large multiscale problem**
  - from the blade boundary layers to the wake/wind farm scale

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Quiet Revolution QR5


Fairwind F64

Motivation and outline

Motivation

- VAWT : inherently unsteady aerodynamics and poorly known wake physics

➡ Use of an efficient Vortex Particle-Mesh (VPM) method to study the large scale VAWT aerodynamics in various configurations

Outline

- Methodology
  - The Vortex-Particle Mesh (VPM) method
  - Dynamic stall modeling
  - Comparison with experimental measurements
- Simulation of a straight-bladed VAWT
  - Investigation of the Dynamic Stall effects
  - Wake physics
- Comparison between straight-blade and swept-blade VAWTs
  - Impact of the rotor dynamics
- Conclusions

Long time - large scale simulations of wake flows

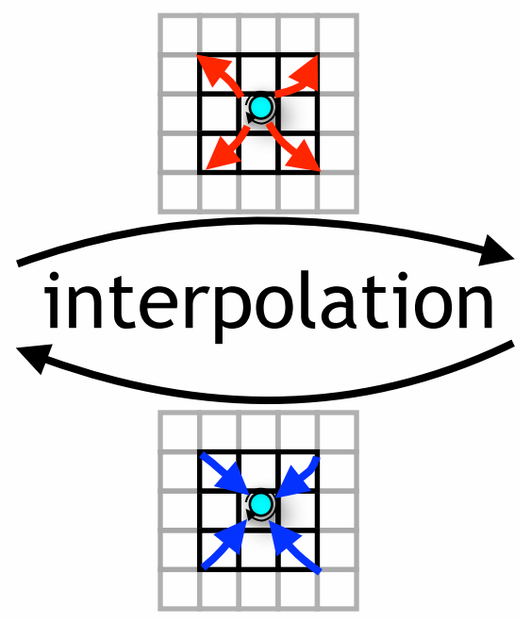
Vortex …

$$\boldsymbol{\omega} = \nabla \times \mathbf{u} \qquad \frac{D\boldsymbol{\omega}}{Dt} = (\boldsymbol{\omega} \cdot \nabla)\mathbf{u} + \nu \nabla^2 \boldsymbol{\omega}$$

… Particle-Mesh method

Advection

$$\mathbf{x}_p \quad \boldsymbol{\alpha}_p = \int_{V_p} \boldsymbol{\omega}\, dV \simeq \boldsymbol{\omega}_p V_p$$



Differential operators
Elliptic problems
Remeshing of particles

➡ Efficiency, low dispersion, low dissipation

\+ Need other ingredients

Long time - large scale simulations of wake flows

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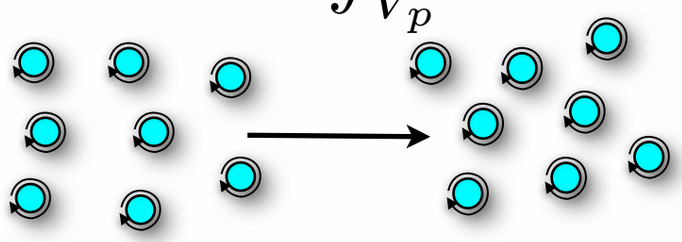

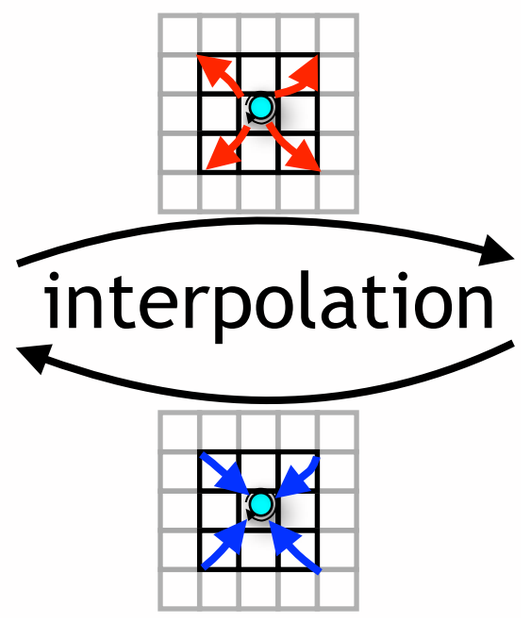

Differential operators
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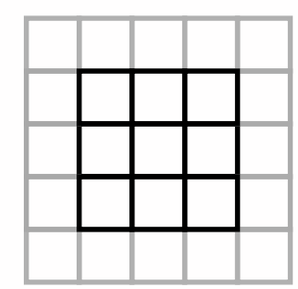

$\boldsymbol{\omega}_{ij}$
$\mathbf{u}_{ij}$
$\Delta\boldsymbol{\omega}_{ij}$

Winckelmans, Encycl. Comp. Mech. 2004

Koumoutsakos, ARFM 2005

➡ Efficiency, low dispersion, low dissipation

\+ Need other ingredients

Chatelain et al., Flow Turb. Comb. 2013

VPM solver

- Based on the PPM Library (http://www.ppm-library.org/) for particle and mesh handling

- Unbounded FFT Poisson solver based on the Hockney-Eastwood algorithm + Inflow/outflow boundary conditions in the streamwise direction

- Multiscale Subgrid-Scale model only applied on the small resolved scales (high-pass filtered $\boldsymbol{\omega}^s$)

$$\frac{\mathrm{D}\boldsymbol{\omega}}{\mathrm{D}t} = \nabla \cdot (\mathbf{u}\,\boldsymbol{\omega}) + \nu \nabla^2 \boldsymbol{\omega} + \boxed{\nabla \cdot \left(\nu^{\mathrm{sgs}} \left(\nabla \boldsymbol{\omega}^s + (\nabla \boldsymbol{\omega}^s)^T\right)\right)}$$

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Chatelain Koumoutsakos, J. Comp. Phys, 2010

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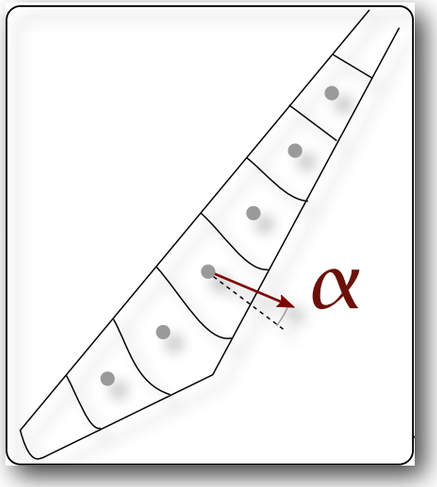
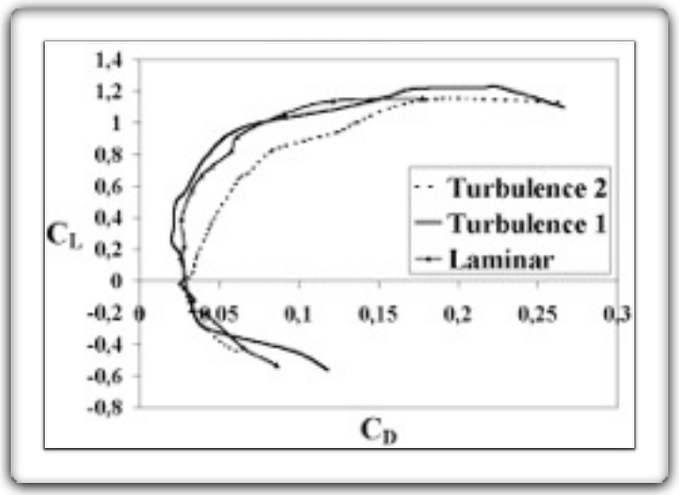
Cocle et al., J. Comp. Phys., 2008

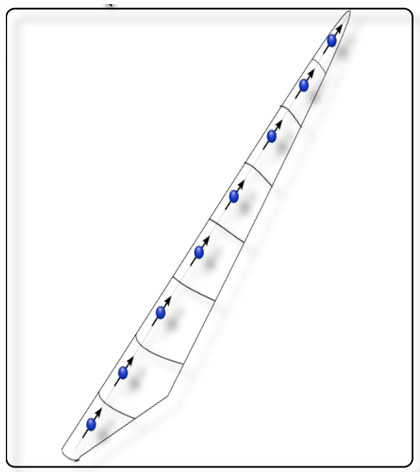
Cocle et al., Phys. Fluids, 2009

Jeanmart and Winckelmans, Phys. Fluids, 2007

Lifting lines, immersed in VPM







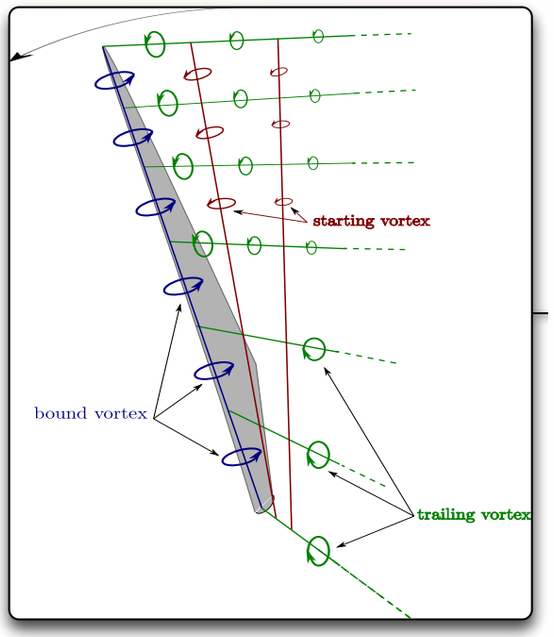
Flow relative to lifting line

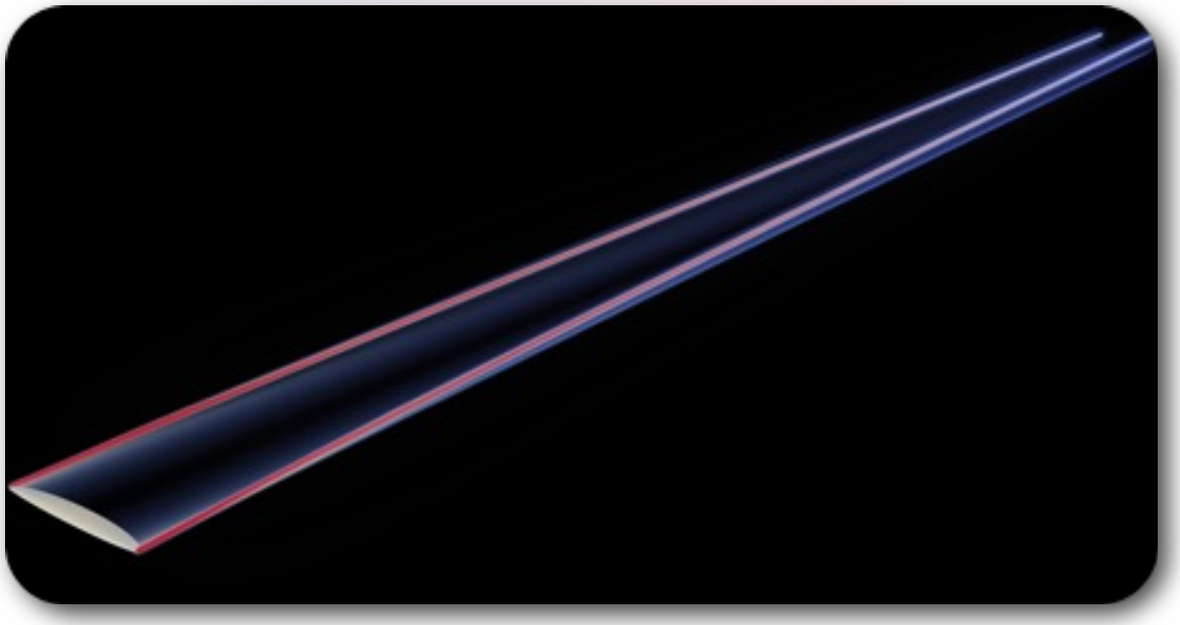
Line configuration (chord)

