Numerical Modelling and Scales in Wind Power

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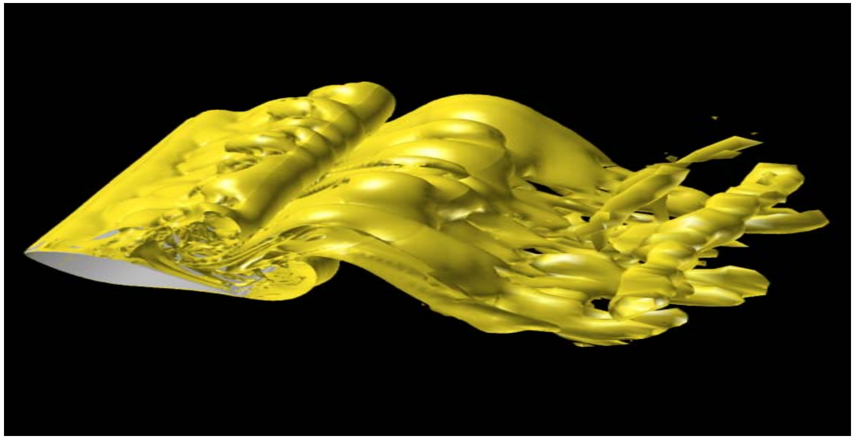

Scale requirements in wind energy

Turbulent scales:

	Length scale (m)	Velocity scale (m/s)	Time scale (s)
Airfoil boundary layer	10^{-3}	10^{2}	10^{-5}
Airfoil	1	10^{2}	10^{-2}
Rotor	10^{2}	10	10
Cluster	10^{3}	10	10^{2}
Wind farm	10^{4}	10	10^{3}

Models in Wind Turbine Aerodynamics

Available models:

- **Blade-Element momentum (BEM) technique**
- **Vortex line / Vortex lattice modelling**
- **Actuator disc / Actuator line technique**
- **Computational Fluid Dynamics (CFD)**

Remark: All models have their individual advantages and disadvantages!

Blade Element Momentum Model

Basic ingredients of the BEM model:

- **Based on 1-D momentum theory assuming annular independency**
- **Loading computed using tabulated static airfoil data**
- **Dynamic stall handled through ’dynamic stall’ models**
- **3-dimensional stall introduced through modifications**
- **Tip Flows based on (Prandtl) tip correction**
- **Yaw treated through simple modifications**
- **Heavily loaded rotors treated through Glauert’s approximation**
- **Wakes and park effects modelled using axisymmetric momentum theory**

Blade Element Momentum Model

Advantages of using the BEM model:

- **Extremely fast on a PC**
- **Can in principle cope with all flow situations**
- **Easy to couple with an aeroelastic conde, such as Flex**
- **Easy to couple with turbulent inflow model**
- **Many years of experience in using the model**
- **Performs very well at design conditions**
- **Capable of delivering results at off-design conditions**

The BEM model is today the industrial standard used by all producers of wind turbines and wind turbine blades

Blade Element Momentum Model

Why not just continue with BEM codes:

- Aerofoil Aerodynamics based on measurements
- Dynamic stall based on phenomenological models
- 3-dimensional stall based on empirical /scaling relations
- Tip Flows modelling questionable
- Yaw modelling not based on rigorous physics
- Heavily loaded rotors intrinsically unsteady
- Wakes and park effects only crudely modelled

Thus, there is also a need for looking into more advanced models

Vortex line/lattice models

Basics of the models:

- Vortex structures substituted by filaments or panels
- Velocity field determined from Biot-Savert integral
- Location of panels are either fixed or free
- The flow field is incompressible, inviscid and irrotational
- The lifting surfaces are thin
- The angle of attack is small, i.e. small angle approximation
- The method may be generalized by coupling it to the viscous boundary layer

Vortex structures in the wake of a rotor

Stable vortex system **Unstable vortex system**

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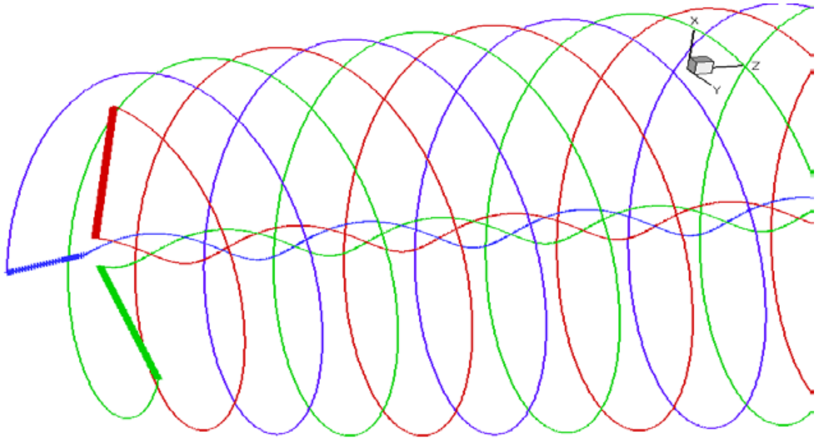
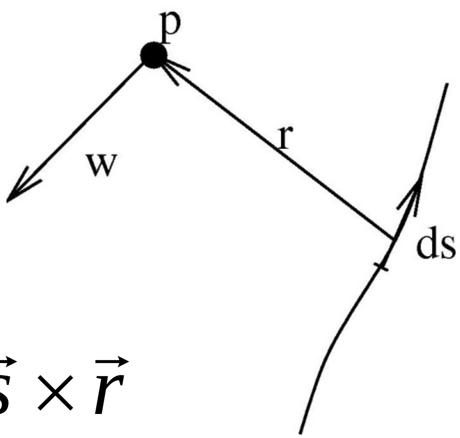
Vortex line/lattice models

Biot-Savart induction law:

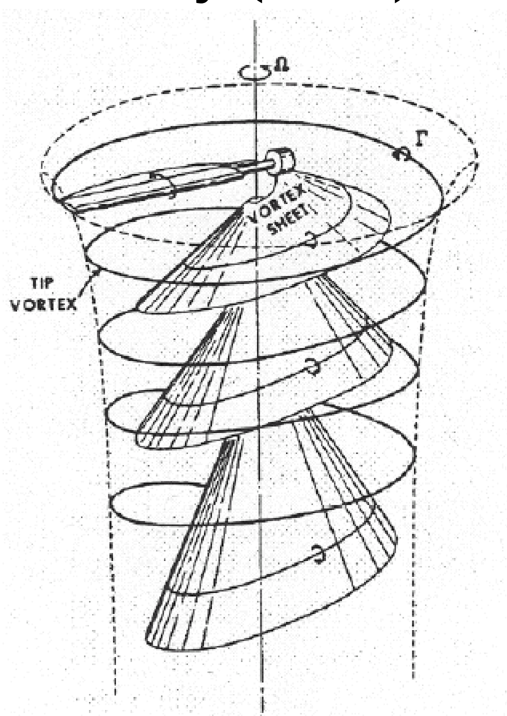




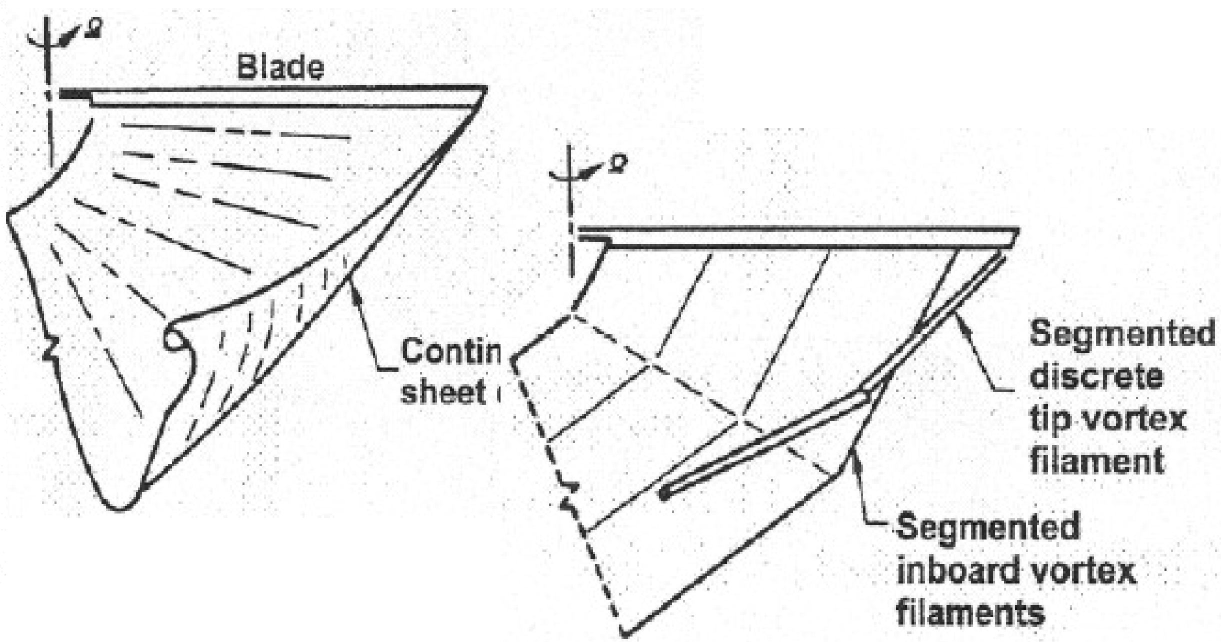
$$\vec{w} = \frac{\Gamma}{4\pi} \oint \frac{d\vec{s} \times \vec{r}}{|\vec{r}|^3}$$

