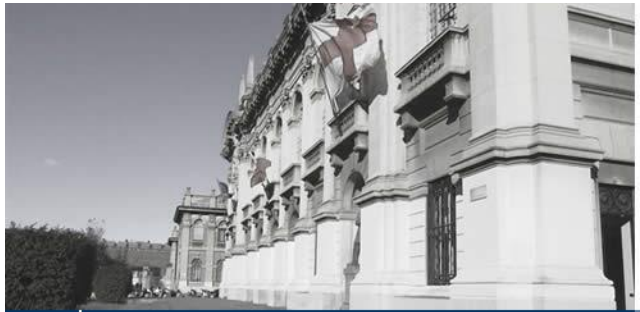


DIPARTIMENTO DI MECCANICA

POLITECNICO DI MILANO





OpenFOAM in Wind Energy: Wind Turbines as a source term

Paolo Schito, Luca Bernini, Alberto Zasso

Analysis of Wind Turbine

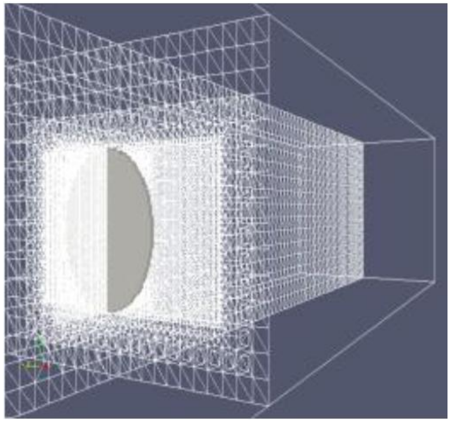
Wind turbine aerodynamics simulation is an important task for develop future bigger wind farm and bigger and more powerful wind turbines.

Actually three main CFD methods of analysis are available.

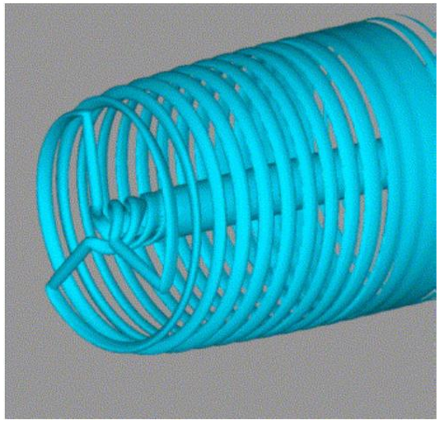
CFD Simulation Type

- **Actuator Disk(AD)**
- **Actuator Line(AL)**
- **Fully resolved blade profile model(FR)**

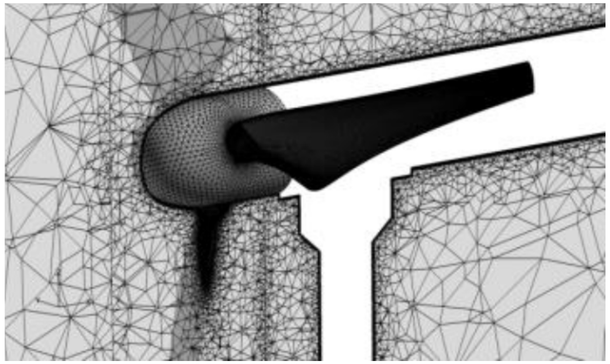
Increasing computational cost



AD



AL



FR

Analysis of Wind Turbine

Chosen method

Analysis type	PRO	CONS
Actuator Disk(AD)	• Simple model. • Few input parameter. • Very low computational cost	• Can't reproduce not-stationary wake structure.
Actuator Line(AL)	• Can potential reproduce detailed wake structure. • Low computational cost	• Input parameter are difficult to handle. • Relay on airfoil tabulated data.
Fully resolved blade profile model(FR)	• Best model in wake reproduction. • Don't relay on airfoil tabulated Data.	• Very high computational cost and correct CFD meshing effort

AL methods seems a good compromise between computational cost and loads prediction-wake reproduction ability

Analysis of Wind Turbine

Scientific and industrial world require accuracy on two different parameter:

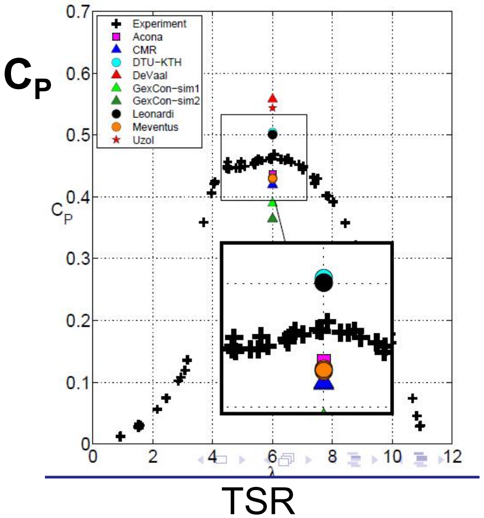
- **Loads on turbine**
- **Turbine generated wake**

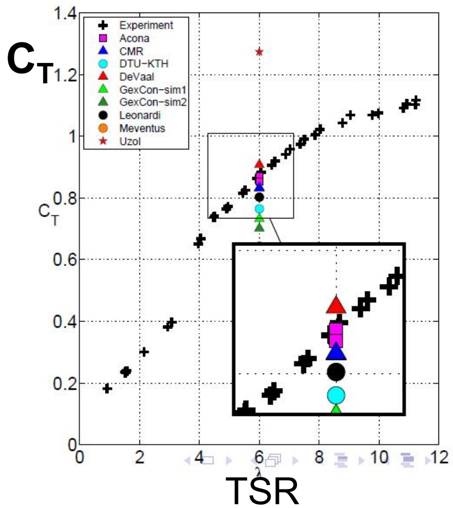
Different study and blind test analysis have been performed to evaluate the level of accuracy of different wind turbine simulation methods AD, AL and FR.

Looking in particular at results from *NORCOWE & NOWITECH* bt1&bt2, it was found that "*Most models are good only at one thing at once*" [F. Pierella, Blind Test 2 calculations, 2013] , and in IEA TASK 29 MexNext conclusion "*none of the calculations from the Mexnext group can predict both the velocities AND loads in a correct way*".

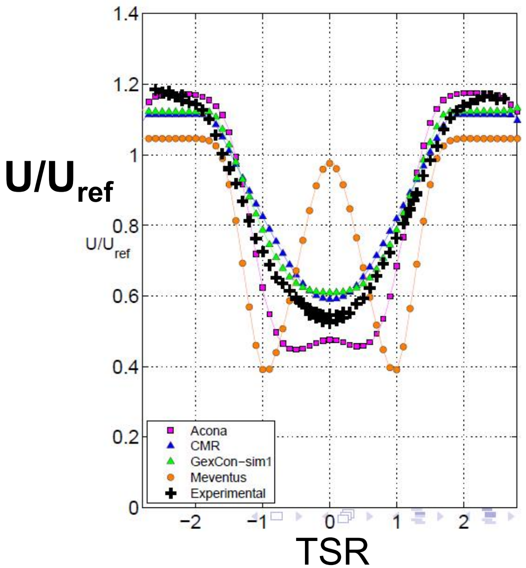
Analysis of Wind Turbine

[F. Pierella, Blind Test 2 calculations]





Cp and Ct predicted value from blind test are very sparse. No AL *(circle-symbol series)* model can't predict one or both parameter with the smallest error



Also wake deficit velocity value aren't reproduced with low error. AL model *(orange series)* is one of the worse in this comparison

SUMMARY

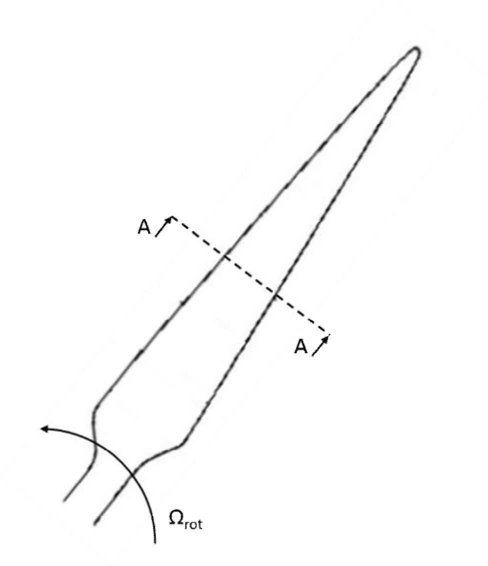
- 2D ANALYSIS OF ACTUATOR FORCES
- 2D DEVELOPENT OF EFFECTIVE VELOCITY MODEL
- 3D ACTUATOR LINE IMPLEMENTATION
- COMPARISON WITH THE DATA FROM A WIND TUNNELSCALED MODEL WIND TURBINE
- COMPARISON WITH BEM COMPUTATIONS
- CONCLUSIONS

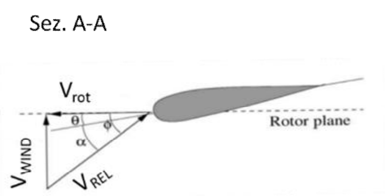
Analysis of Wind Turbine

The cited blind test showed how FR model are actually most accurate in “a priori” simulation (without the possibility to have an experimental benchmark for setting up the input parameter) on the other hand AL model have a lot a critic aspects connected to the numerous input parameter needed by these model.