$\alpha \quad \boldsymbol{u}_{\mathrm{rel}}$ → Lift, Circulation → Bound vorticity

Shed vorticity

Added to bulk vorticity



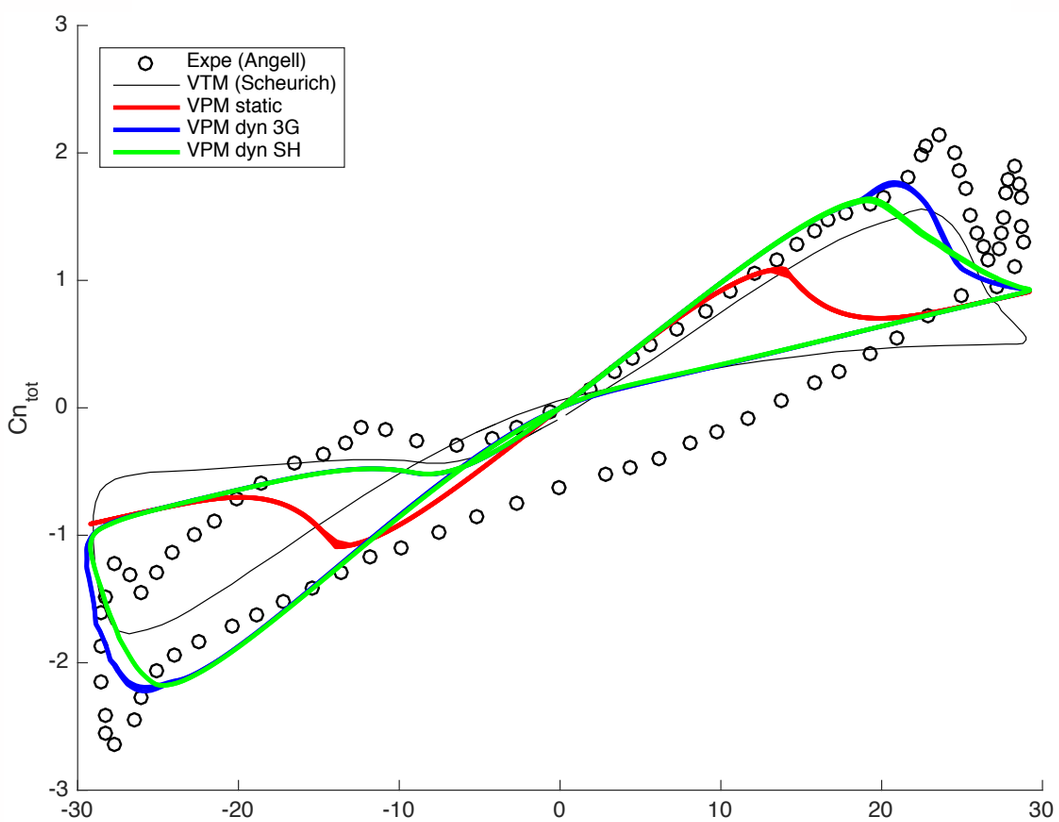


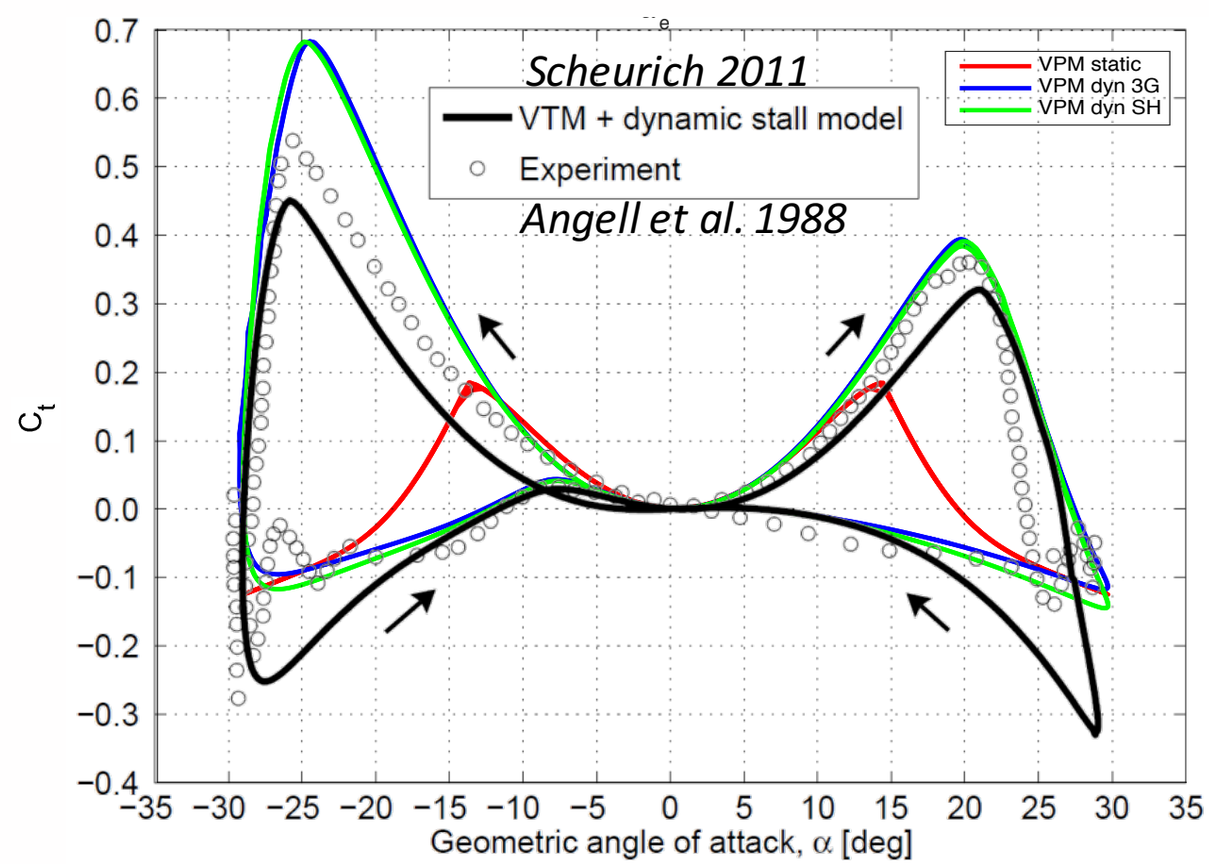
Dynamic Stall Modeling for VAWT

- Even in the optimum operation regime, VAWT blades experience
  - cyclic loading
  - high Angles-of-Attack

➡ Unsteady stall of the blades

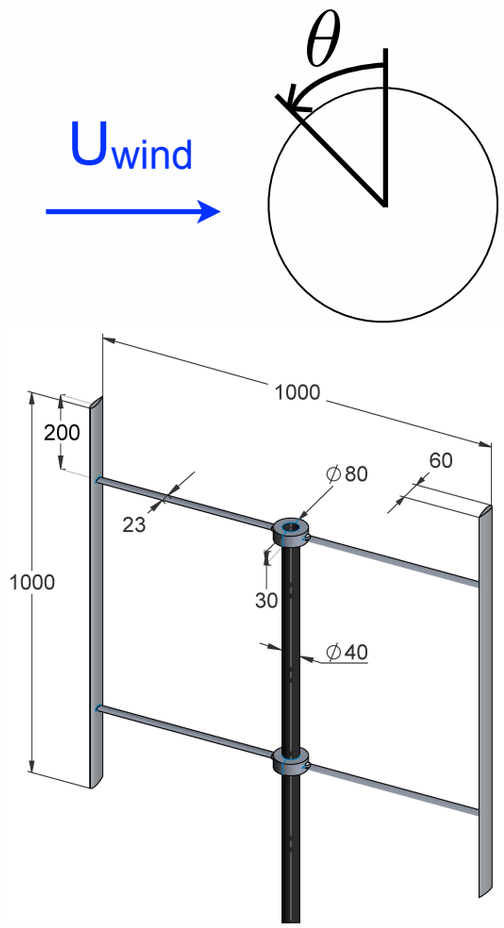
- Use of the Leishman-Beddoes dynamic stall model (1993)