Models of vortex systems behinds rotors

Gray (1955)



Circulation redistribution by rolling up the vorticity sheet around the tip vortex (Landgrebe, 1972)



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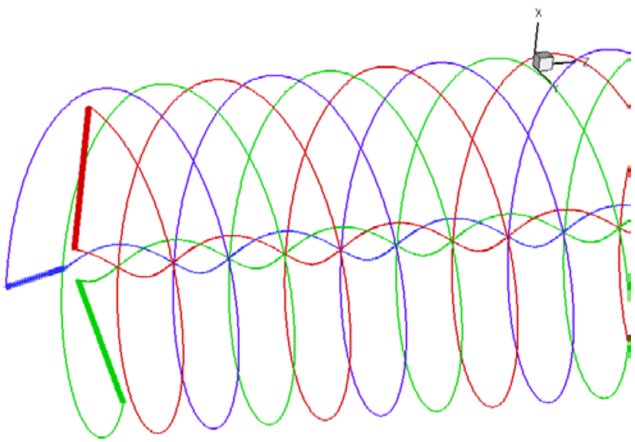
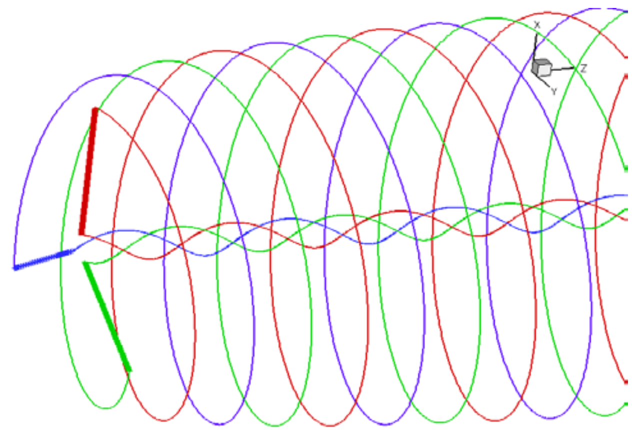
Vortex line/lattice models

Fixed wake analysis:



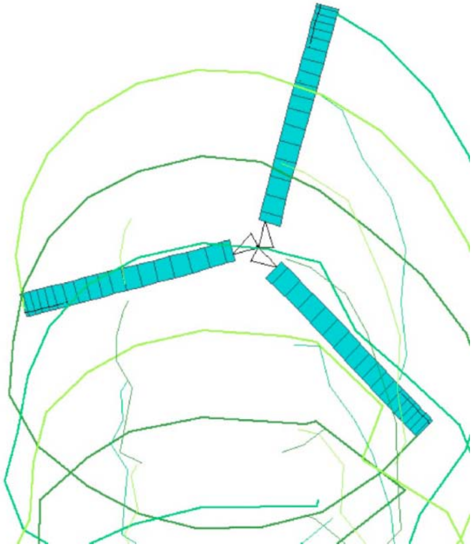
Without expansion

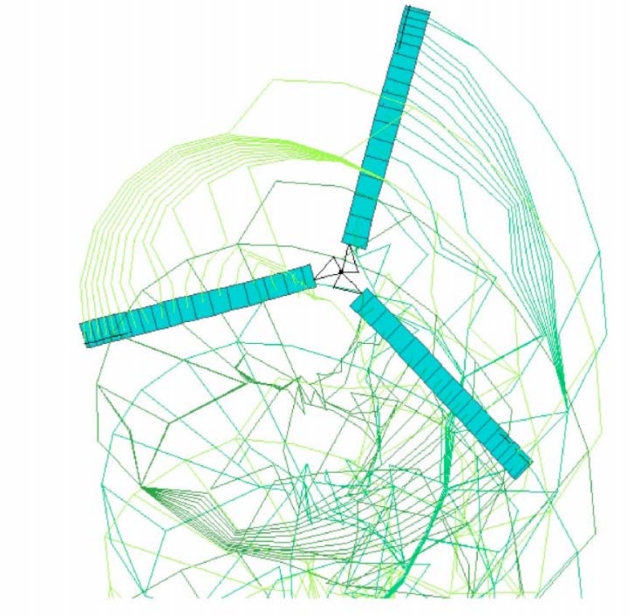


With expansion

Vortex line/lattice models

Free wake analysis:



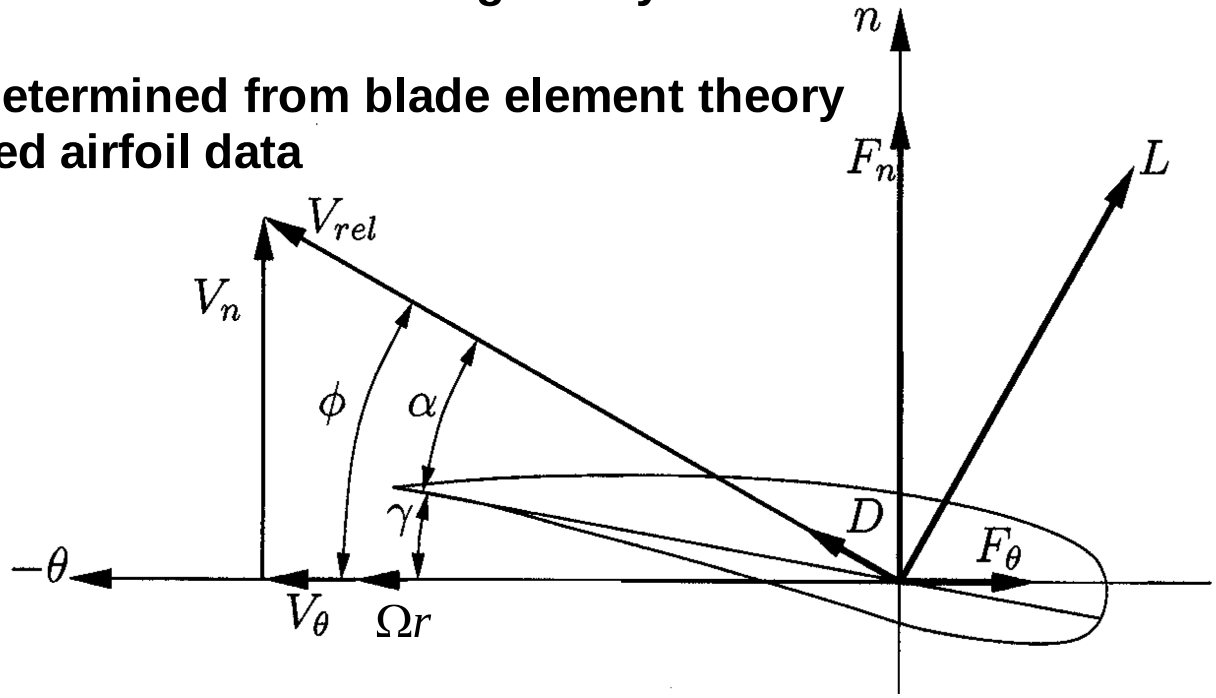


The flow field tend to become chaotic

Actuator disc models

Basic elements of the model:

- Flow governed by Euler or Navier-Stokes equations
- Influence of rotor introduced through body force
- Body forces determined from blade element theory using tabulated airfoil data