It is necessary to investigate if it is possible to correctly simulate a real turbine blade with AL methods.

The first step in AL methods analysis can be done looking at the generic blade section





Blade section is a generic tabulated airfoil defined by turbine characteristics.

Blade loads and wake can be correctly modeled if it is possible to model every section of the blade itself

Actuator Force Model

Using as benchmark a fully resolved airfoil (FRA) profile simulation, a **2D simulation with a force source** instead of the airfoil shape was performed, this simulation can be called Actuator Force (AF) methods, being the application of AL methods on a single blade section and thus on a single force point.

About this AF methods two question arise:

1. **If the correct force is inserted, the wake generated is similar to FRA one?**

2. **Is it possible to correctly estimate the force to be inserted for every angle of attack from the velocity fields near the airfoil position?**

- **AF vs FRA comparison**

Fully resolved airfoil and AF model equivalence is tested on stationary 2D flow .

Physical equation

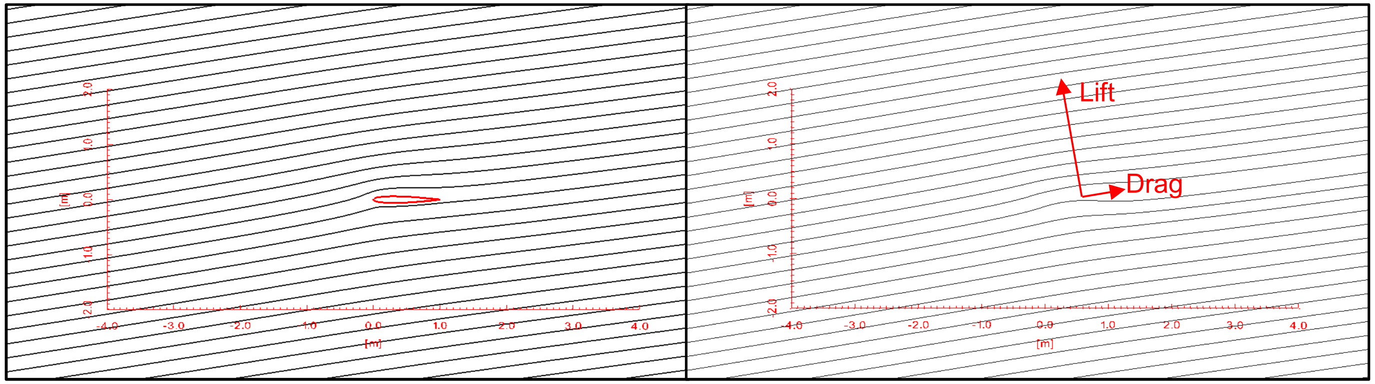
FRA

$$\nabla \cdot \rho \boldsymbol{UU} - \nabla \cdot \mu \nabla \boldsymbol{U} = -\nabla \mathrm{p}$$
$$\nabla \cdot \boldsymbol{U} = 0$$
$$\boldsymbol{U}_{\boldsymbol{airfoil\,wall}} = 0$$

AF

$$\nabla \cdot \rho \boldsymbol{UU} - \nabla \cdot \mu \nabla \boldsymbol{U} + \boldsymbol{f} = -\nabla \mathrm{p}$$
$$\nabla \cdot \boldsymbol{U} = 0$$
$$\boldsymbol{f} = airfoil\ aerodynamic\ force$$

$$\boldsymbol{f} = \int_{\boldsymbol{airfoil\,wall}} (\boldsymbol{p} * \overline{\boldsymbol{n}} + \boldsymbol{\tau} * \overline{\boldsymbol{t}}) * \boldsymbol{ds}$$



- **AF vs FRA comparison**

Solver equation

FRA

$$\nabla \cdot \rho \overline{\boldsymbol{U}}\,\overline{\boldsymbol{U}} - \nabla \cdot \left((\mu + \mu_t)\nabla \overline{\boldsymbol{U}}\right) = -\nabla p$$
$$\nabla \cdot \overline{\boldsymbol{U}} = 0$$
$$\mu_t \rightarrow eddy\ viscosity$$
$$\overline{\boldsymbol{U}}_{\boldsymbol{airfoil\,wall}} = 0$$

```
tmp<fvVectorMatrix> UEqn
    (
      fvm::div(phi, U)
    + turbulence->divDevReff(U)
    ==
      fvOptions(U)
    );
    fvOptions.constrain(UEqn());
    solve(UEqn() == -fvc::grad(p));
```

AF

$$\nabla \cdot \rho \overline{\boldsymbol{U}}\,\overline{\boldsymbol{U}} - \nabla \cdot \left((\mu + \mu_t)\nabla \overline{\boldsymbol{U}}\right) + \boldsymbol{f} = -\nabla p$$
$$\nabla \cdot \overline{\boldsymbol{U}} = 0$$
$$\mu_t \rightarrow eddy\ viscosity$$
$$\boldsymbol{f} = airfoil\ aerodynamic\ force$$

```
tmp<fvVectorMatrix> UEqn
    (
      fvm::div(phi, U)
    + turbulence->divDevReff(U)
    + volumeForce
    ==
      fvOptions(U)
    );
    fvOptions.constrain(UEqn());
    solve(UEqn() == -fvc::grad(p));
```

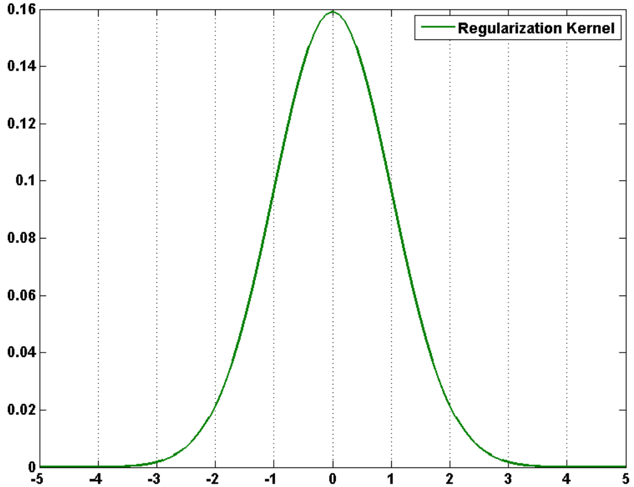
k – ω SST turbulence model is used for both FRA and AF simulation

- **<u>AF vs FRA comparison</u>**

As reported in several previous works (Sorensen,2002; Troldborg,2008) **the AF aerodynamic forces need to be distributed smoothly on several mesh points in order to avoid singular behaviour**. In practice the aerodynamic blade forces are spatially distributed with a 2-dimensional normal distribution

$$f(x) = \frac{1}{\sqrt{(2\pi)^2 \cdot \epsilon^4}} \cdot e^{-\frac{1}{2}\cdot\frac{d^2}{\epsilon^2}}$$

In this work εisfixequal to one time the length of computational mesh for avoid numerical spatial oscillation.