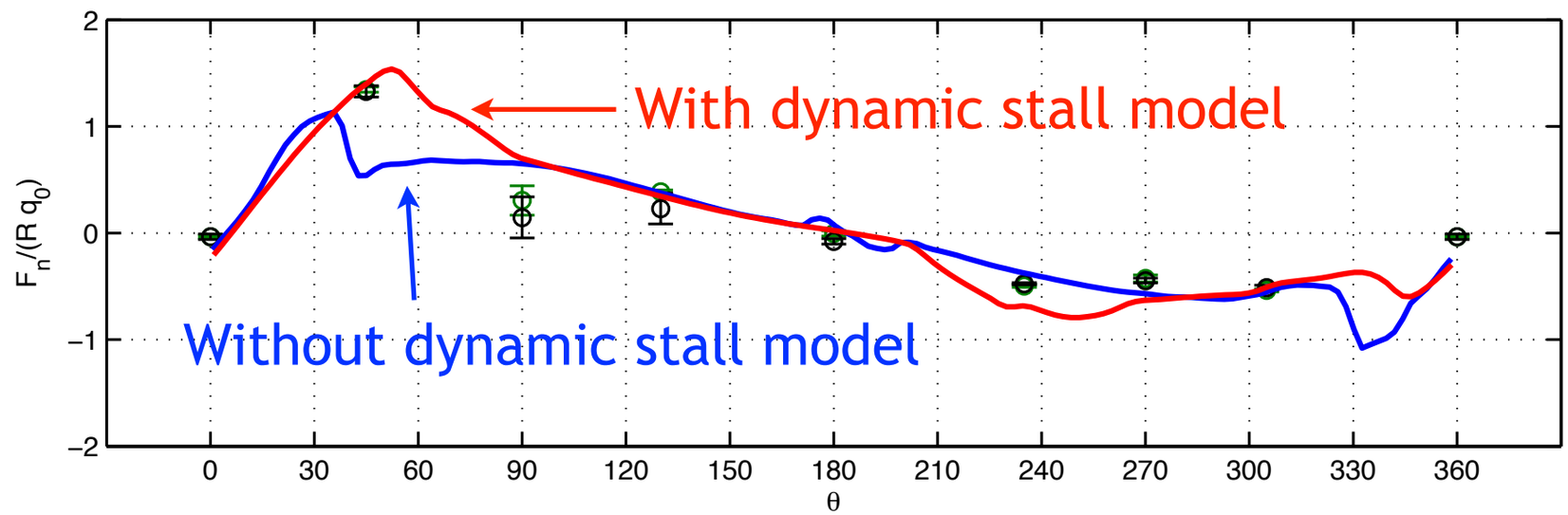
Comparison with small scale experiment

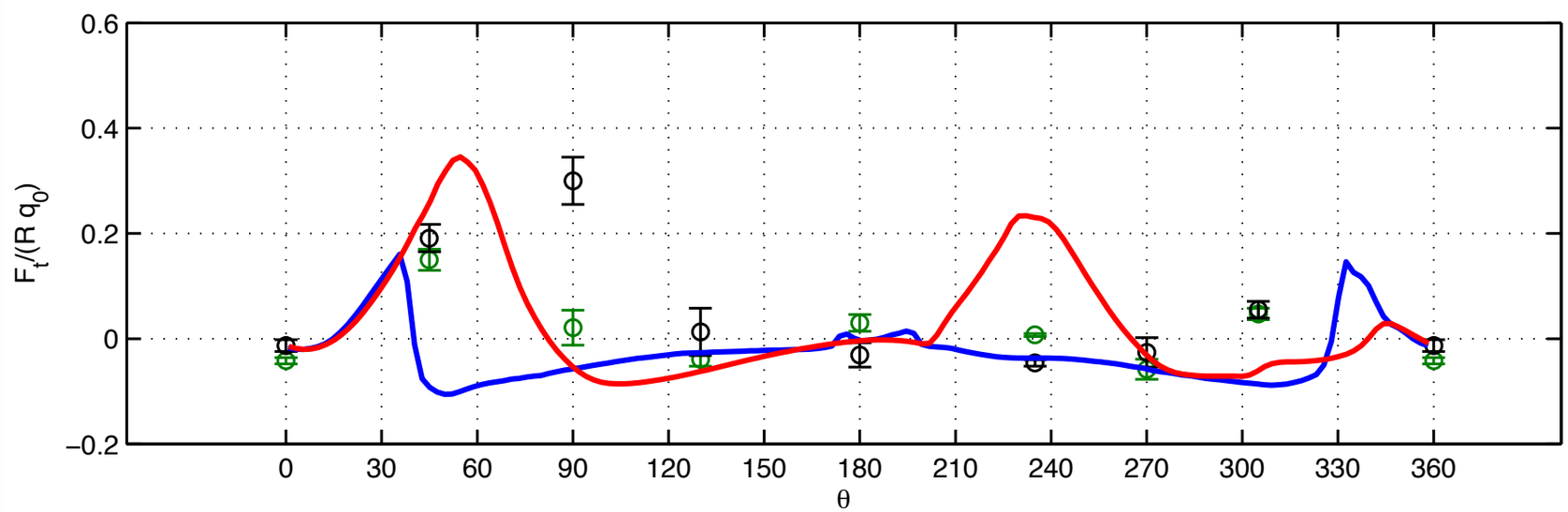
- Simulation of the 2-bladed VAWT in wind tunnel experiments using PIV post-processing by Castelein (2015)



From Castelein (2015)

tip speed ratio = 2.0

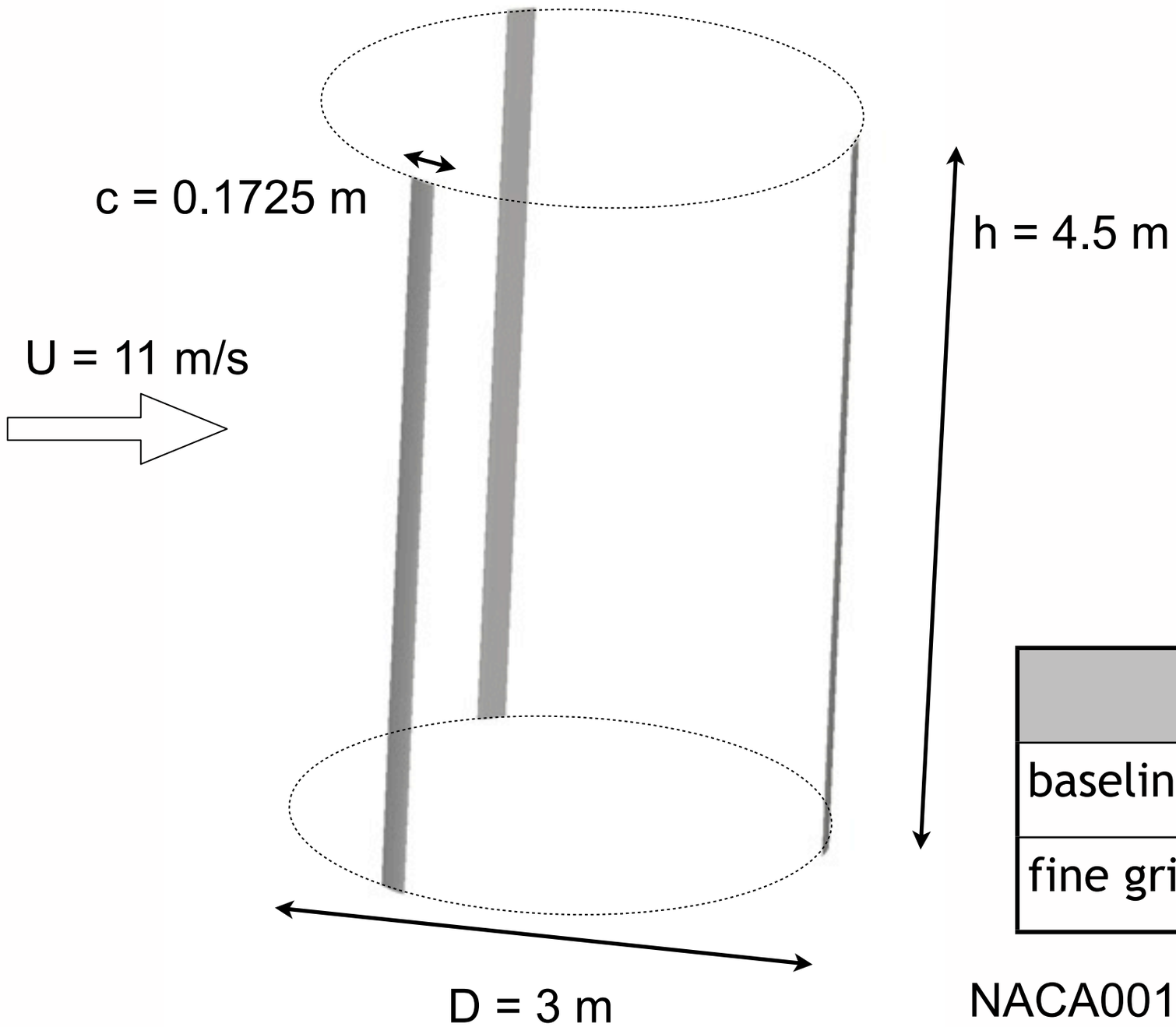




Satisfactory agreement given the limitations/ uncertainties of the experiment and of the model

H-type VAWT configuration

- 3 straight-bladed VAWT in a uniform stream



$$AR = \frac{h}{D} = 1.5$$

$$\sigma = \frac{nc}{D} = 0.1725$$

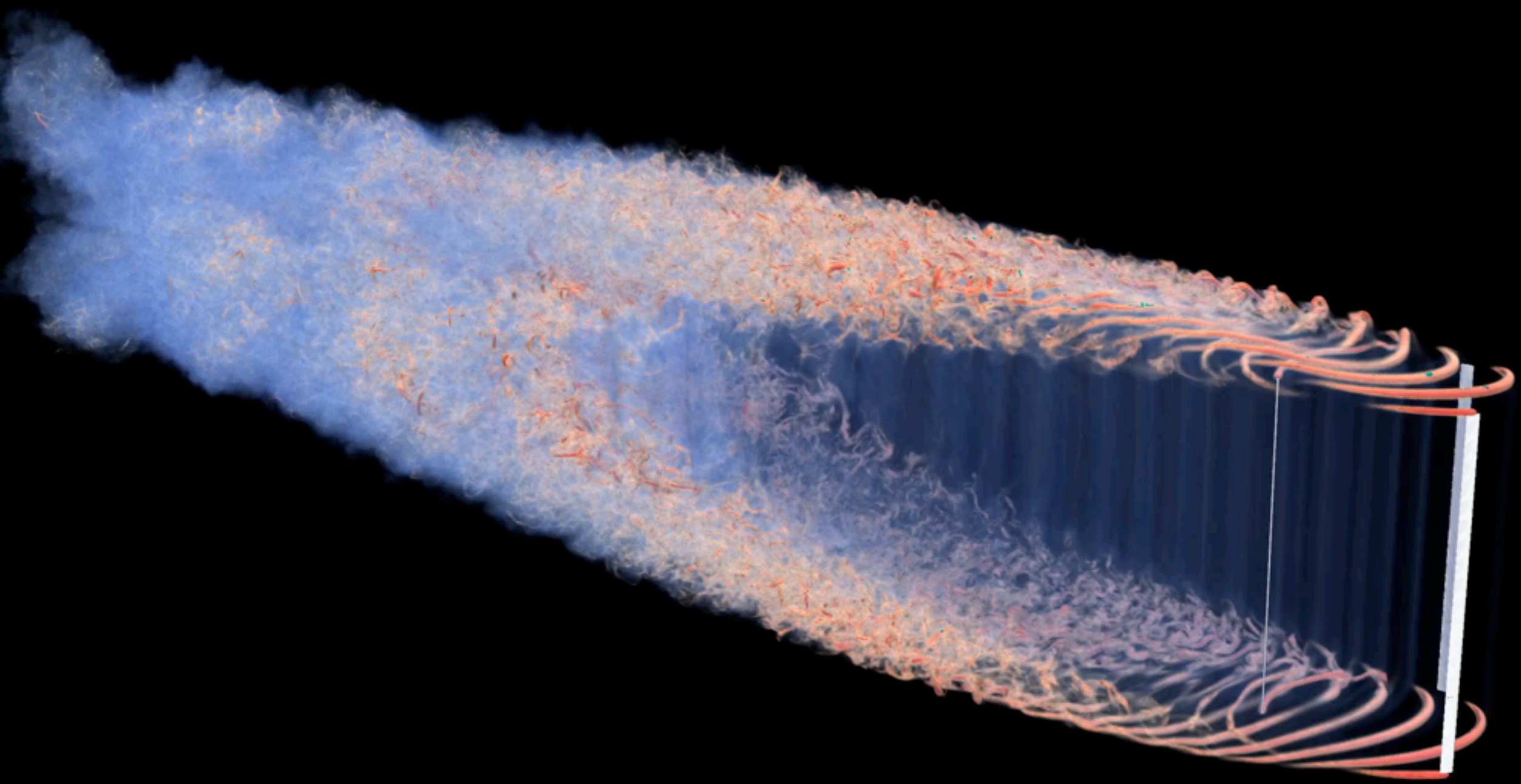
$$\lambda = \frac{\omega R}{U} = 2.5 - 5.0$$