Actuator disc models

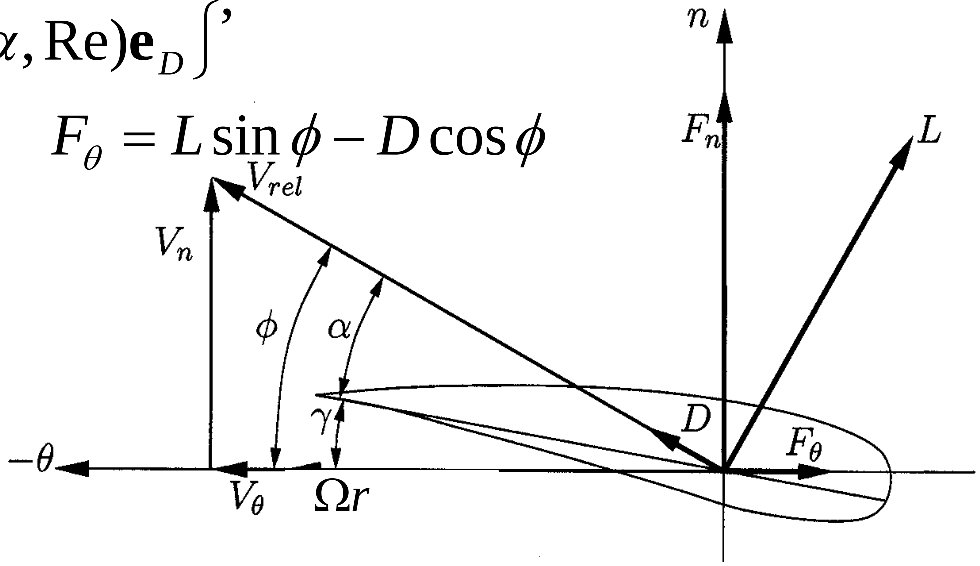
Airfoil data and body forces:

$$\phi = \tan^{-1}\left(\frac{V_n}{\Omega r - V_\theta}\right), \quad \alpha = \phi - \gamma$$

$$V_{rel}^2 = V_n^{\,2} + (\Omega r - V_\theta)^2 \,, \quad V_n = V_z$$

$$\begin{Bmatrix} \mathbf{L} \\ \mathbf{D} \end{Bmatrix} = \tfrac{1}{2}\rho V_{rel}^2 cB \begin{Bmatrix} C_L(\alpha, \mathrm{Re})\mathbf{e}_L \\ C_D(\alpha, \mathrm{Re})\mathbf{e}_D \end{Bmatrix},$$

$$F_z = L\cos\phi + D\sin\phi, \quad F_\theta = L\sin\phi - D\cos\phi$$



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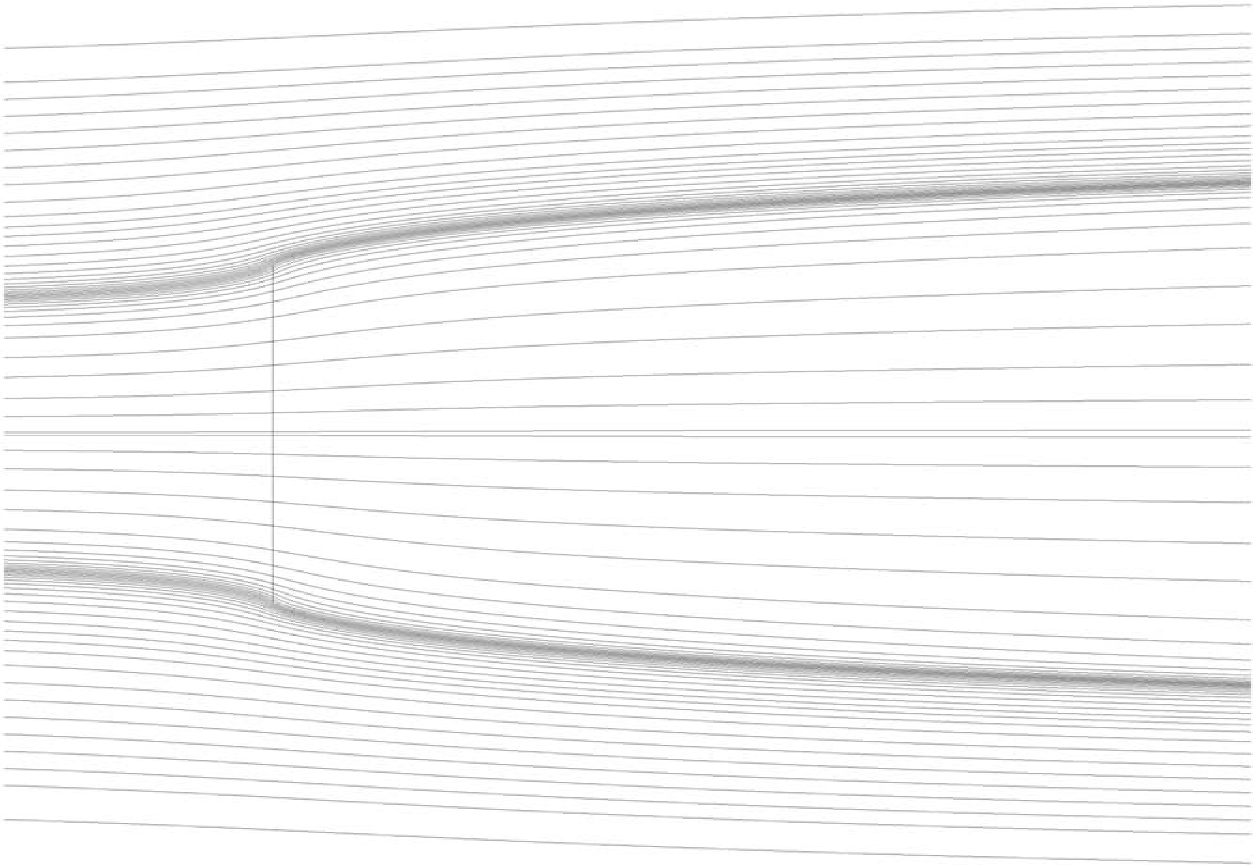
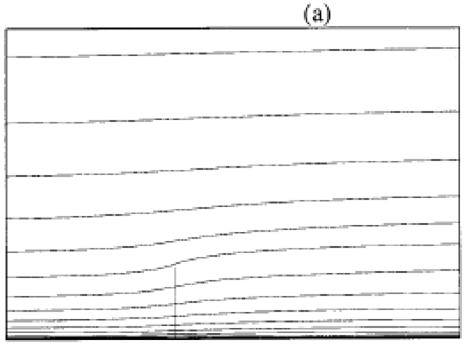
Actuator disc models

Axisymmetric case with constant loading:

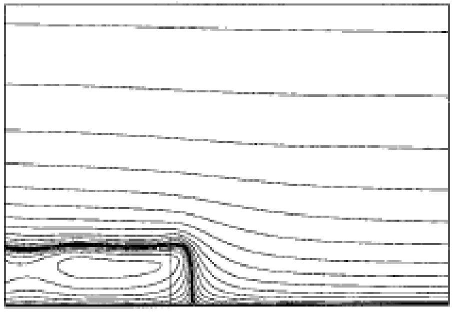


Actuator disc models

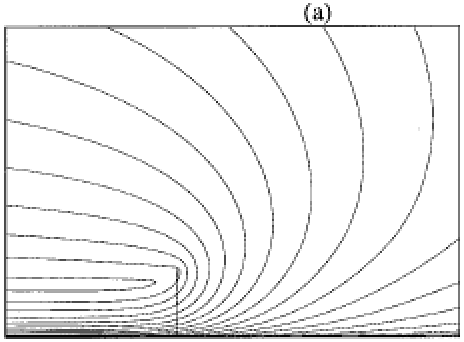
Axisymmetric cases with constant loading:



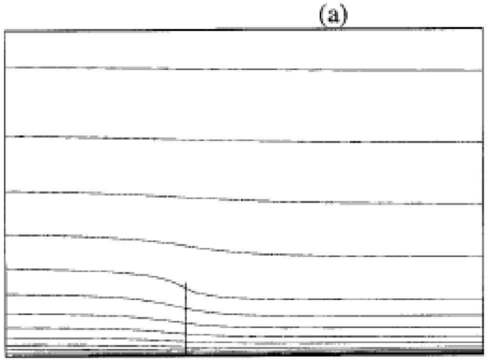
Wind turbine state



Vortex ring state



Hover state



Propeller state

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Actuator disc models

Wake states:

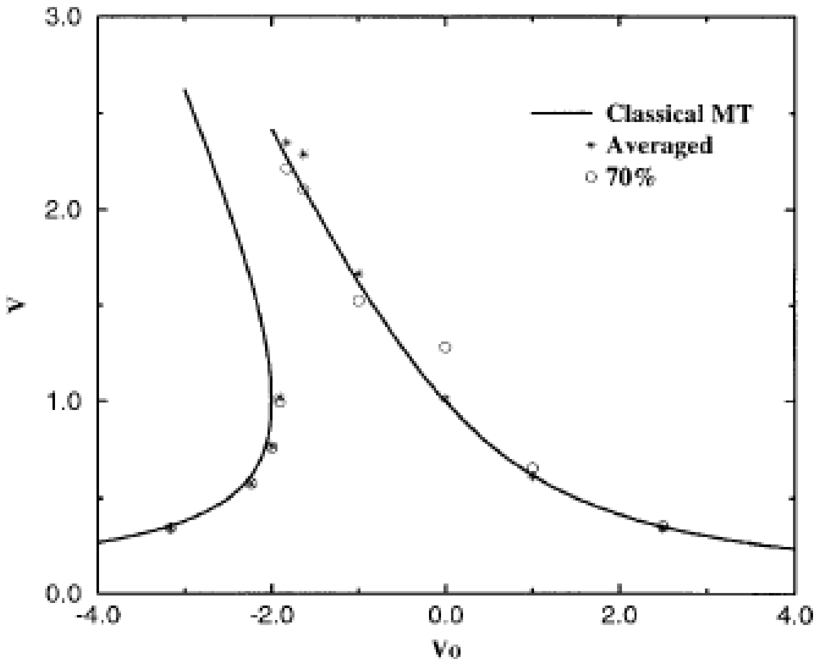

Figure 15. Induced velocity versus undisturbed velocity

$$\bar{V}_o = \frac{V_o}{\sqrt{T/2\rho A}}, \qquad \bar{v} = \frac{v}{\sqrt{T/2\rho A}}$$

$$\bar{V}_o = \begin{cases} -\bar{v} - 1/\bar{v} & \text{for the windmill brake state} \\ -\bar{v} + 1/\bar{v} & \text{for the propeller state} \end{cases}$$

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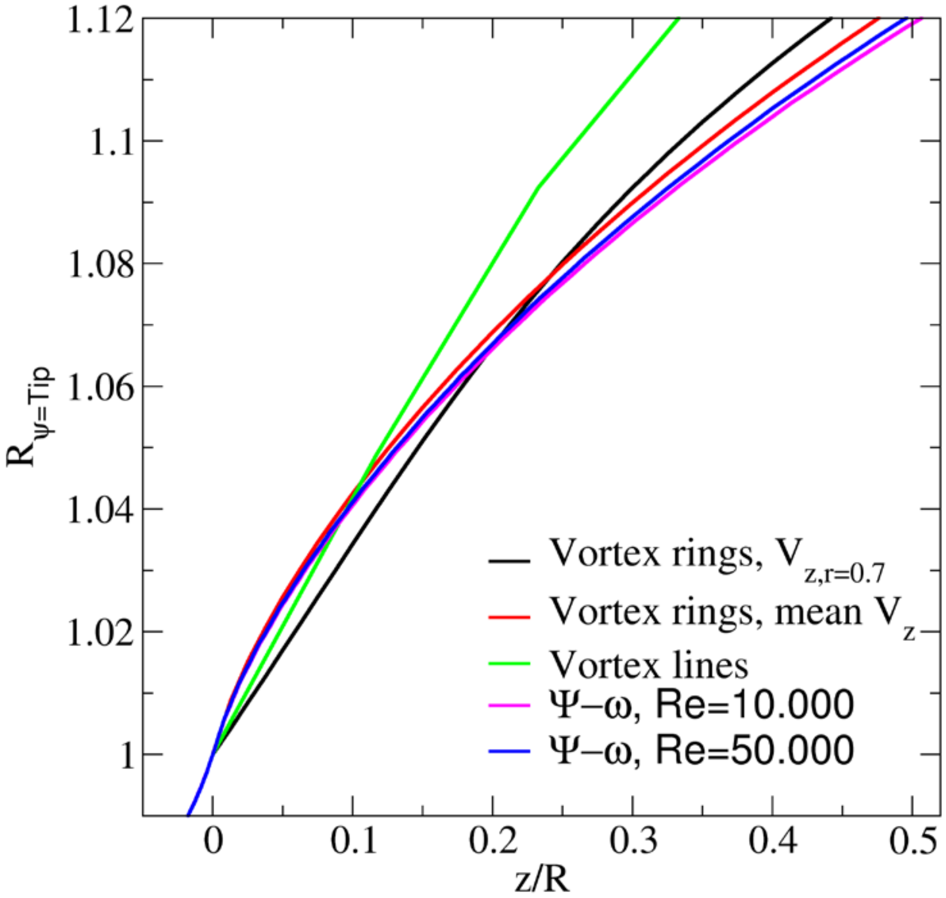
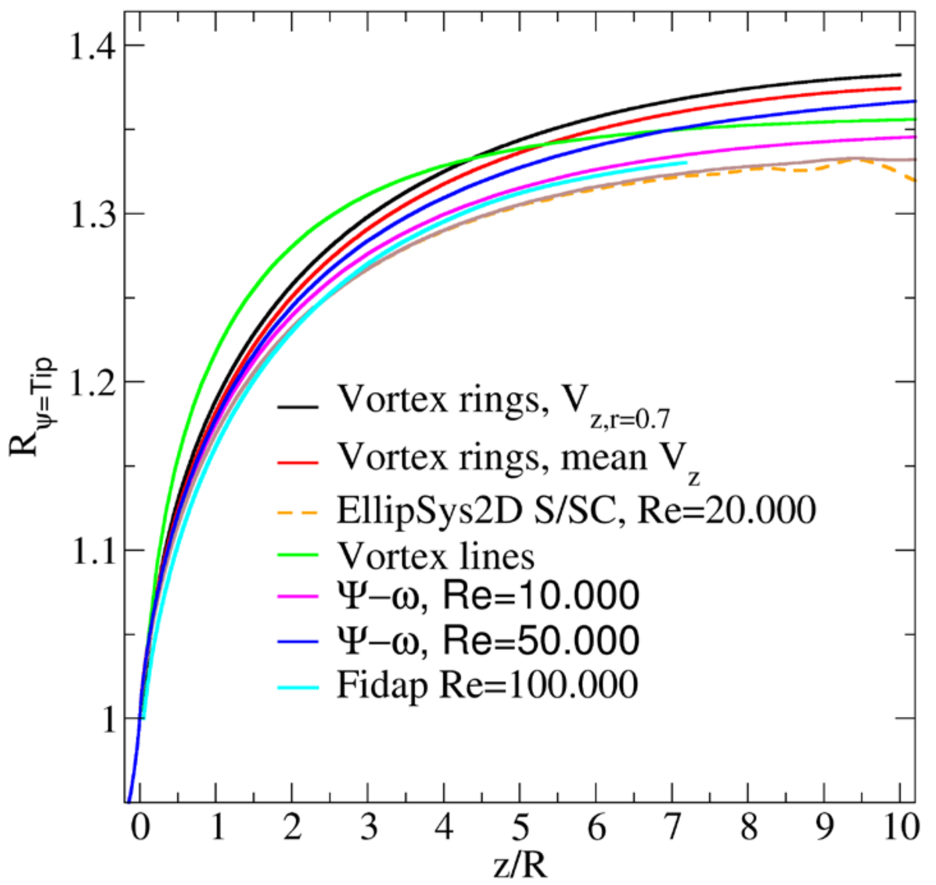
Wake ekspansion, tip-strømlinje





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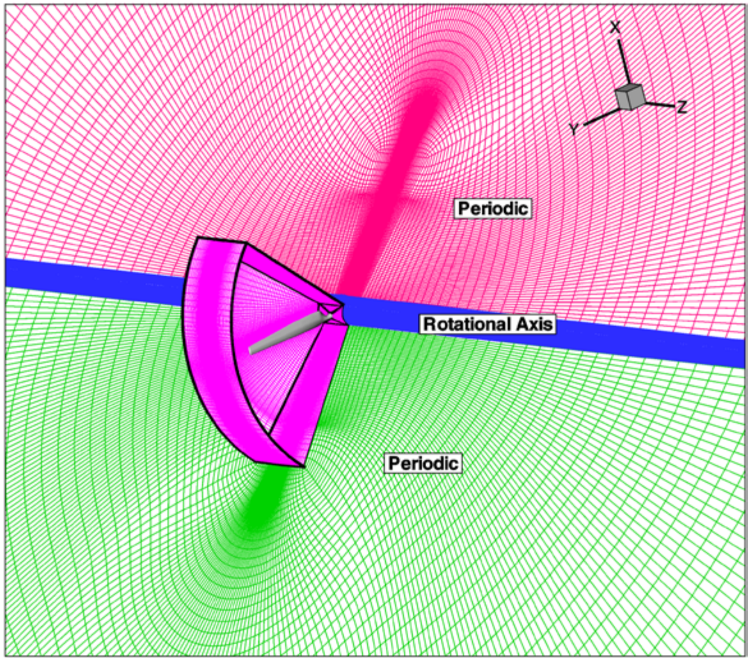
CFD: The Numerical Wind Tunnel

Basic Elements

- **Discretization technique**
- **Mesh generation**
- **Turbulence/transition modelling**
- **Efficient computing algorithms**
- **High-performance computers**
- **Post-processing facilities (Validation)**