$f(x)$

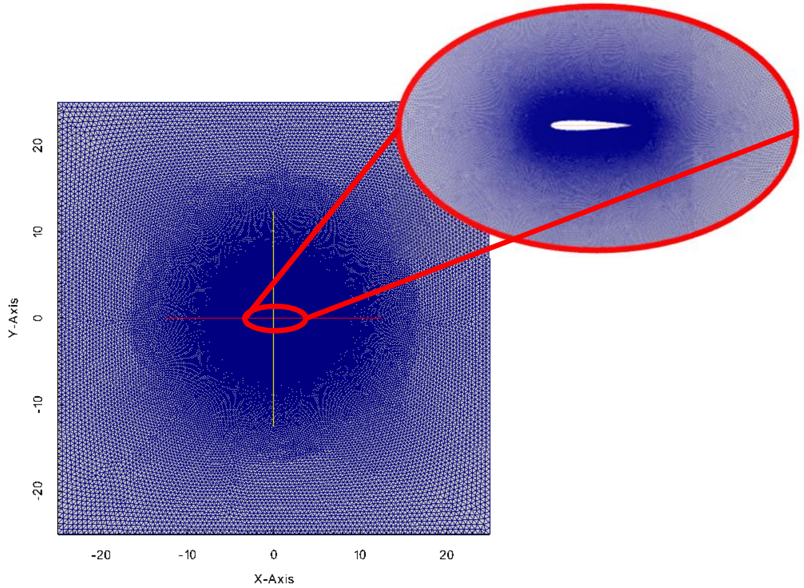
Mesh cells

Actuator Force Model

- **AF vs FRA comparison**

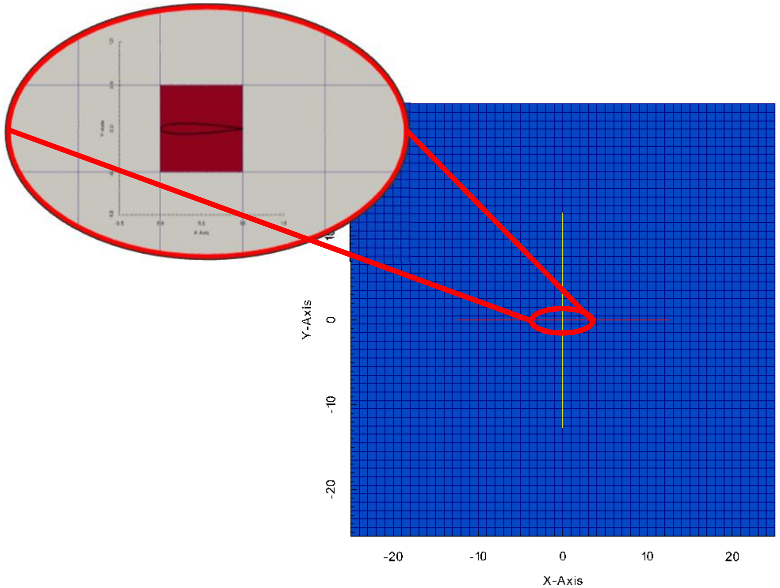
Mesh Structure

FRA



- 50*50m domain
- 430’000 cells (100 grid points along the airfoil chord)
- Chord length=1m

AF



- 50*50m domain
- 2500 cells
- Cell length=1m

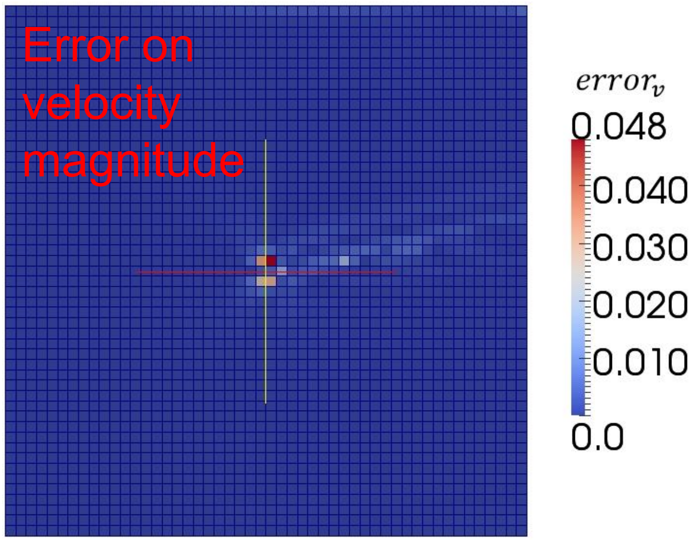
Actuator Force Model

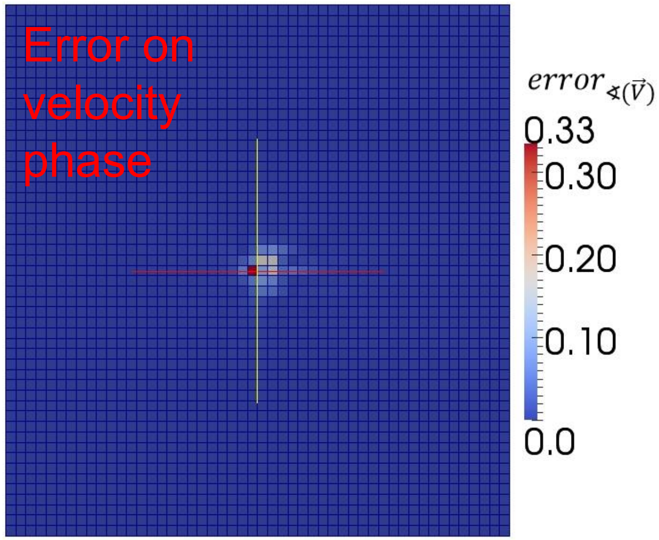
- **<u>AF vs FRA comparison</u>**

  Fixed boundary inflow condition (V_∞magnitude=10m/s; V_∞ phase=10°)

$$error_v^i = \left|\frac{\left(V_{AF}^i - V_{FRA}^i\right)}{V_{FRA}^i}\right|$$

$$error_{\sphericalangle(\vec{V})}^i = \left|\frac{\left(\sphericalangle\vec{V}_{AF}^i - \sphericalangle\vec{V}_{FRA}^i\right)}{\sphericalangle\vec{V}_{FRA}^i}\right|$$





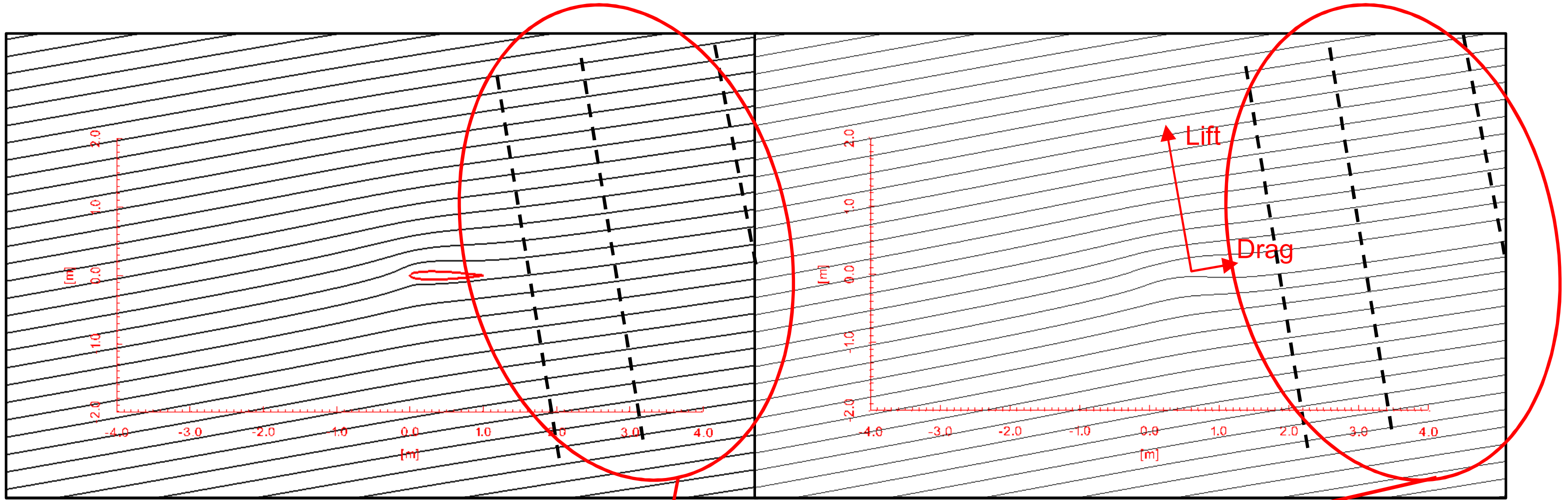
Computed velocity difference form FRA and AF simulation are globally small and increase only very near to AF force application force.