$$Re = \frac{\lambda U c}{\nu} = 3.2 - 6.3 \times 10^5$$

	$D/\Delta x$	L_{domain}/D	N_{grid}
baseline	48	14	19M
fine grid	96	20	237M

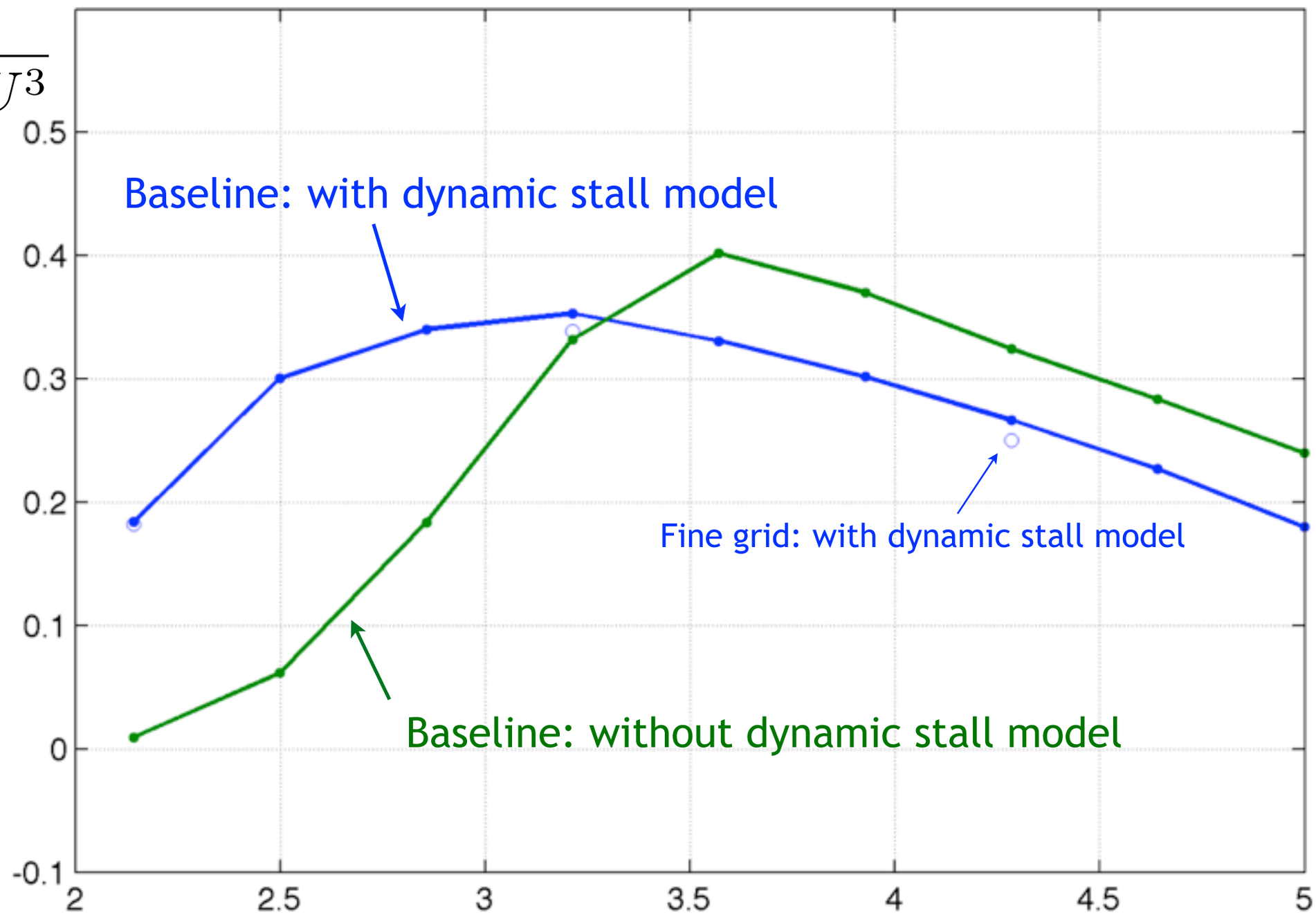
NACA0015 airfoil : experimental polars by Sheldahl & Klimas (1981) or Leishman-Beddoes Dynamic Stall model

3D Visualization of the wake using vorticity magnitude



Effect of the dynamic stall on the power curve

$$C_P = \frac{P}{\frac{1}{2}\rho A U^3}$$

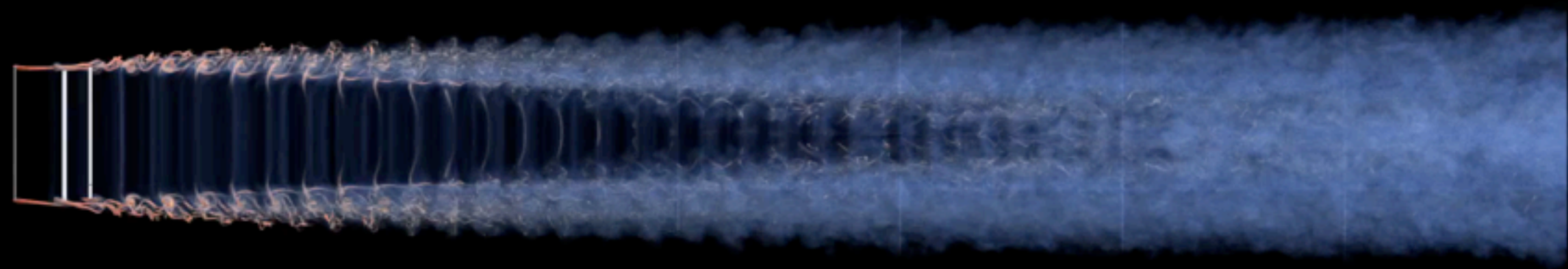


$$\lambda = \frac{\omega R}{U}$$

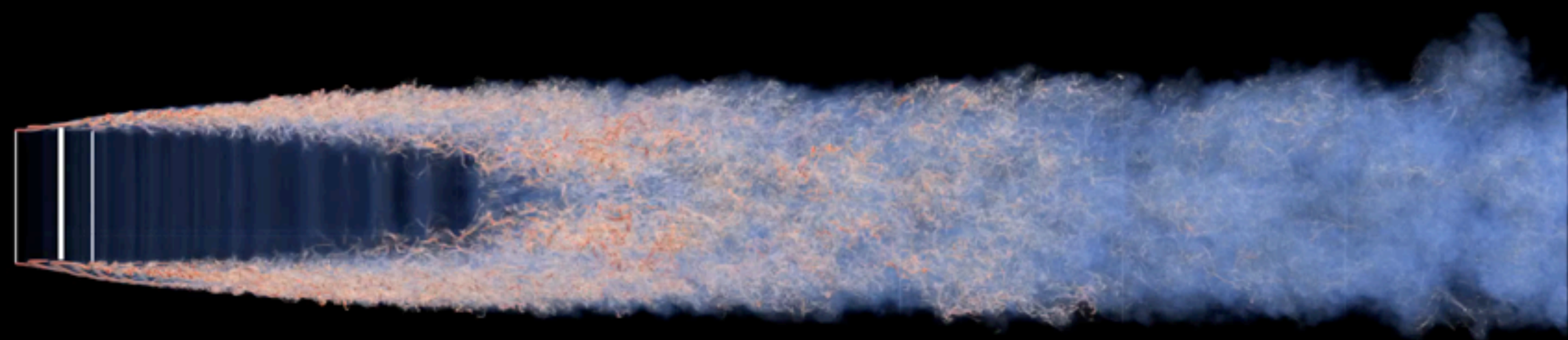
The dynamic stall decreases the power production and lowers the optimum λ