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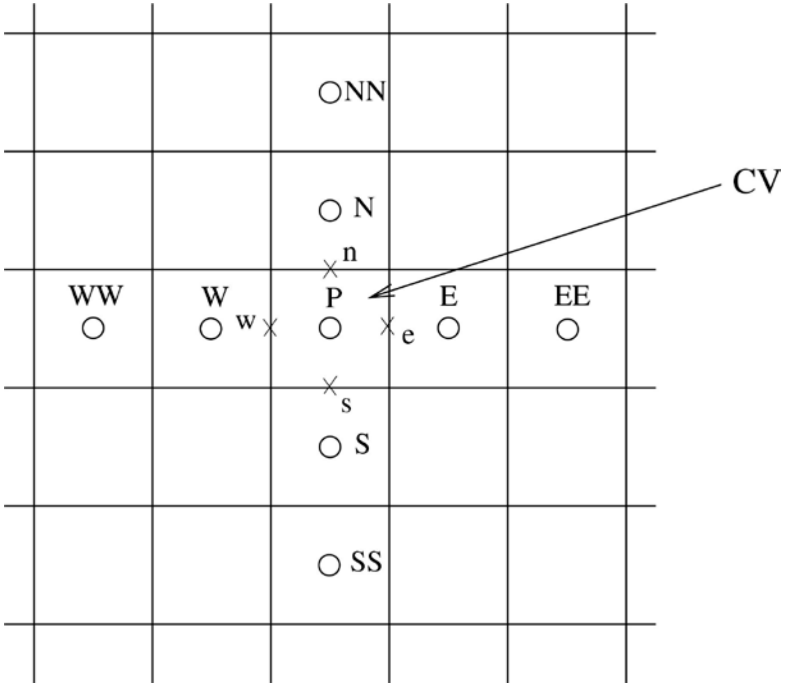
CFD: The Numerical Wind Tunnel

Discretization techniques

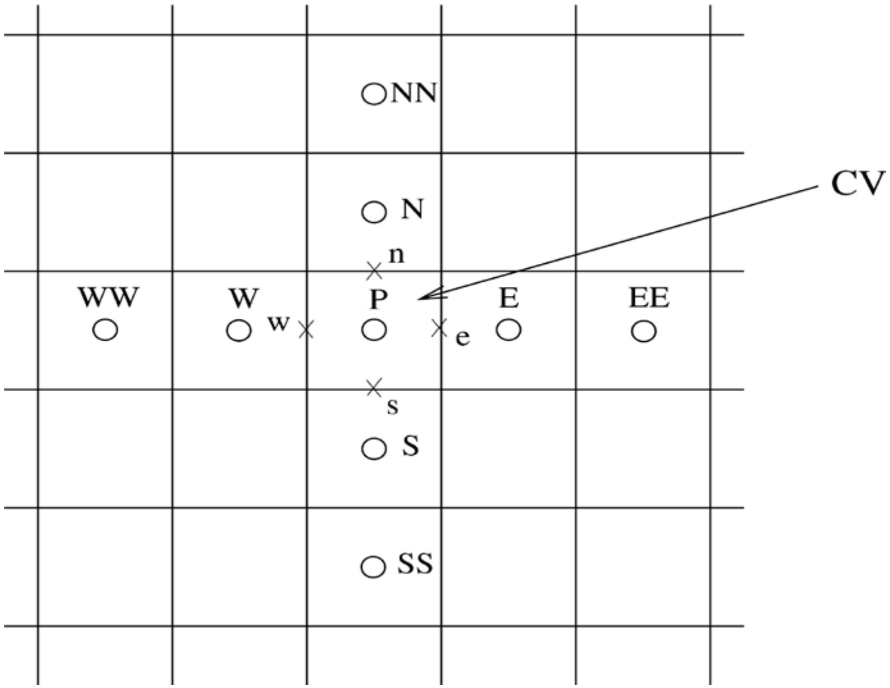
- **Finite difference**
- **Finite volume**
- **Finite Element**
- **Spectral**
- **Spectral element**
- **Vortex particle**



The Finite Volume Method

- Advantages
  - Can be used on any type of grids
  - Easy to understand and program
  - It has a physical meaning for all discretized terms (Fluxes)

- Disadvantage:
  - Difficult to extend to higher orders



Mesh generation

– Structured grid

– Block-structured grid

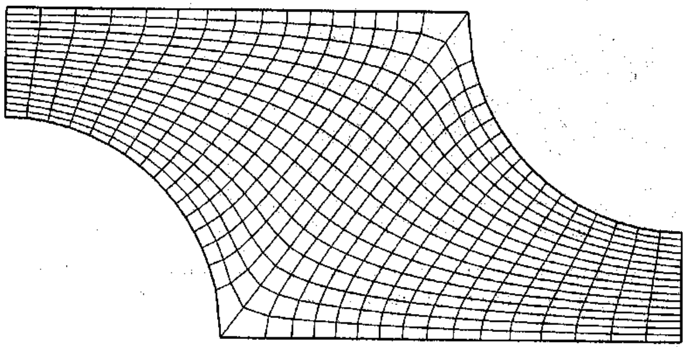


Fig. 2.1. Example of a 2D, structured, non-orthogonal grid, designed for calculation of flow in a symmetry segment of a staggered tube bank

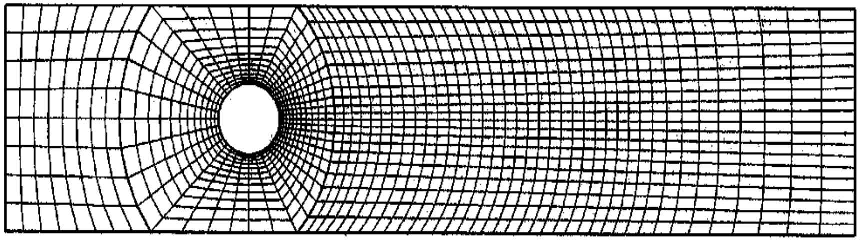


Fig. 2.2. Example of a 2D block-structured grid which matches at interfaces, used to calculate flow around a cylinder in a channel

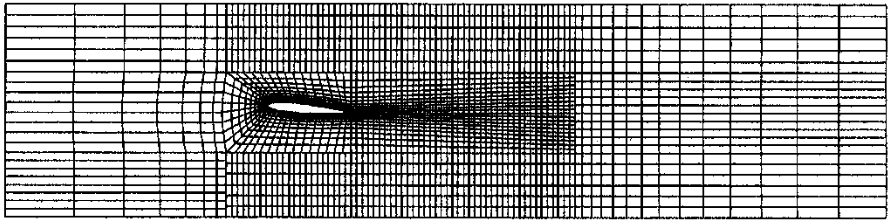


Fig. 2.3. Example of a 2D block-structured grid which does not match at interfaces, designed for calculation of flow around a hydrofoil under a water surface