If the <u>correct force</u> is inserted velocity fields can be reproduced correctly

Actuator Force Model

- **<u>AF vs FRA comparison</u>**

More important the airfoil wake generated by AF model is very close to the one generated by FRA model

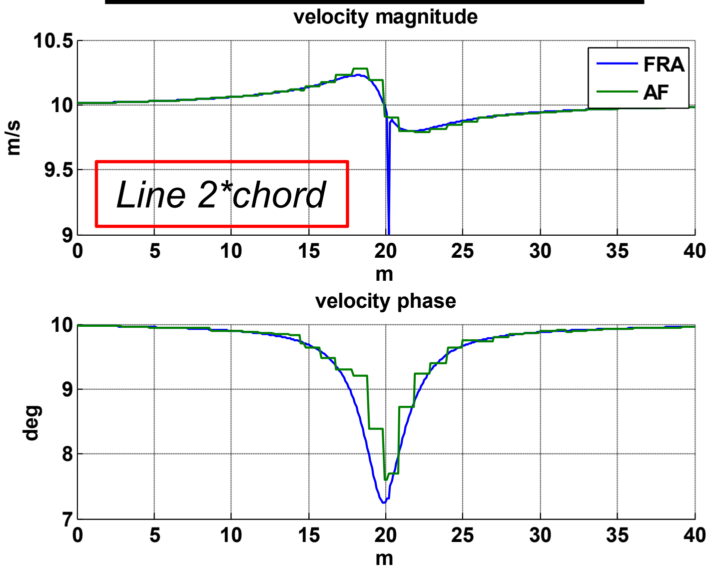


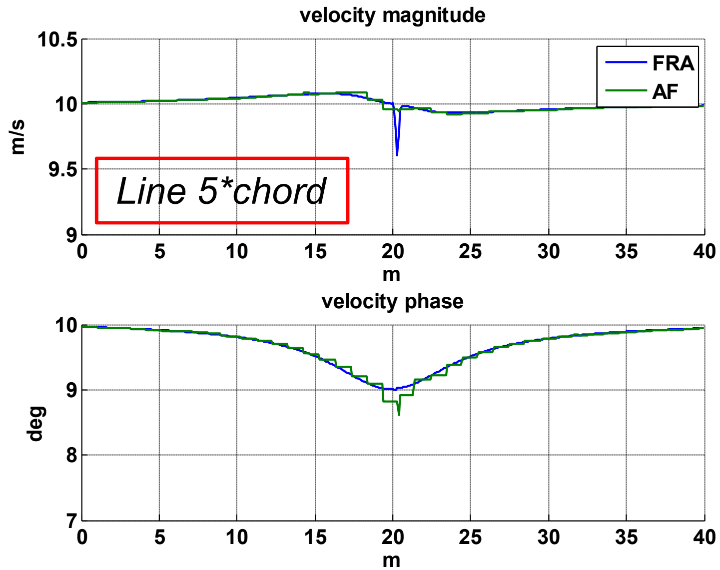
Velocity field sampling lines placed:

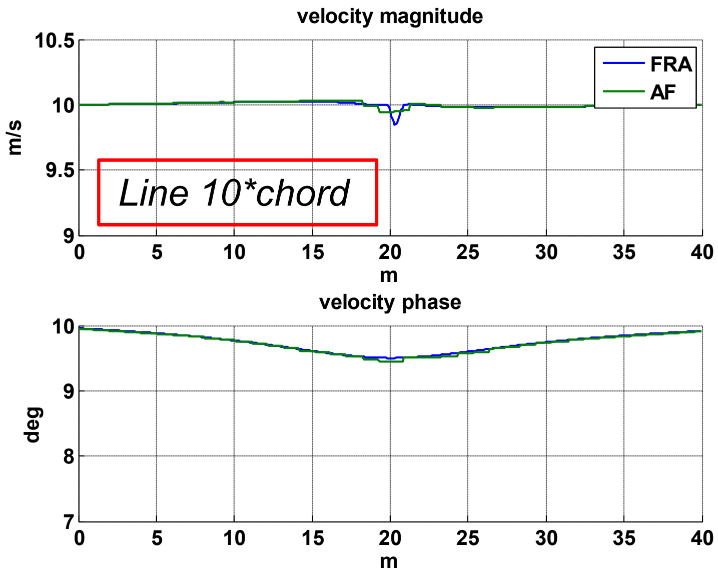
- 2*chord; 5*chord; 10*chord *(airfoil chord=AF cell length=1m)*

FRA and AF wake are compared on these sampling lines for testing their effective equivalence

- **<u>AF vs FRA comparison</u>**







Actuator Force Model

- **AF force prediction with EVM**

It was showed that, knowing the correct force to insert, AF results can be very close to Fully Resolved airfoil shape ones.

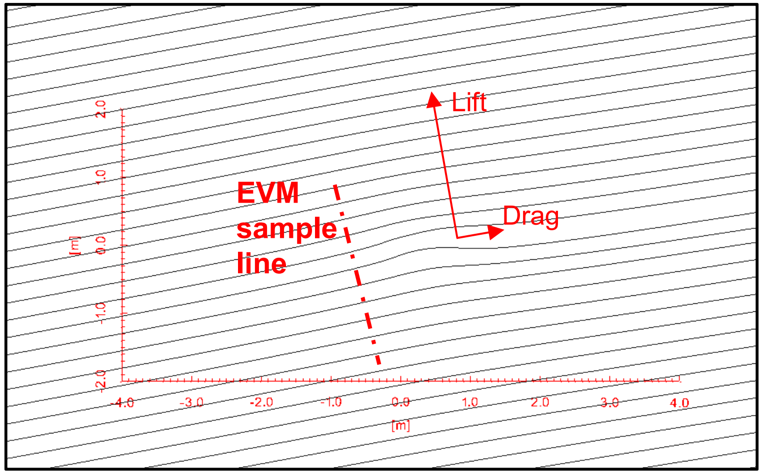
It is now necessary to study a methods for finding the correct force at runtime and not from Fully Resolved benchmark simulation.

In most AL models like Troldborg, Leonardi and Churchfield ones the force to be inserted in AL is calculated by tabulated airfoil polar curves using as reference the flow velocity in the exact point of force insertion, this method will be called **local reference velocity**.

In our code we propose an innovative method that sample the blade incoming wind characteristics on multiple point and after an average extrapolate the reference velocity to be used in airfoil polar table lookup, this method will be called **EVM reference velocity**.

Effective velocity model

- **AF force prediction with EVM**



Considering a generic section of a wind turbine blade, the velocity field is investigated along a sample line very close to the AF force point position.

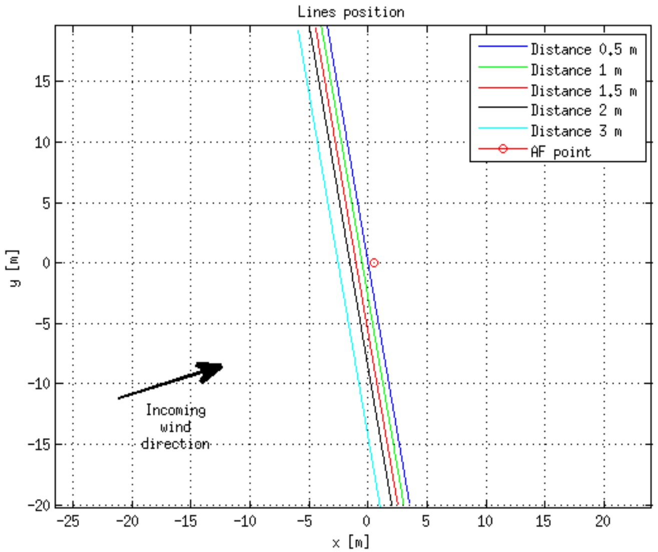
The line is chosen to be perpendicular to relative velocity direction placed some distance upstream the force point.