Side visualizations of the wake at various TSR

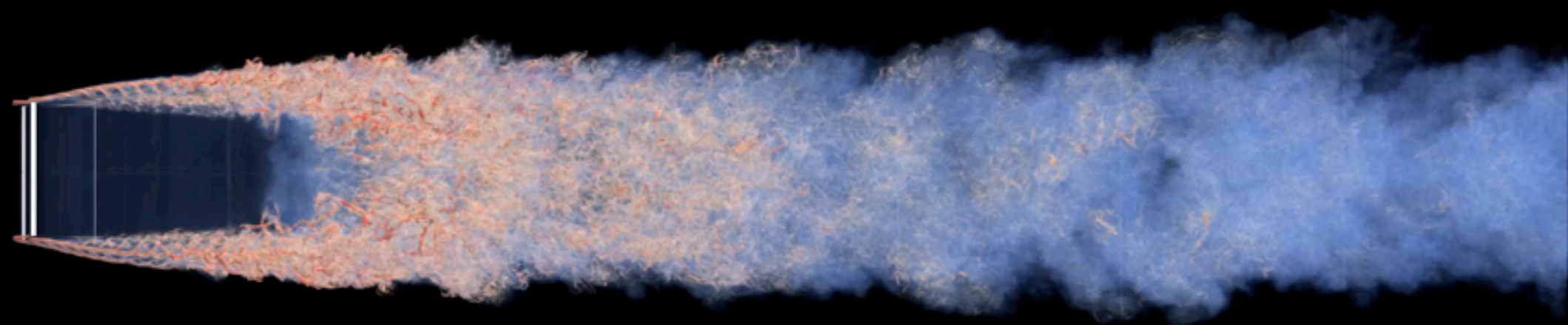
λ = 2.14



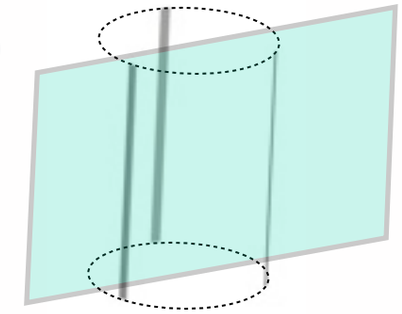
λ = 3.21

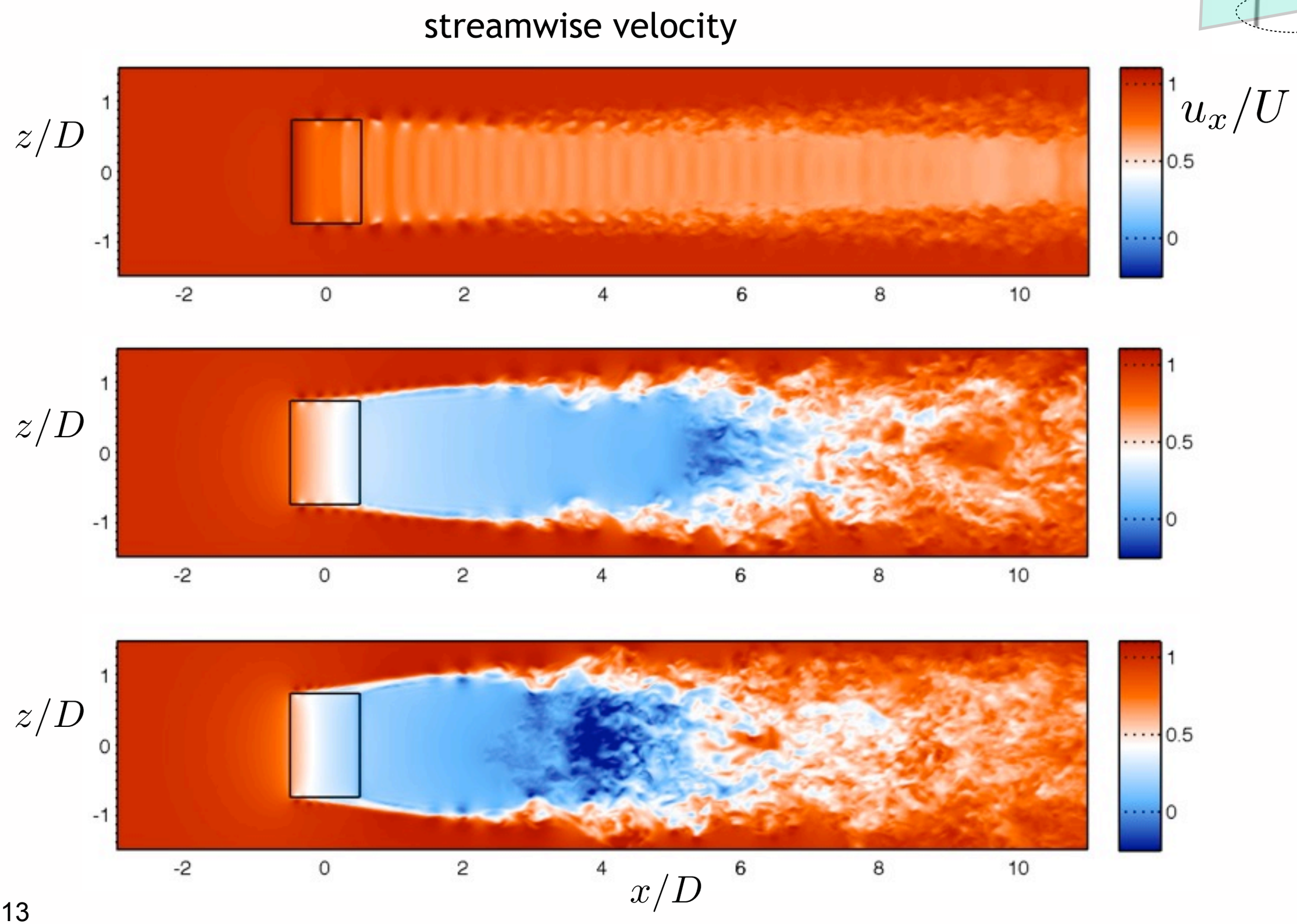


λ = 4.28



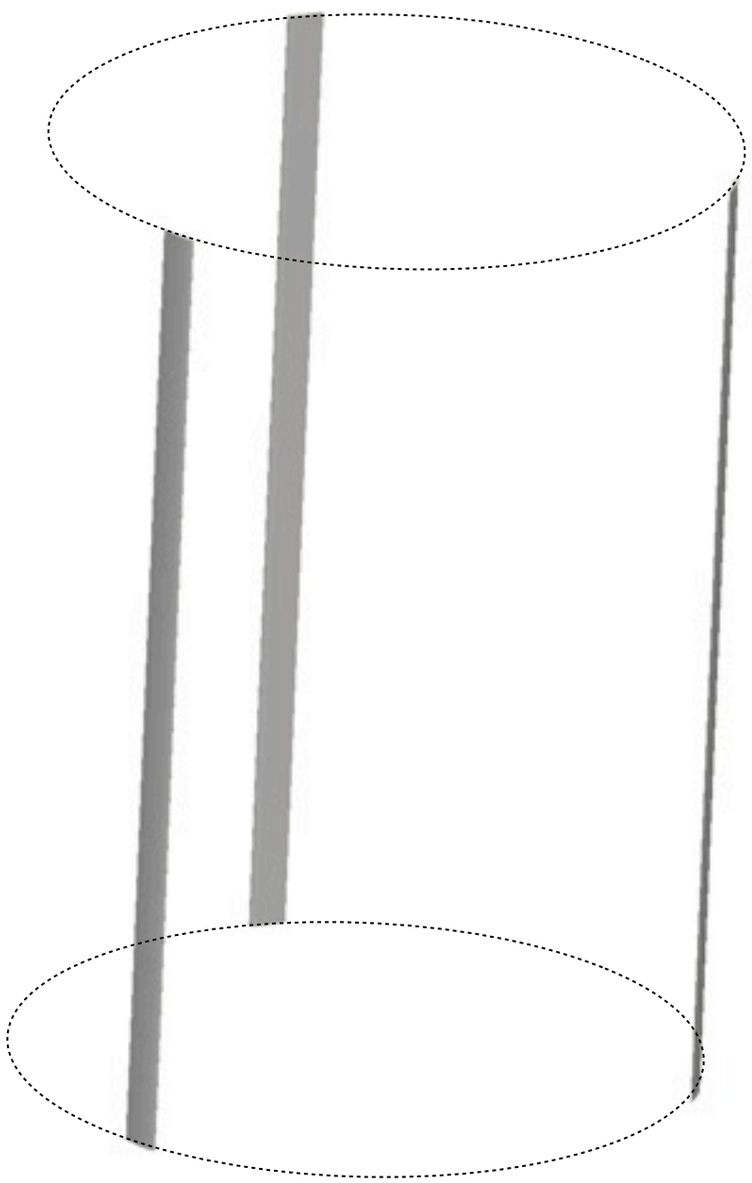
Effect of the operating point on the wake