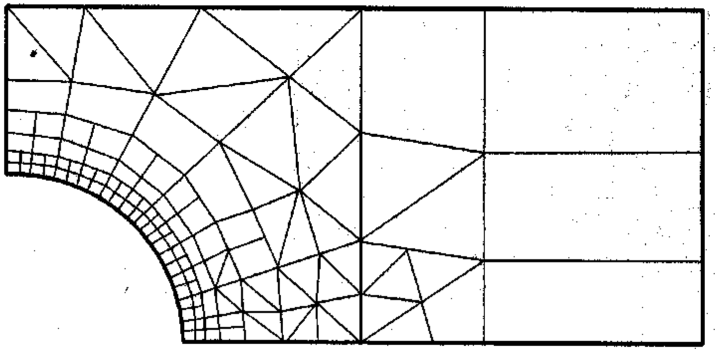


Fig. 2.5. Example of a 2D unstructured grid

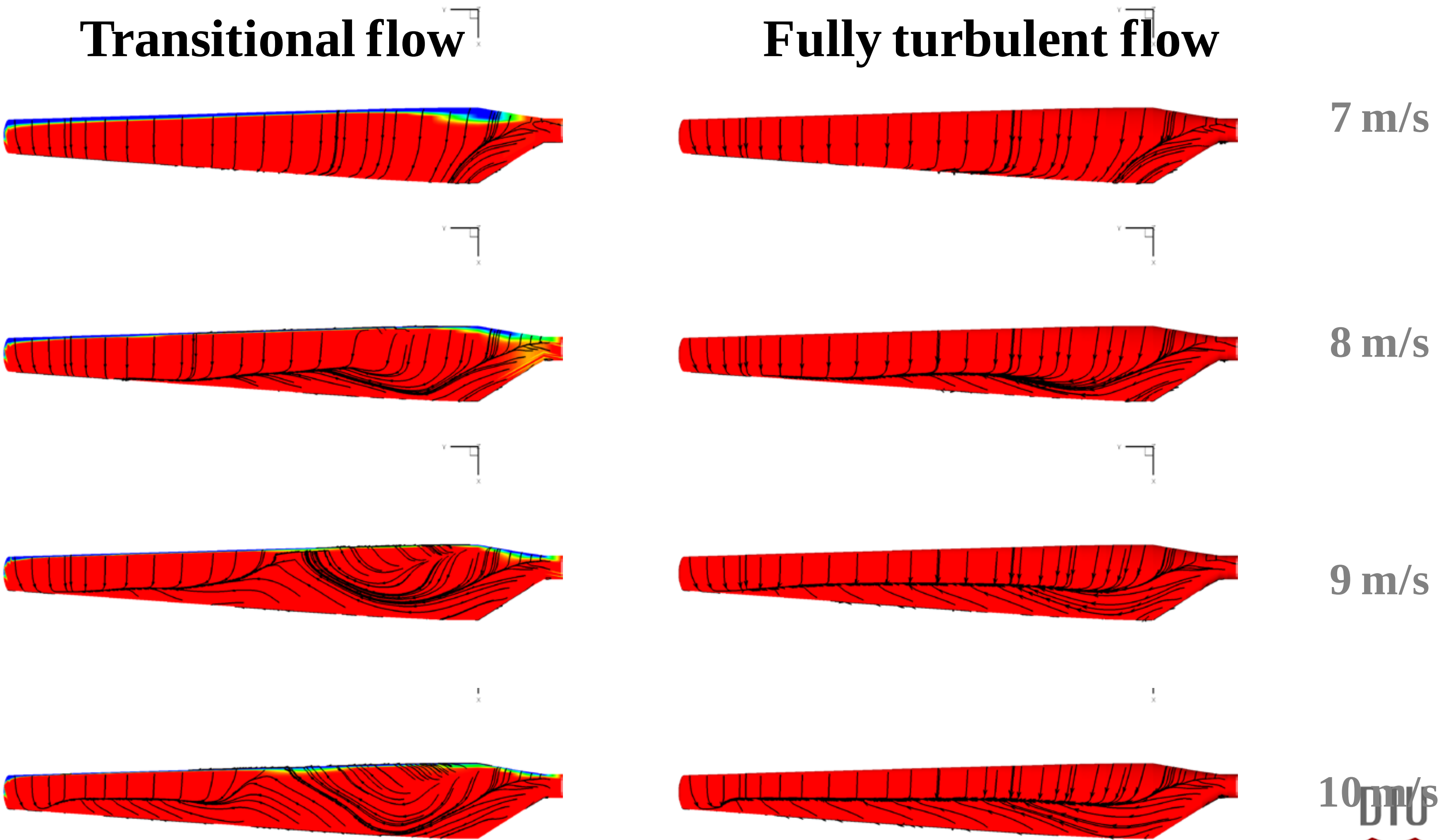
CFD: The Numerical Wind Tunnel

Turbulence modeling

- **0-Equation models: Prandtl, Cebei-Smith, Baldwin-Lomax**
- **1-Equation model: Spalart-Allmaras, Baldwin-Barth**
- **2-Equation model: K-Epsilon, K-Omega, K-Omega SST**
- **Reynolds stress models**
- **Sub-grid scale models (LES)**
- **Combining LES and RANS: Detached Eddy Simulation**

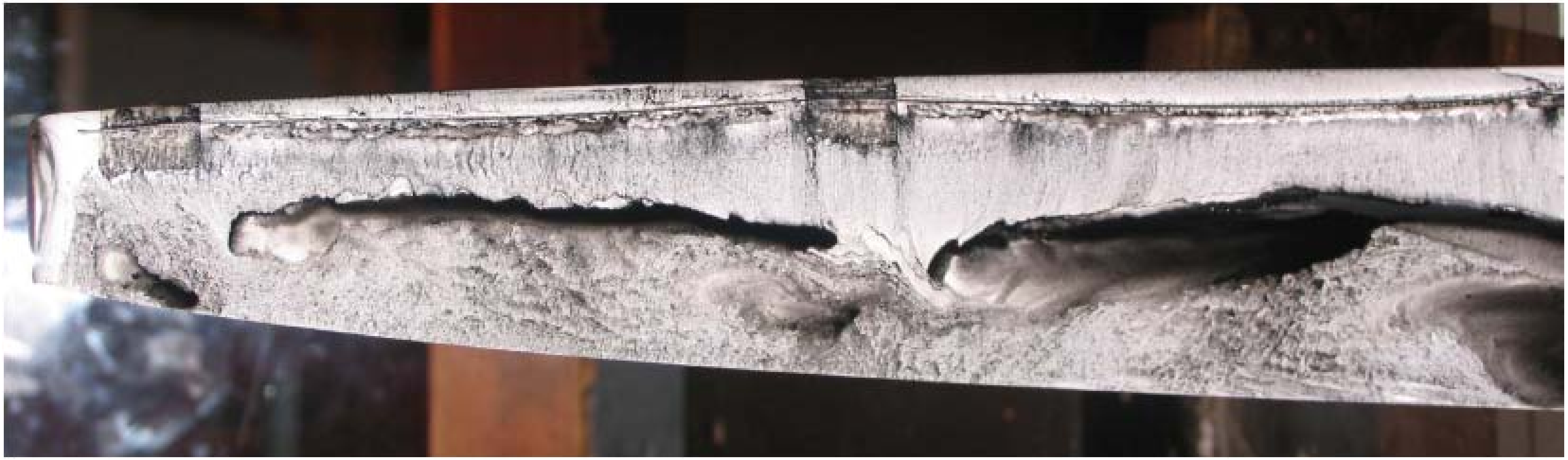
CFD: The Numerical Wind Tunnel

Transition modeling

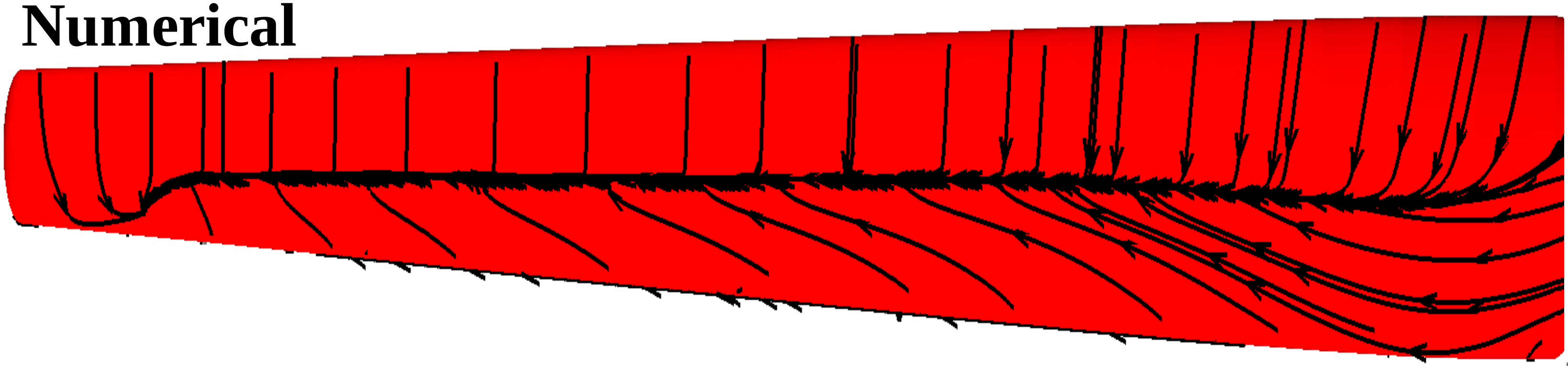


Validation: CFD and Experiment

Experimental



Numerical



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EllipSys3D

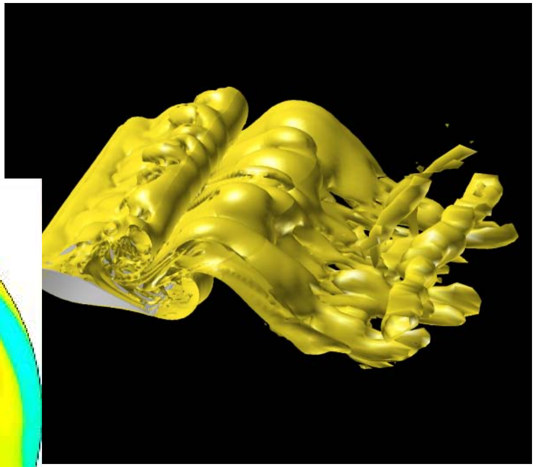
Developed in collaboration between DTU and Risø