The velocity sampled on line is then averaged and a correction due to local up-wash generated by applied force vortex circulation is applied.

Effective velocity model

- **<u>AF force prediction with EVM</u>**

The tuning of EVM sample line position and length is based on the equality of FRA flow and AF flow.



Different possible sample line are placed at multiple distance from AF force application force.

Velocity fields from FRA and AF simulation are almost equal apart from the area very close to the airfoil.

The line was selected as a compromise between keeping it the shortest and nearest to airfoil and don't placing it in the region where the velocity computed by the two simulation show significant discrepancy

Effective velocity model

- <u>**AF force prediction with EVM**</u>

EVM sample line is, like regularization kernel, an AF methods numerical tool, and, like regularization kernel, its parameters are defined as a function of the computational cell length:

Line distance Upwind	**1*cell length**
Line length	**5*cell length**

The difference between sampled velocity angle and angle imposed as boundary condition (α_∞ = angle of attack AOA) has been analyzed for this EVM parameters.

To quantify the $\Delta\alpha$ correction a series of test was made considering a large variation for all the influential parameters:

- C_l, C_d aerodynamic coefficient
- Modelled airfoil chord length (c)
- Computational cell length (M)

Effective velocity model

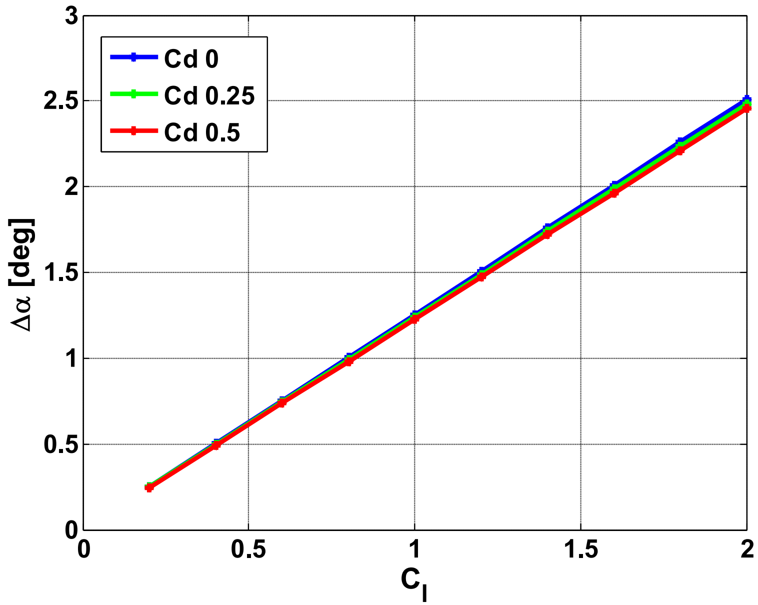
- **AF force prediction with EVM**

The following evidences have been found

- **Δα(C_l) is a linear function;**
- **the correction depends primarily by C_l**, but the influence of C_d is clearly visible, as an alteration of the slope of Δα (C_l) line;
- **the non-dimensional ratio c/M impact linearly to the Δα value**.

Hence this is the proposed correction:

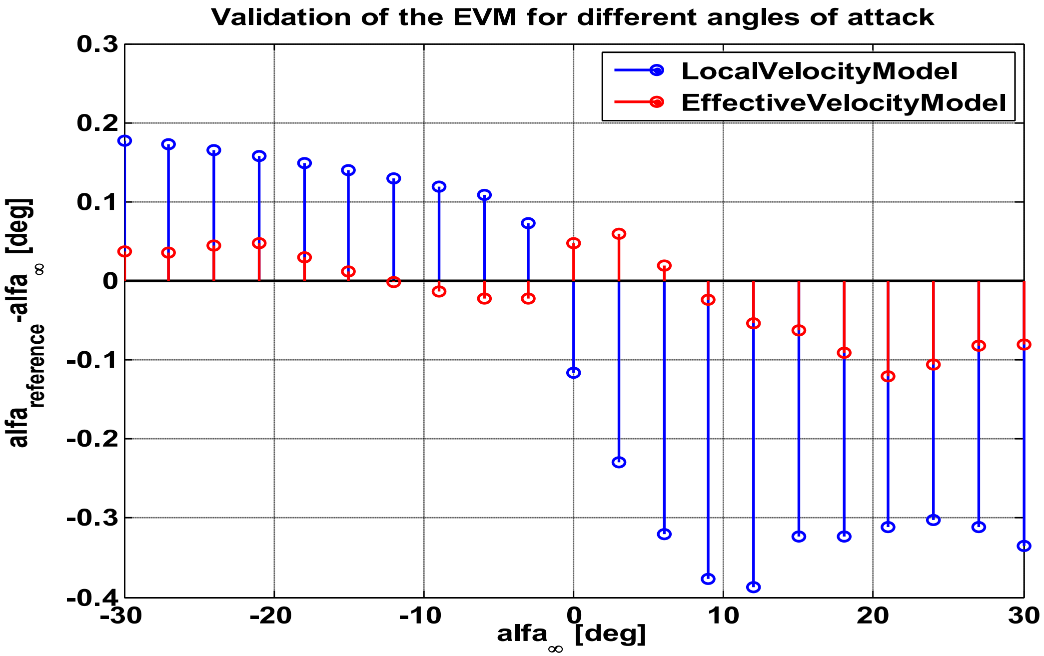
$$\Delta\alpha = \alpha_{\text{EVM sample line}} - \text{AOA} = {}^{c}/_{M} \cdot (1.25\,5\,3 - 0.0\,5\,5\,2\,C_d)\,C_l$$



Effective velocity model

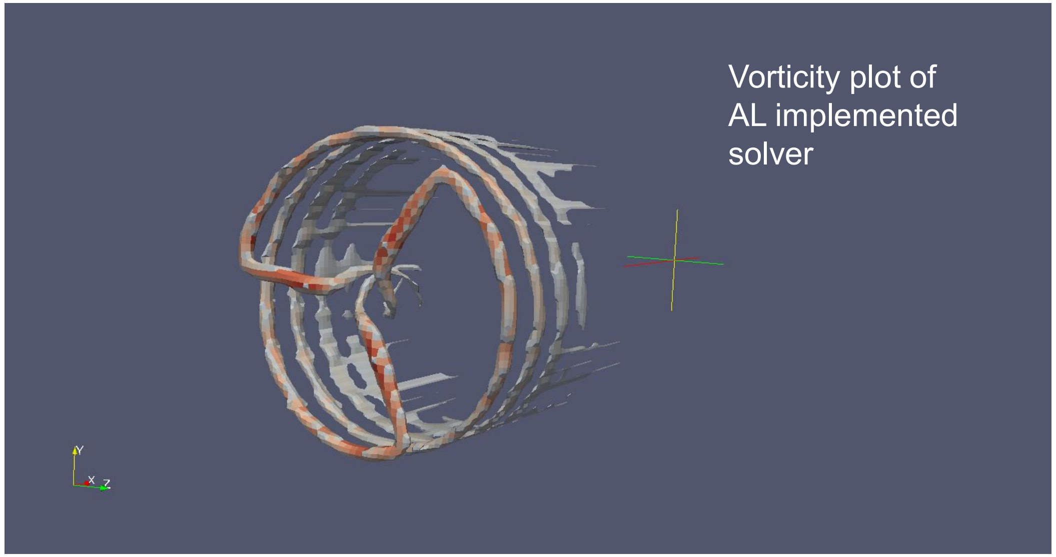
- **AF force prediction with EVM**

EVM ability to correctly output the effective velocity and AOA are compared with local reference velocity method in stationary flow for different angle of attack imposed as simulation boundary condition.