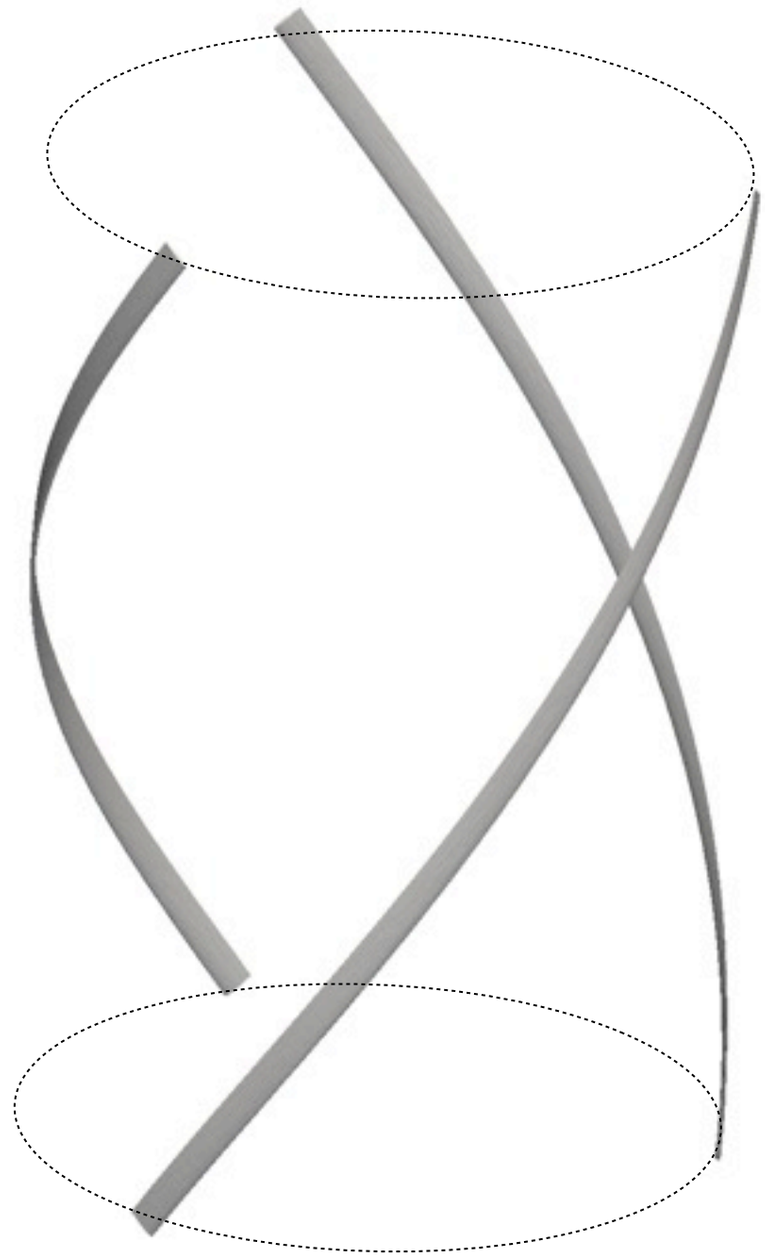


Effect of the blade configuration

H-type : straight blades

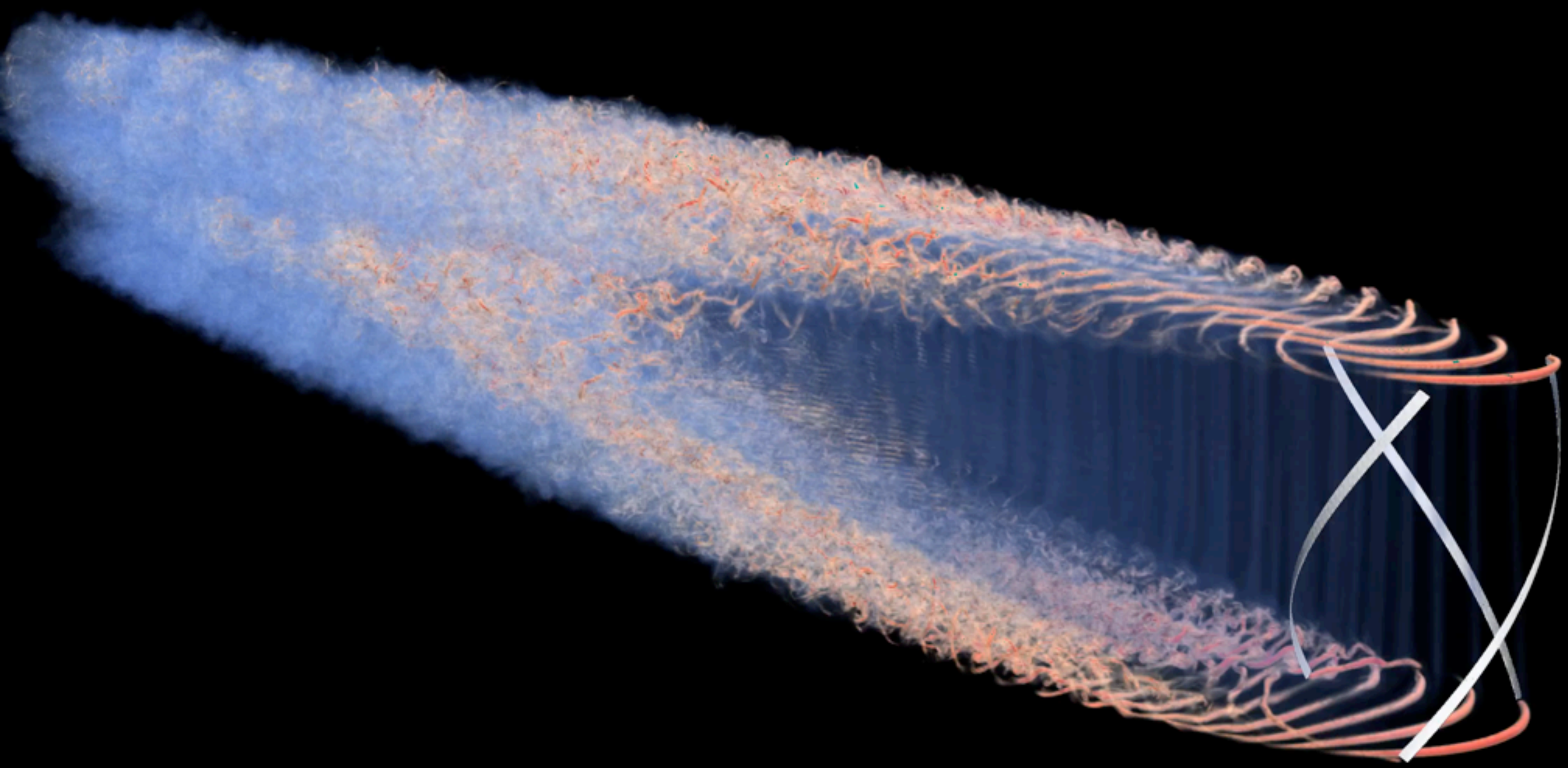


S-type : swept blades on the surface of the cylinder

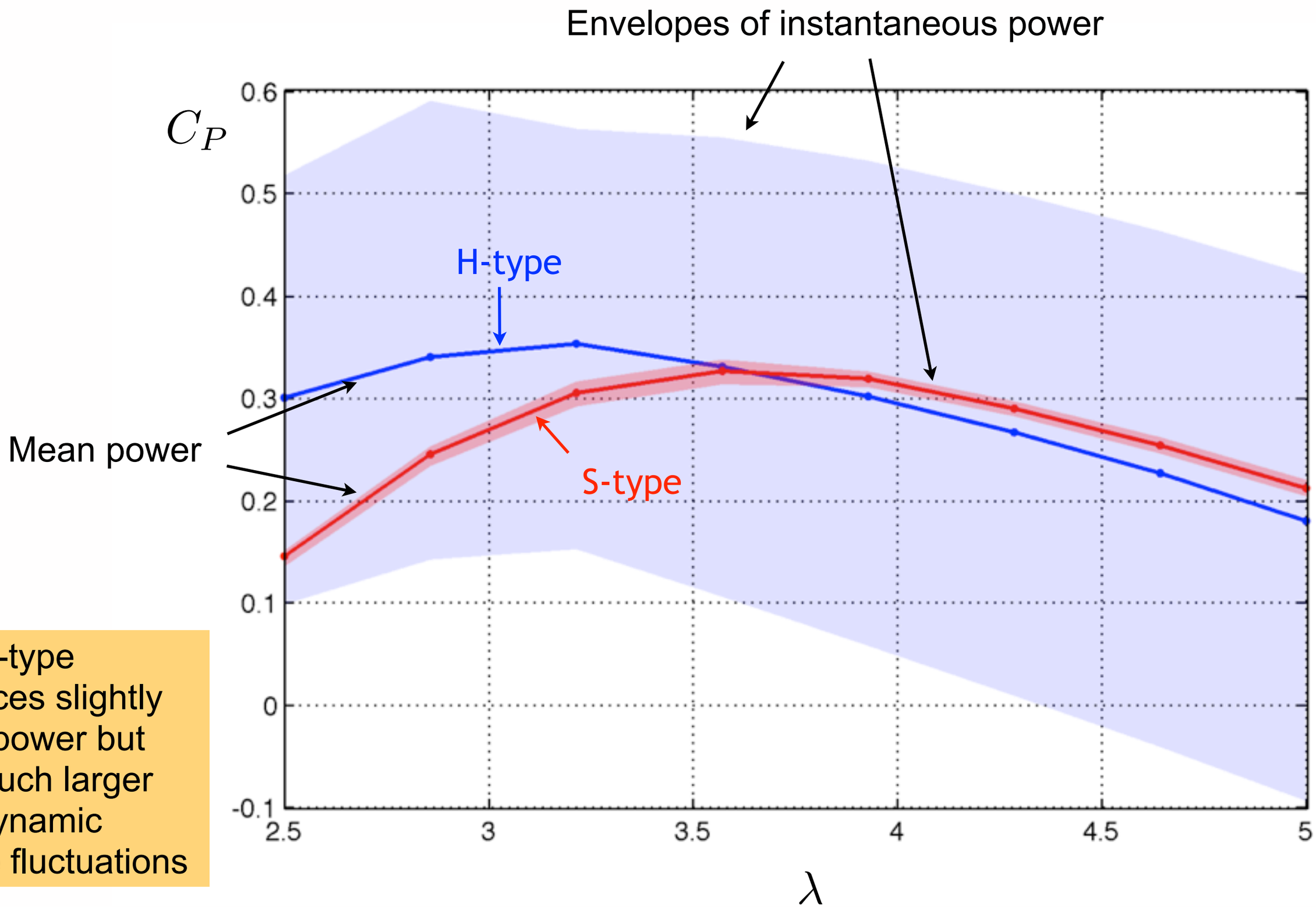


Same horizontal chord
⇒ same solidity

3D Visualization of the wake using vorticity magnitude : S-type VAWT



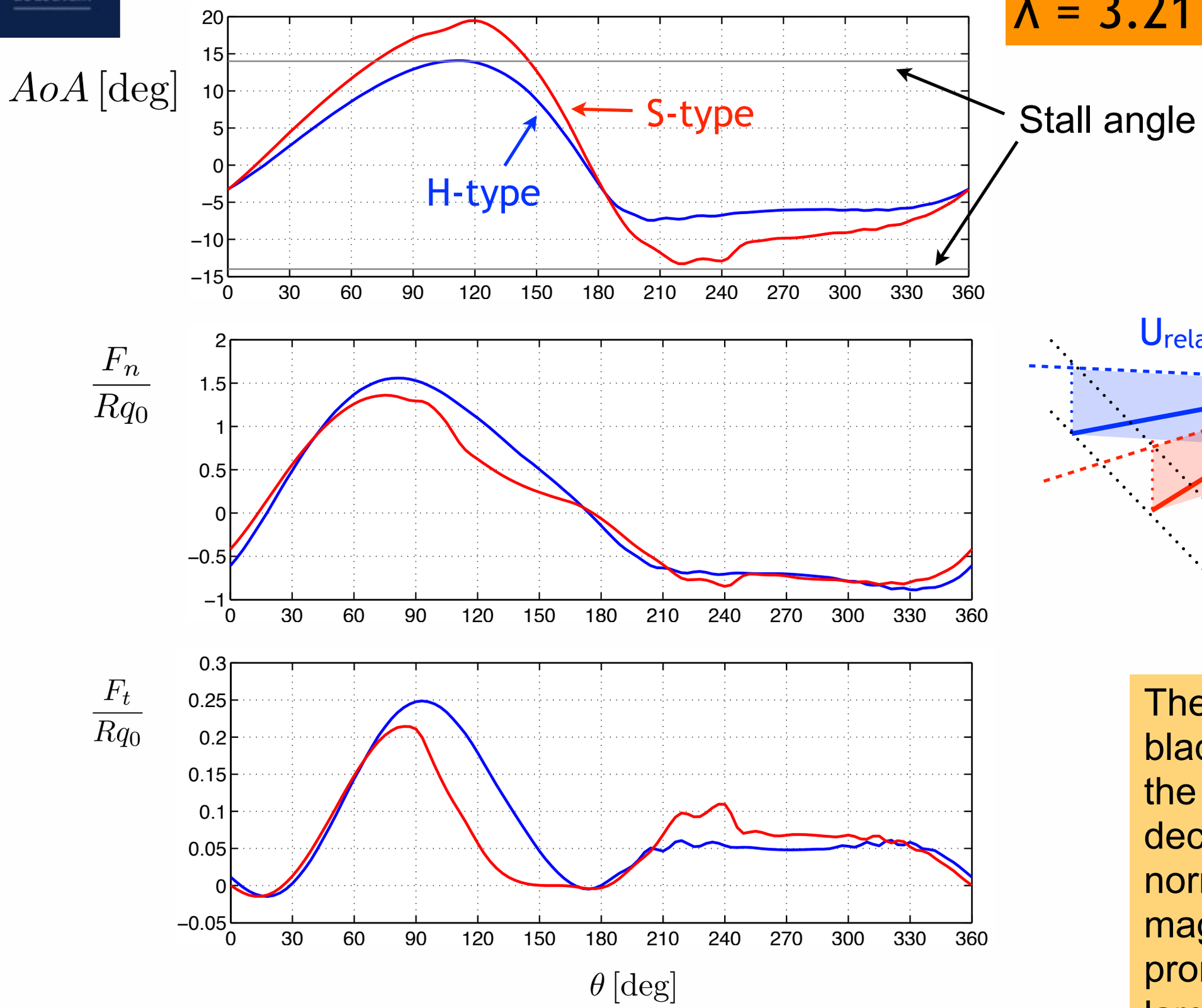
Effect of the configuration : power curve