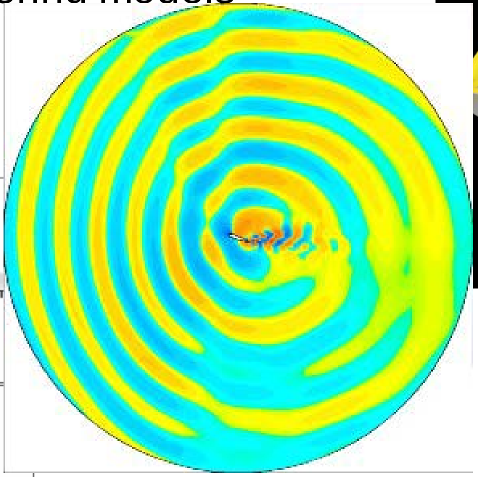
- **Incompressible Navier-Stokes, 2D and 3D**
- **Block structured – Multi block / Multi grid**
- **Parallelized using MPI – Up to 50 million mesh points possible today**
- **Turbulence models: K-ε, K-ω, DES, LES, 3D Transition**
- **Yggdrasil (DTU): 210 CPU's**

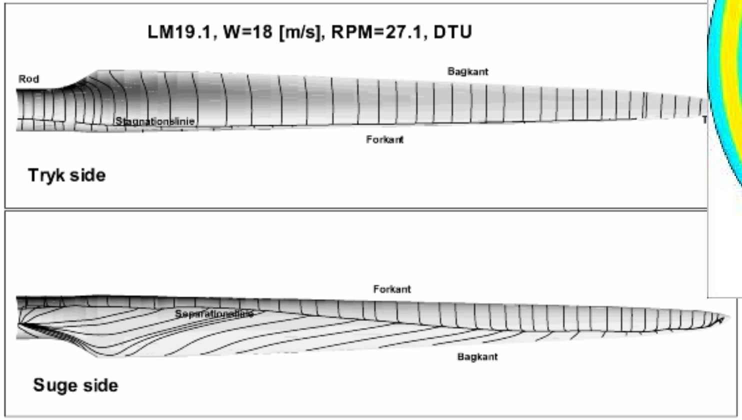
The Numerical Wind Tunnel (*EllipSys*)

Developed in close collaboration between DTU and Risø with the aim of:

- Optimizing rotors with respect to performance and noise
- Analysing existing designs
- Verification of simple engineering models
- Gain physical understanding