For both reference velocity evaluating methods the error remains small for every AOA, EVM works a little better

AL implementation



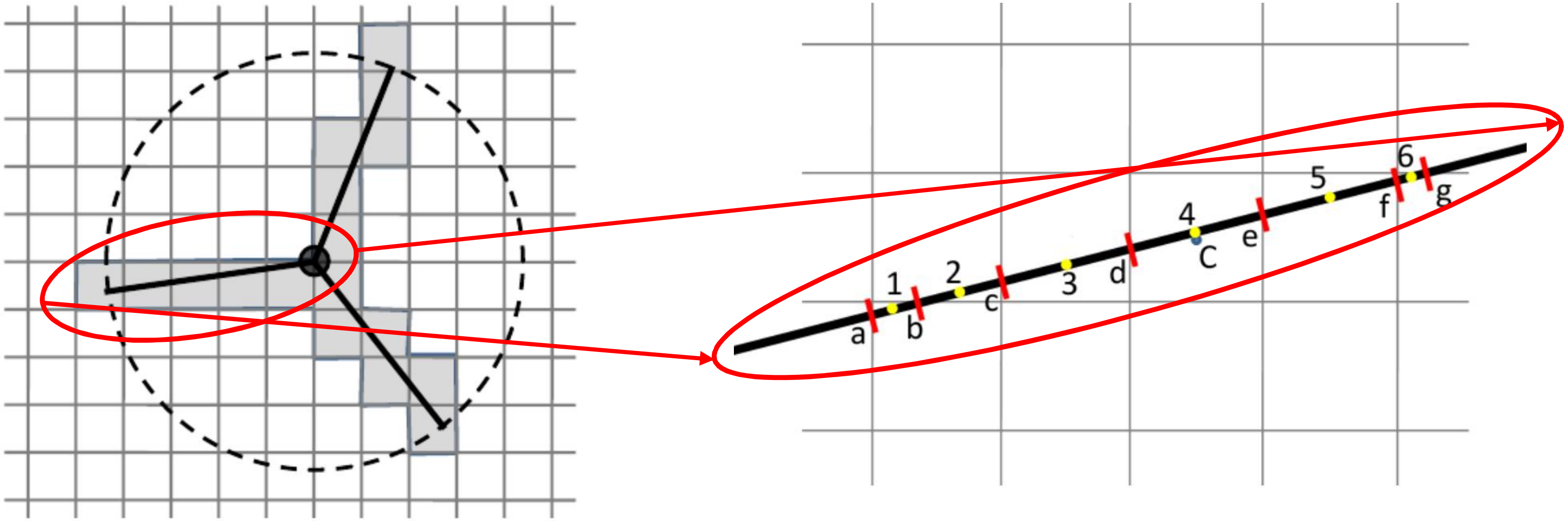
At this point it was showed that **it is possible to correctly simulate a Fully Resolved Airfoil** with an equivalent source force both in term of loads and wake reproduction.

The 2 dimensional EVM set up is utilized as foundation for correctly evaluate AL line forces from incoming velocity fields.

It is expected that this method, tuned in 2 dimension, can correctly work also in 3 dimensional wind turbine using an AL model.

AL implementation

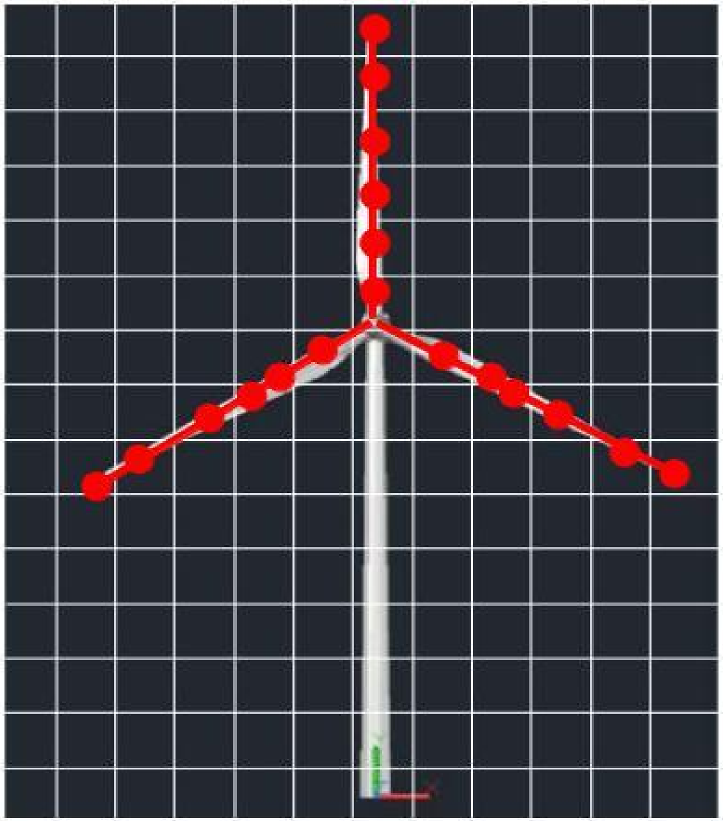
The turbine blade is modelled as one lifting line, the line is the divided in segment based on line-mesh intersection.



Every line section have to model a generic blade section

Blade section → airfoil profile → AF model

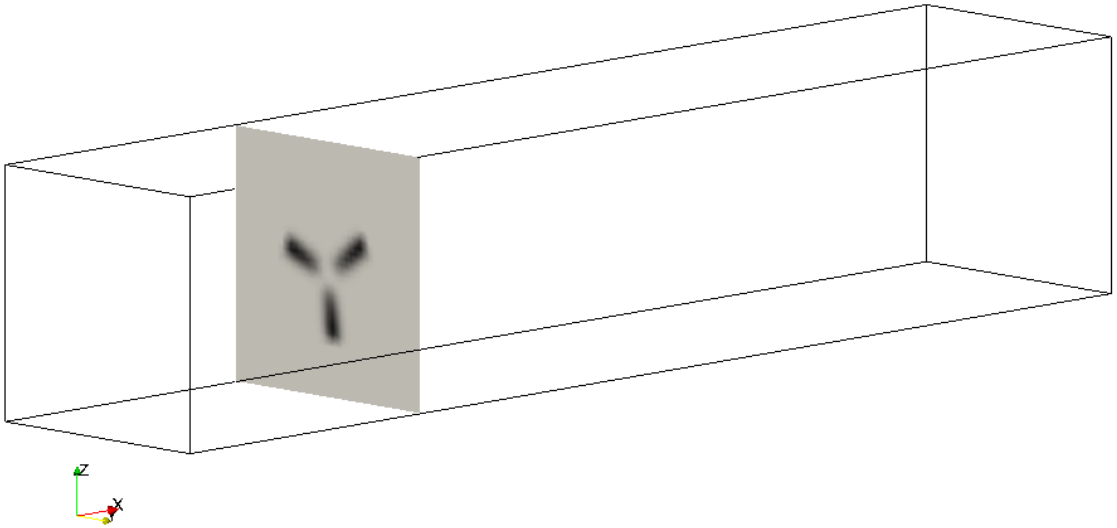
Simulation of an horizontal axis wind turbine.
New solver based on a modified PISO version:
Actuator Line model
+
Effective Velocity Model

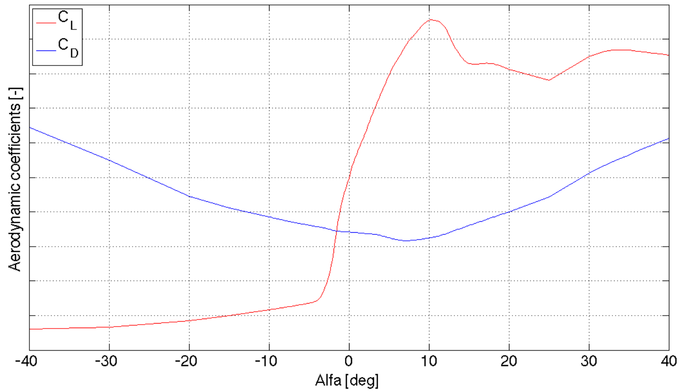


-New class *intersectionData* is used to find the AL points, giving as input the hub and the blade tip positions run-time updated it found every intersection with computational mesh. **The AL force distribution resolution in directly linked to mesh refinement level**.

-*turbineProperties* dictionary contains all the data about the turbine. The data about the blades are discretized for different radial positions and correspondent information about chord length, twist angle and airfoil type are provided.