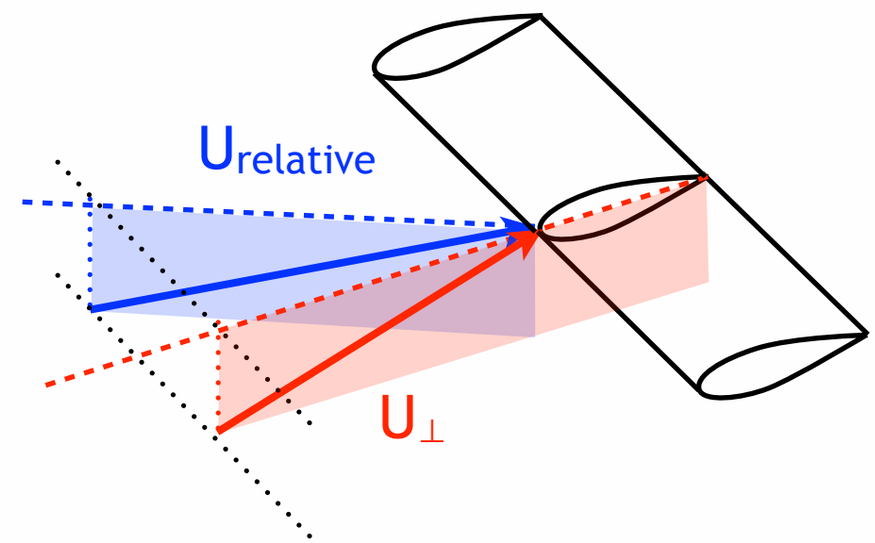


The H-type produces slightly more power but has much larger aerodynamic torque fluctuations