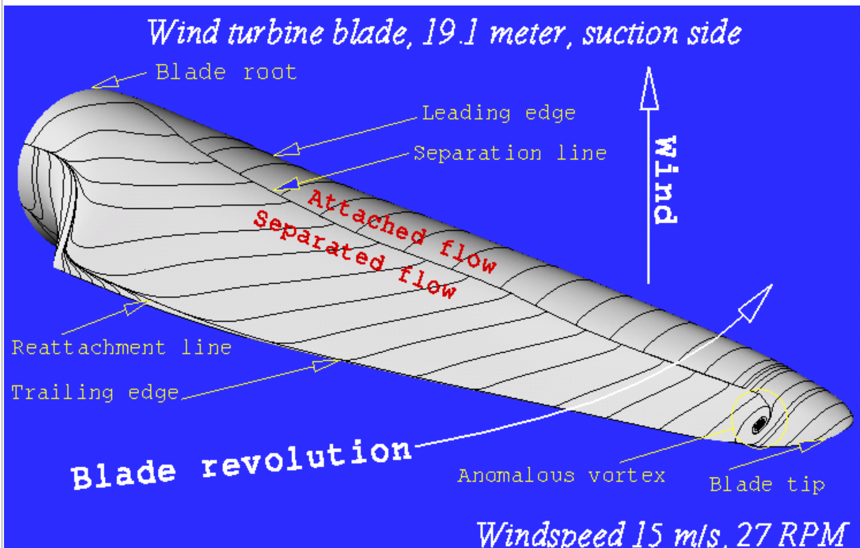


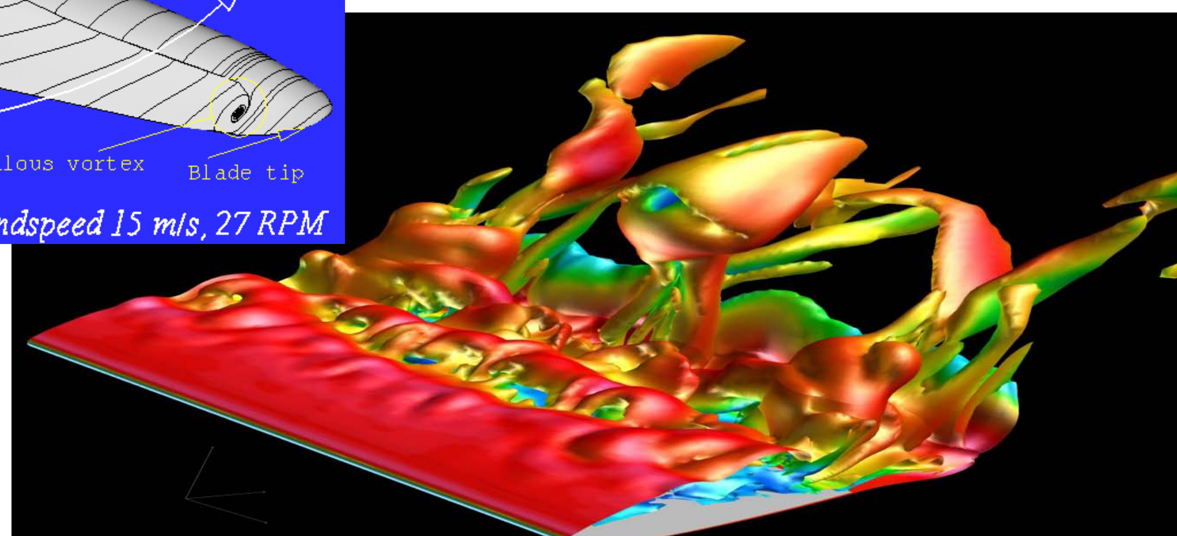




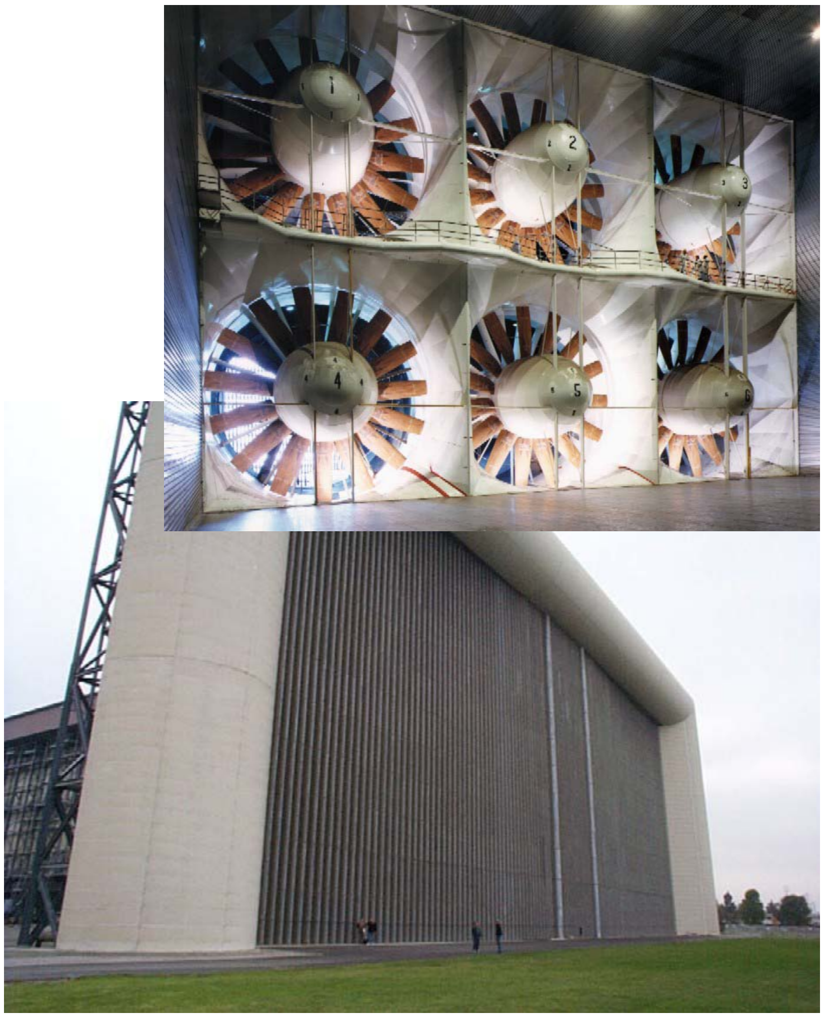
The Numerical Wind Tunnel

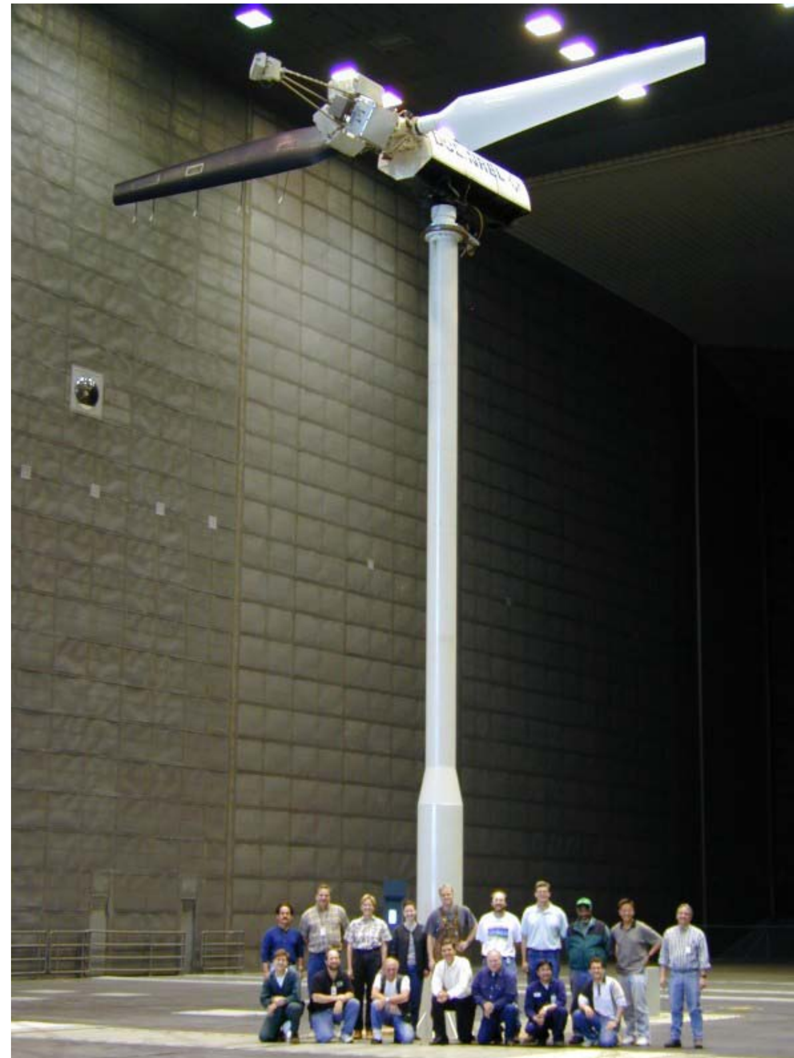
Wind Turbine Aerodynamics:





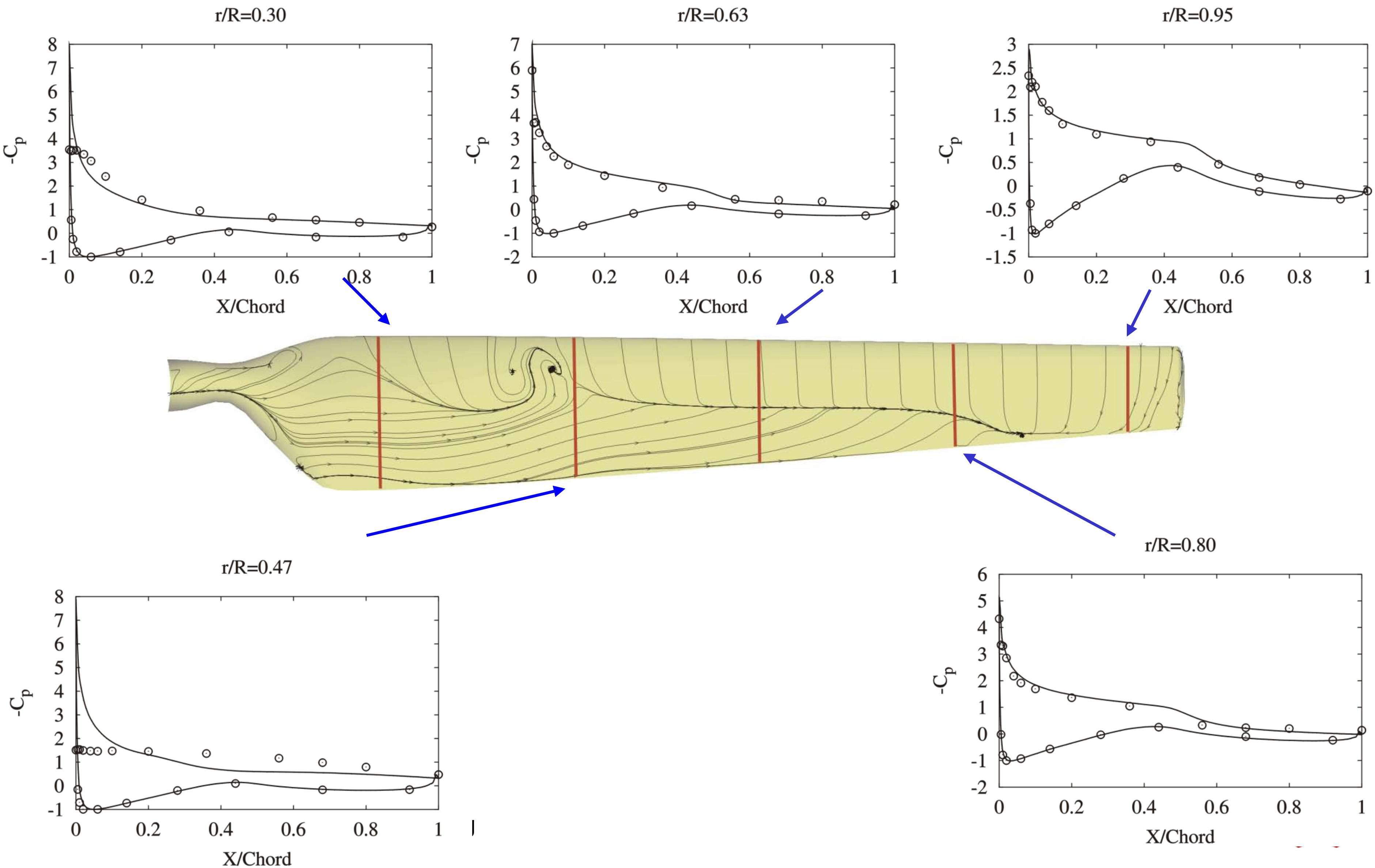
NASA Ames Tunnel (24.4x36.6 m)





Pressure Distributions at 10 m/s

(Courtesy: Niels N. Sørensen, Risø)



Aerodynamic Computations

Requirements for Direct Navier-Stokes computations:

Smallest turbulent length scale: ℓ
Largest geometrical length scale: L

Estimate based on scales:

$L/\ell \approx Re^{**}(3/4)$

Reynolds Number: $Re=L \cdot U/\nu$,
where

L: Length of object
U: Typical velocity
ν: Kinematic viscosity

Number of mesh points: $N \approx (L/\ell)^{**}3 = Re^{**}(9/4)$

Typically Re = O(10**6) - O(10**7), thus N = O(10**15)

Computing performance is generally 10-doubled every 5 years, hence full DNS simulations can be anticipated in about (15-8) x 5 = 35 years.

Rotor Aerodynamics

CFD models

- **Viscous-Inviscid Interaction (VII)**
- **Reynolds Averaged Navier-Stokes (RANS)**
- **Unsteady Averaged Navier-Stokes (URANS)**
- **Detached Eddy Simulation (DES)**
- **Large Eddy Simulation (LES)**
- **Actuator Disc/Line - LES (AD/L-LES)**

Aerodynamic Computations

Airfoil aerodynamics:

	No. Mesh points	CPU-time	Range of applicability	Comments
VII	O(100)	< 10s	2D- steady	Stall not well captured
RANS	O(10**5)	< 1h	2D-steady	- do -
URANS	O(10**6)	< 10h	2D-unsteady	- do -
DES	O(10**7)	< 1-2 days	3D-unsteady	Deep stall not well captured
LES	O(10**7)	< 1 week	3D-unsteady	Deep stall not well captured
LES	O(10**8)	< 1 month	3D-unsteady	Full polar

Aerodynamic Computations

Rotor aerodynamics:

	No. Mesh points	CPU-time	Comments
BEM	O(50)	< 0.1 s	Based on airfoil data
Lifting Line	O(10**4)	< 1 min	- do -
Lifting Surface	O(10**6)	< 10 h	Inviscid
RANS	O(10**6)	< 10 h	Stall not well captured
URANS/DES	O(10**8)	< 1 week	Deep stall not well captured
LES	O(10**15)	N/A	Full polar

Aerodynamic Computations

Wakes and clusters:

	No. Mesh points	CPU-time	Comments
PNS	O(10**6)	< 1h	Both axisymm. and 3D
AD-NS	O(10**5)	< 1h	Polar coordinates
RANS	O(10**7)	< 10h	Steady
DES	O(10**9)	< 1 month	3D-Unsteady
AL-LES	O(10**8)	< 1 week	Airfoil data required
LES	O(10**18)	N/A	3D-unsteady