Simulation of an horizontal axis wind turbine.
New solver based on a modified PISO version:
Actuator Line model
+
Effective Velocity Model





-**Aerodynamic forces** computed via look-up tables (*turbineProperties*, *airfoilProperties* dictionaries) and investigating the velocity field in AL points.
-**Regularization kernel** used to avoid numerical oscillations.

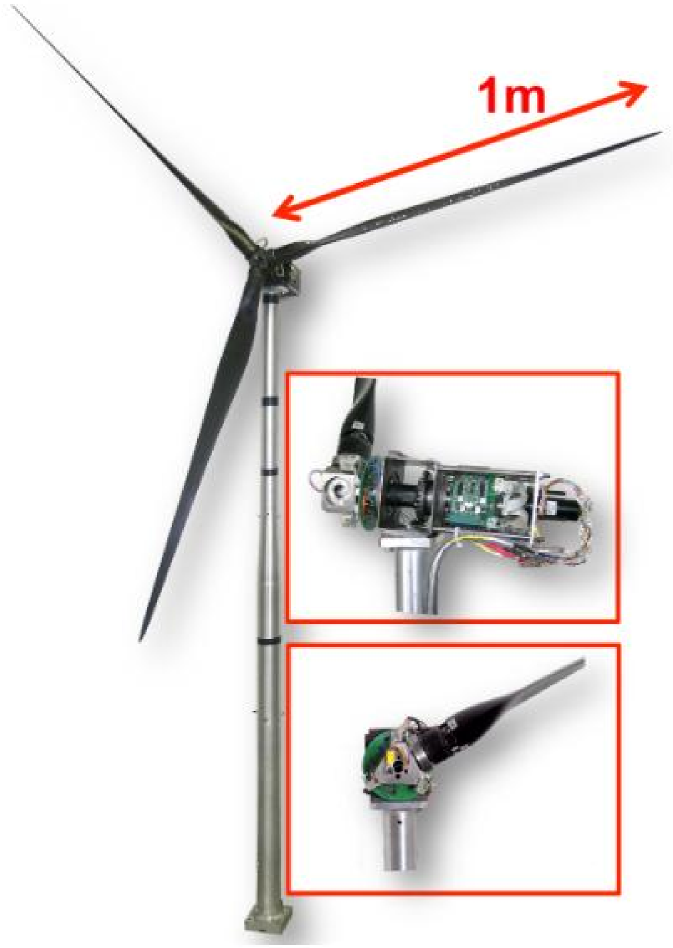
Tested case

Scaled model of a ***Vestas V90*** wind turbine:
- 3-bladed horizontal axis wind turbine.
- 2 m rotor diameter.
- Hub height 1.9 m.

WIND TURBINE MODEL

- Rigid – Aeroelastic Blades
- Pitch Actuator
- Torque Actuator
- Pitch Control Unit
- Torque Control Unit
- Blade Strain Gauges
- Main Shaft Torque Gauges
- Pylon Base Forces and Moments

Possibility for RealTime Control



Tested in 2011 at Politecnico di Milano, Wind Tunnel by C.L. Bottasso and F. Campagnolo (Aerospace Engineering Department).

Tested case

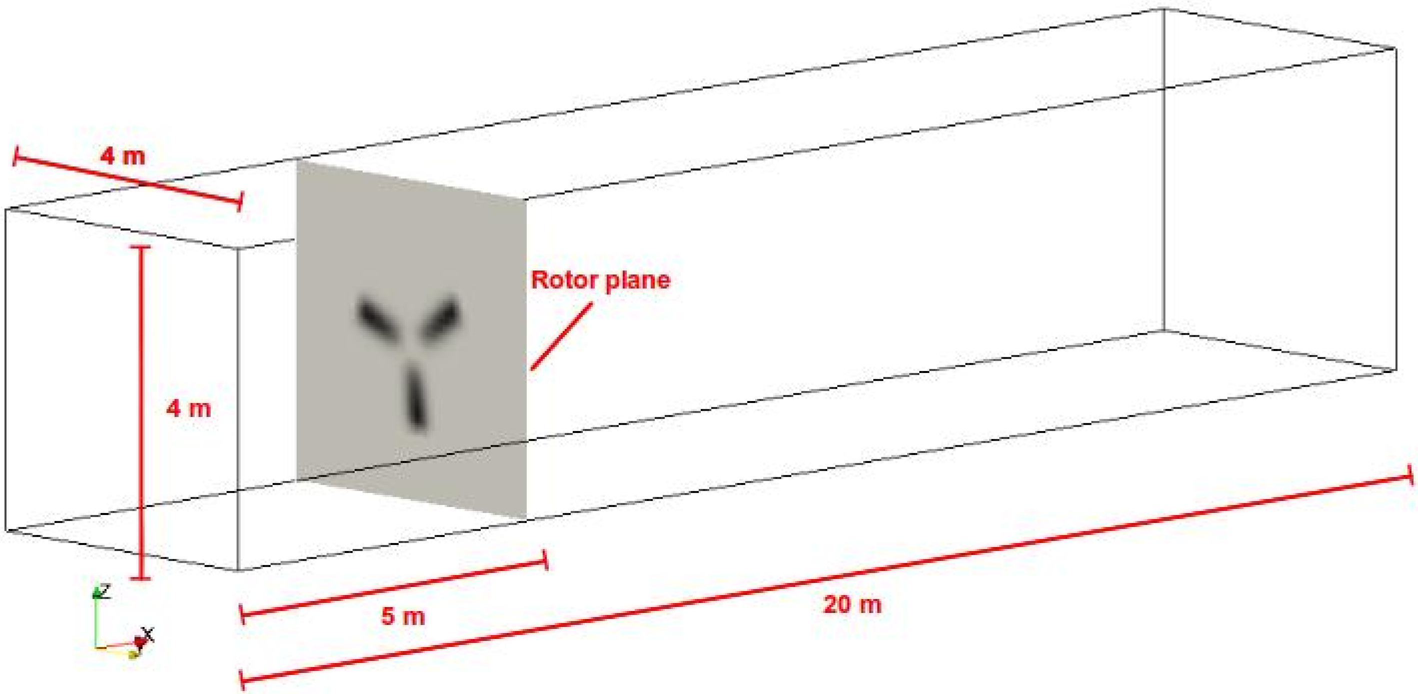
Computational domain reproducing the high-speed duct of the Wind Tunnel:

-Section: 4 x 4 m.

-Length: 20 m.

-Structured mesh adopted: cubic cells (0.1 m side dimension) → ≈ 20 grid cells across the rotor diameter .

-Also finer mesh tested (0.05 m in side dimension) → ≈ 40 grid cells across the rotor diameter.



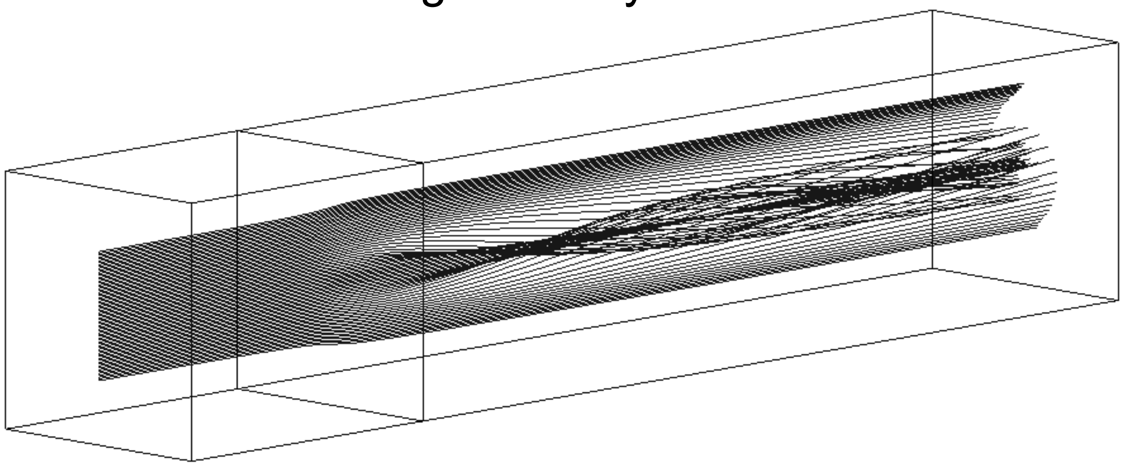
-**Regularization kernel** width parameter ε is set equal to the characteristic mesh.