Effect of the configuration : blade aerodynamics

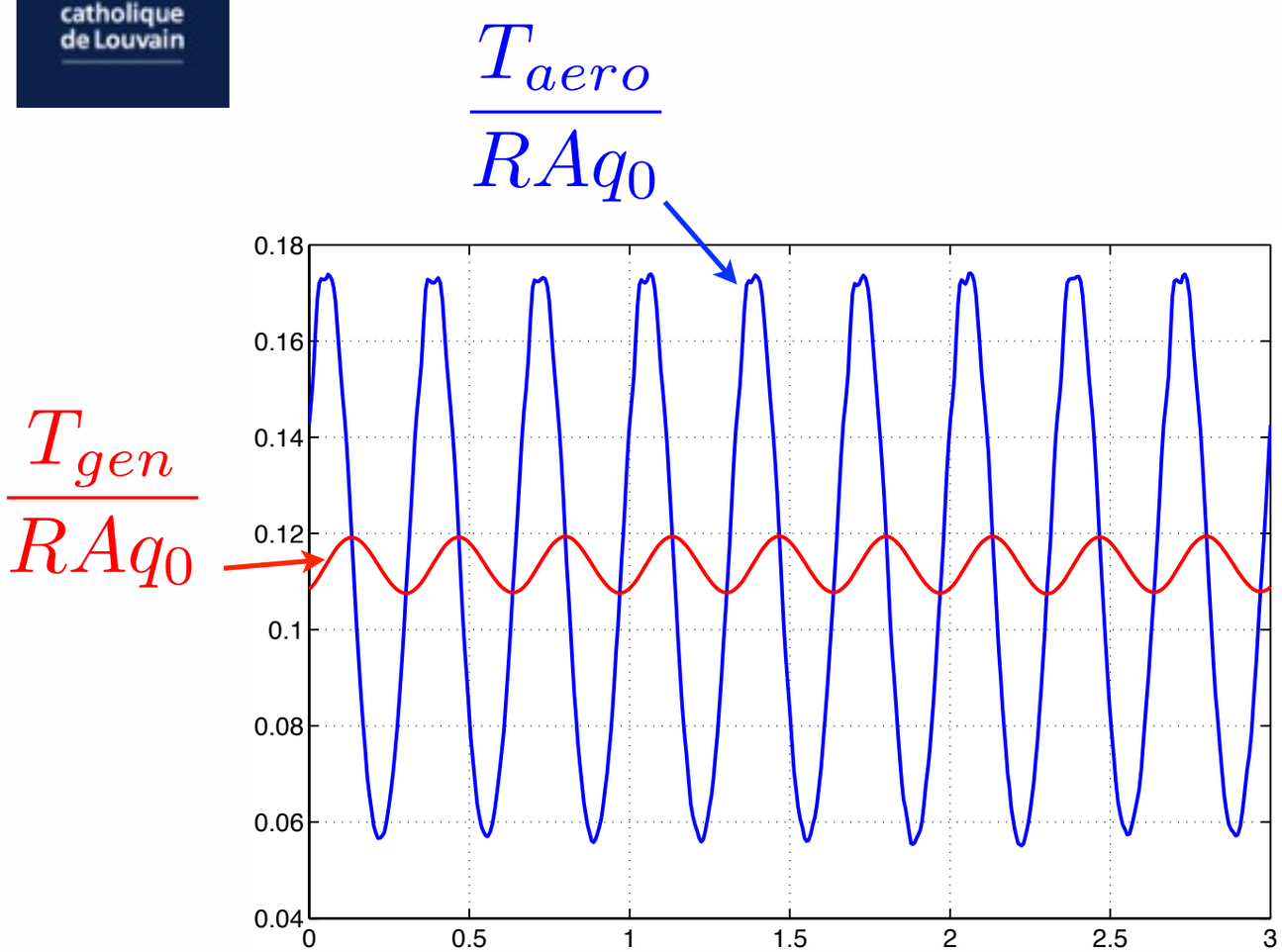
$\lambda = 3.21$

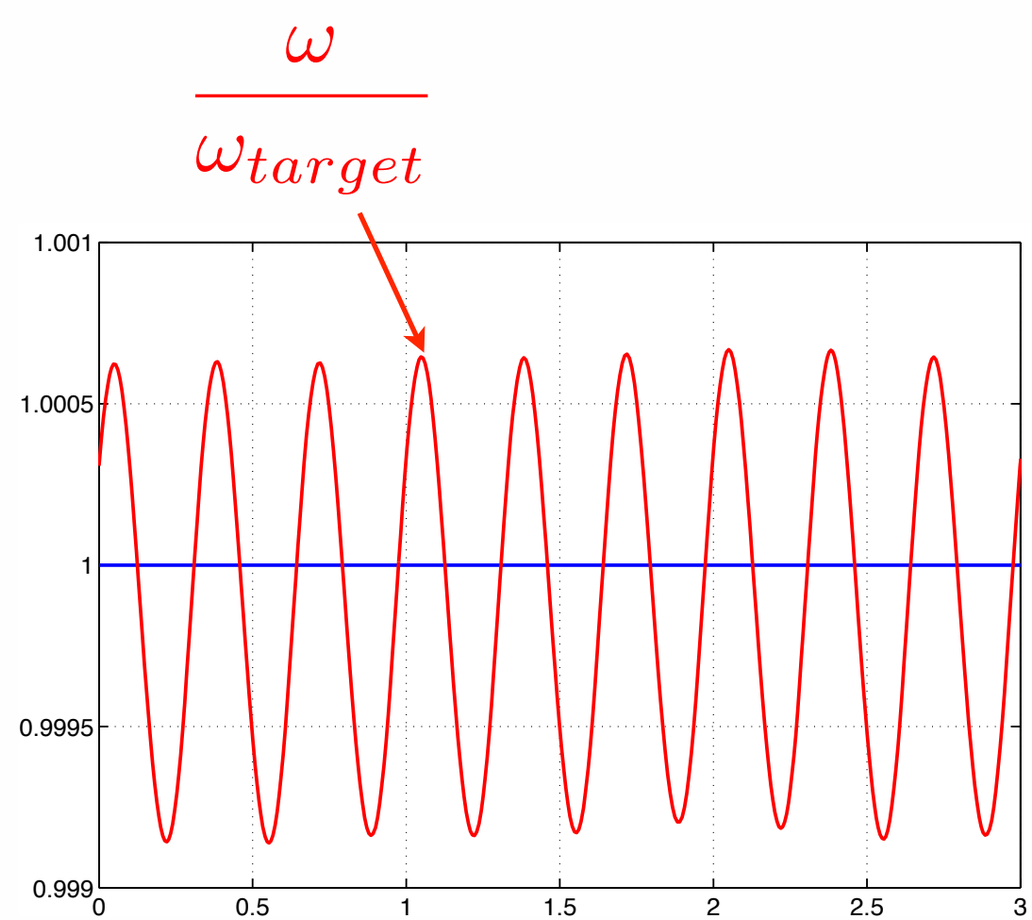


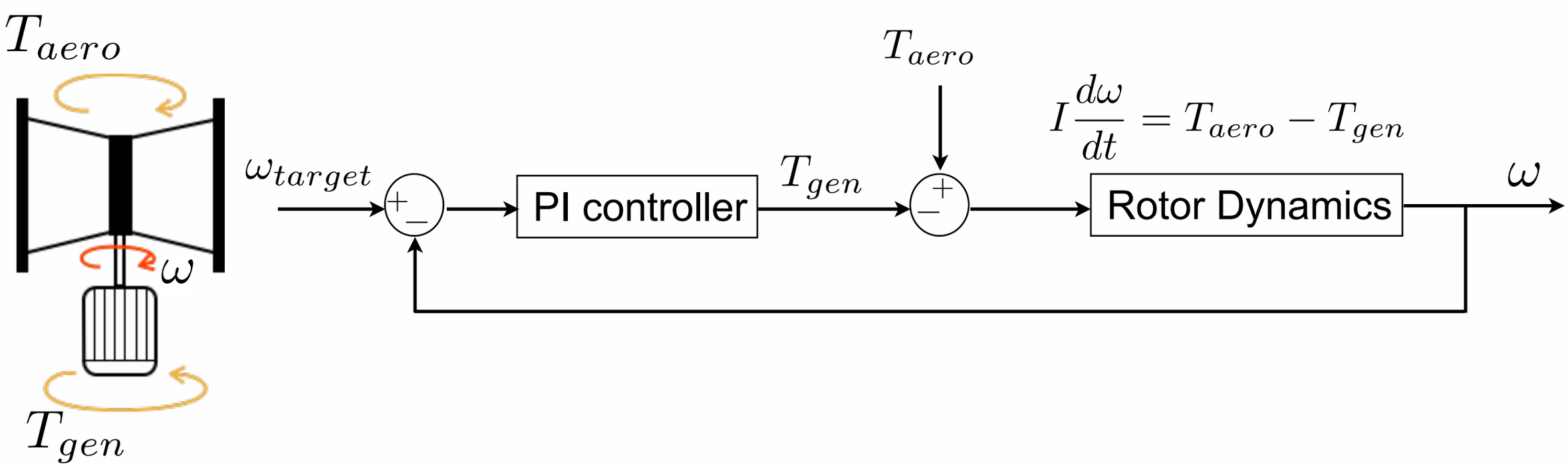


The sweep of the blade increases the AoA and decreases the normal velocity magnitude, thus promoting stall at larger λ

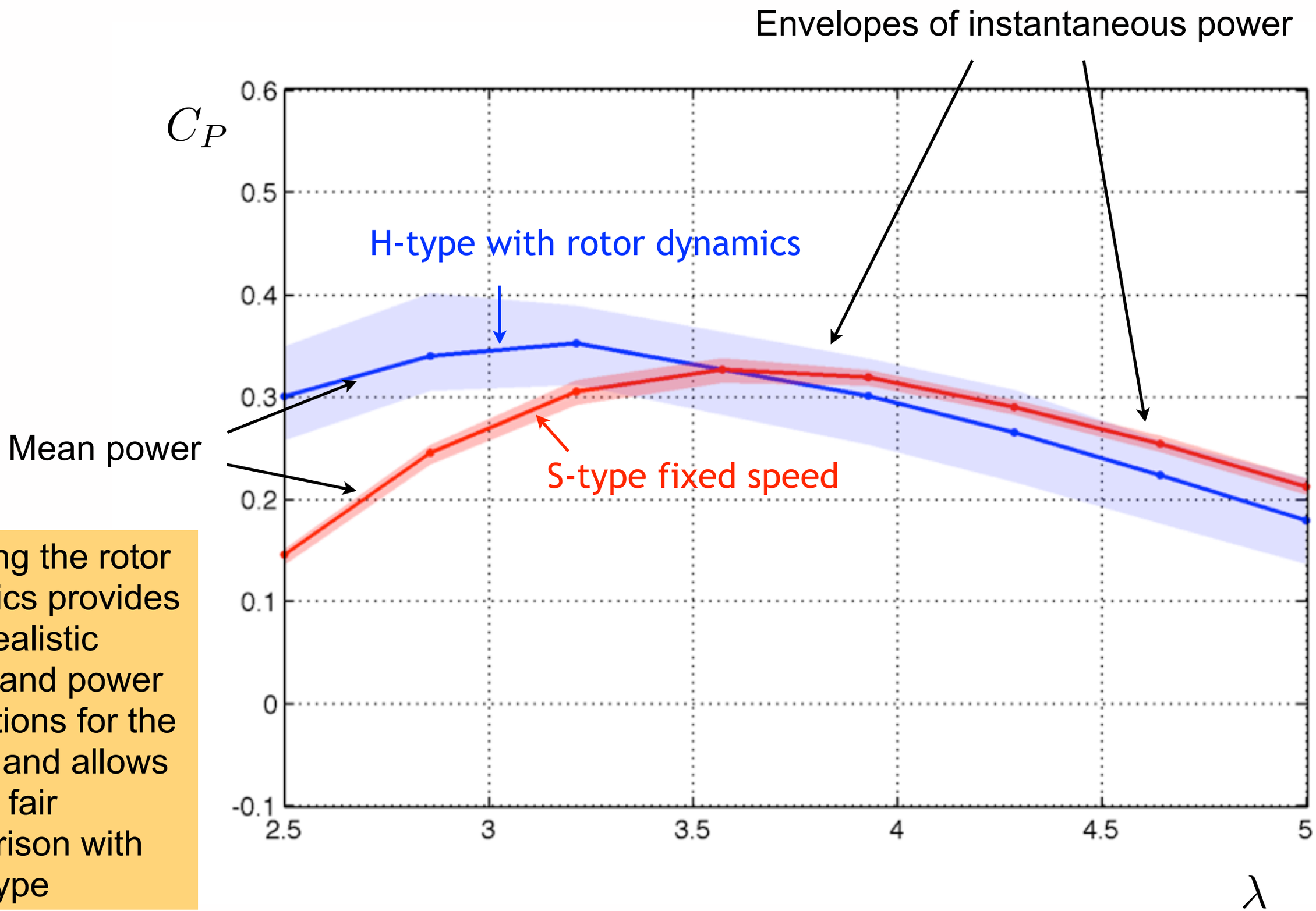
Torque fluctuations in H-type VAWTs







Effect of rotor dynamics : power curve



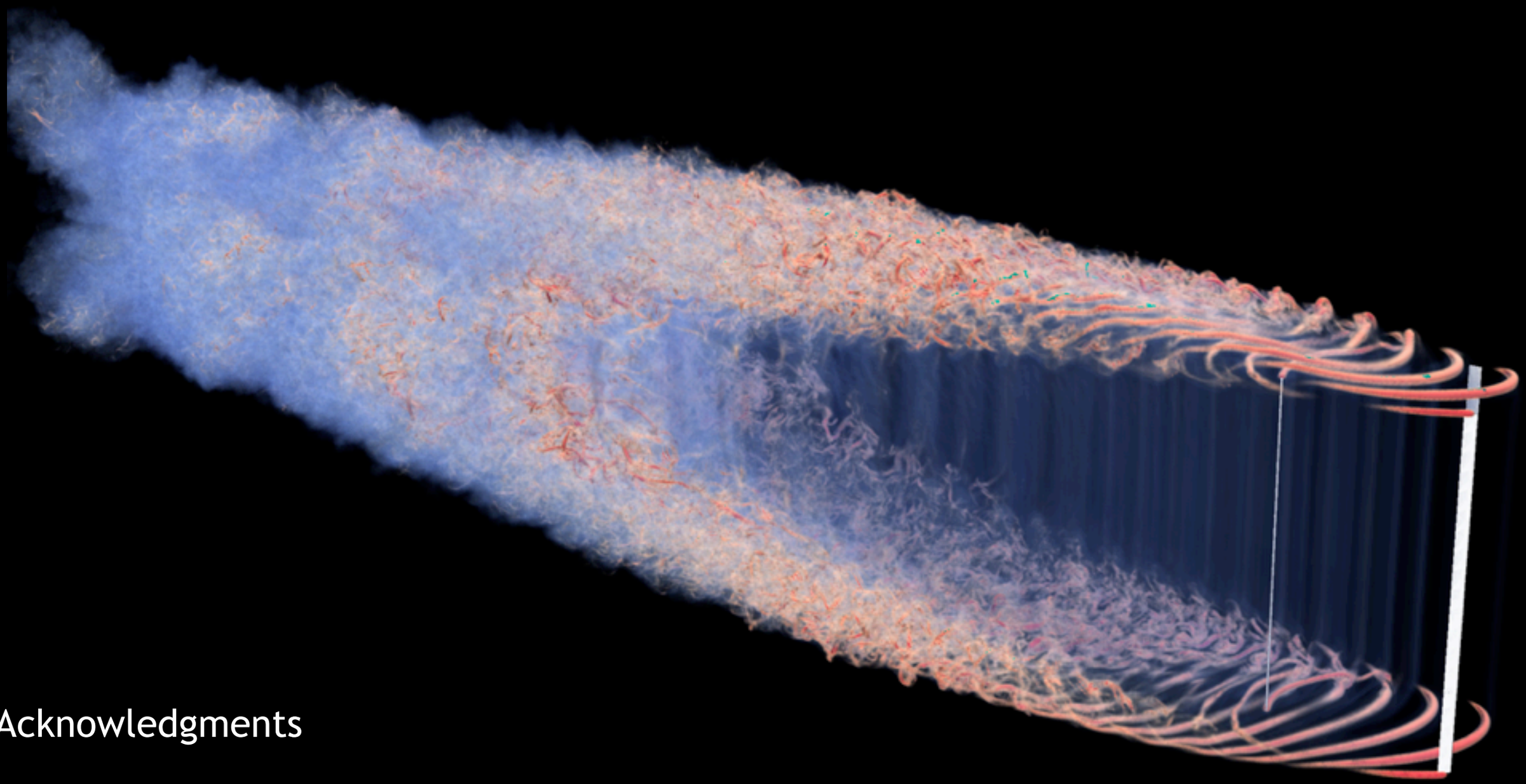
Including the rotor dynamics provides more realistic torque and power fluctuations for the H-type and allows a more fair comparison with the S-type

Conclusions

- Application of Vortex Particle-Mesh method to the investigation of VAWT performances and wakes
- Validation against experimental experiments
- Investigation of two different blade configurations
  - straight-blade H-type
  - swept-blade S-type
- Investigation of the effect of the rotor dynamics

- Importance of the dynamic stall phenomenon
- Complex wake resulting from the interaction between the tip vortices and the lateral vortex sheets

- Slightly larger power output for the H-type but at the cost of larger torque fluctuations
- Importance of taking the rotor dynamics into account to realistically predicts generator torque fluctuations



Acknowledgments

The **PPM** (Parallel Particle Mesh) library diaspora

UCL CISM - Institut de Calcul Intensif et de Stockage de Masse
CECI - Consortium des Equipements de Calcul Intensif
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