Tested case

Boundary conditions:
-Lateral sides (sky, ground, sides) → walls.
-Inlet and outlet sections.

Initial conditions:
-Uniform flow at the inlet.
-Different TSRs have been tested.

Turbulence:
-LES approach.
-Smagorinsky model.
-No turbulence is created at the surfaces, turbulent eddies due to interaction of the volume force rotation and the incoming flow only.



TSR	5	7	9	11
Ω [rad/s]	35	42	42	42
U_{INLET} [m/s]	7	6	4.67	3.82

Tested case

Simulation control parameters:

-Δt = 0.001 s.

-End time = 4 s.

Calculation support supplied by CINECA – HPC Eurora :

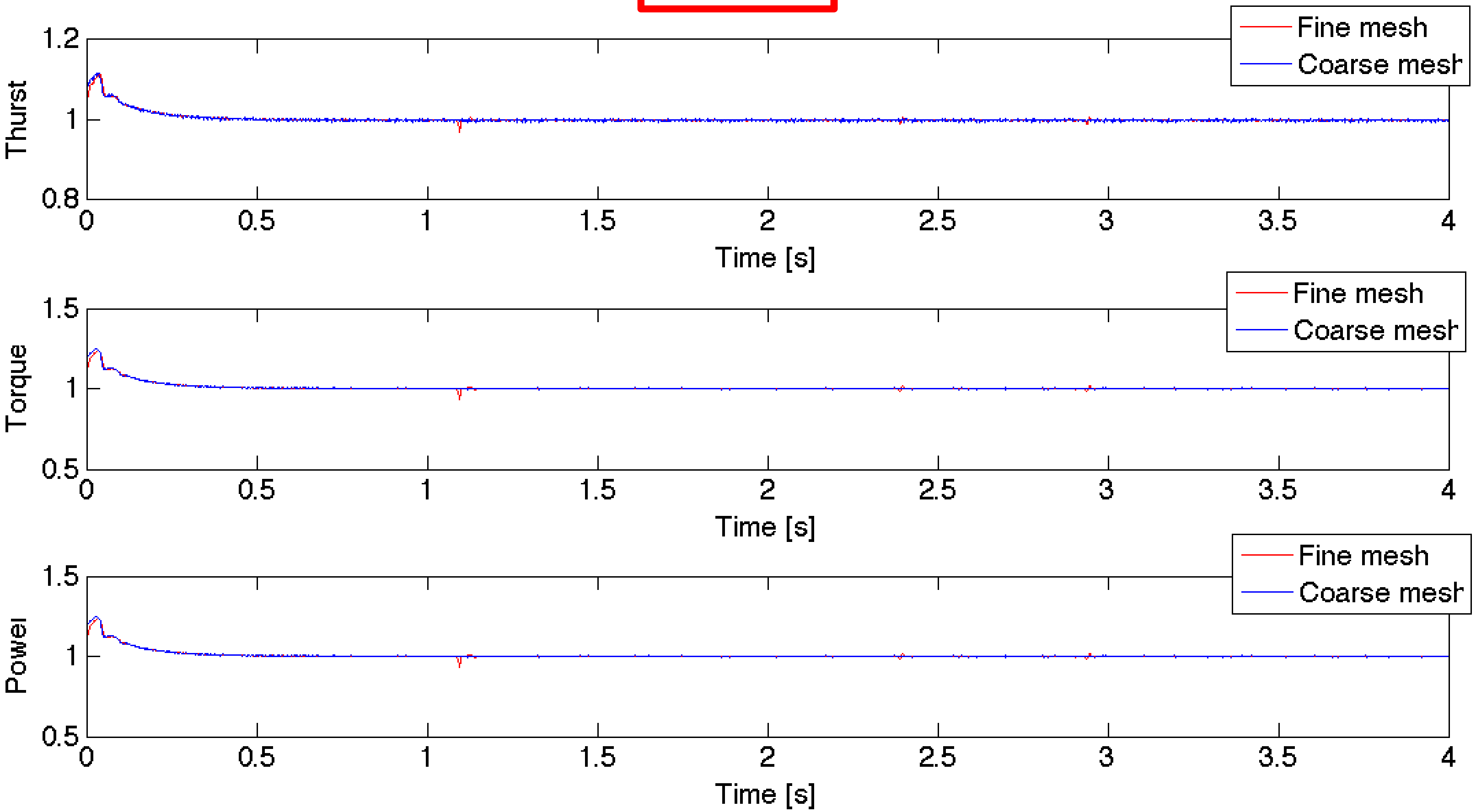
-Coarse mesh case, 320,000 cells → 2 nodes, 32 Intel Xeon 3.10 GHz CPUs, 24 GB RAM.

-Fine mesh case, 2,560,000 cells → 4 nodes, 64 Intel Xeon 3.10 GHz CPUs, 48 GB RAM.

CINECA

Results – Turbine performances

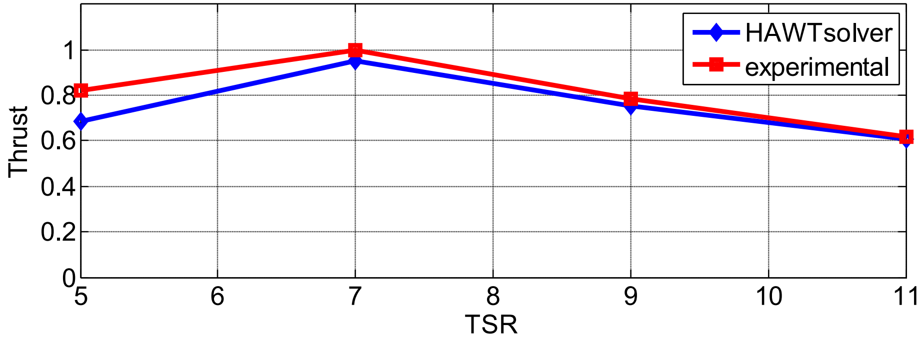
TSR 7

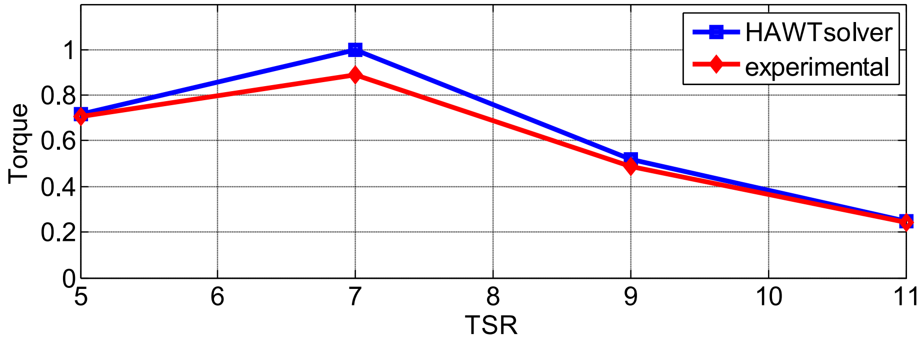


Performance evaluation does not suffer the mesh grid dimension, limited differences between coarse and fine mesh cases.

Results – Simulation vs experimental data

All the different TSR simulations show a good agreement with experimental data.





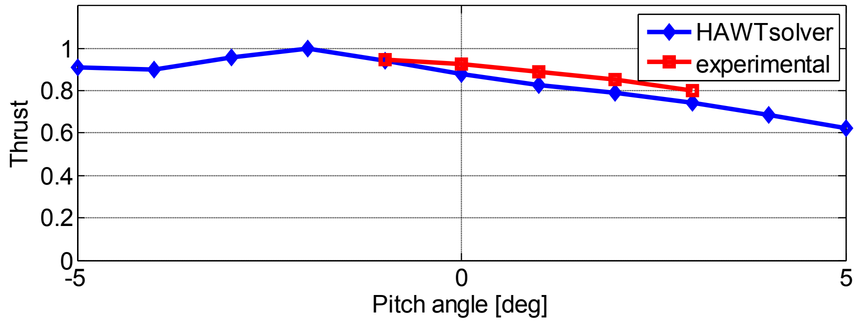
Discrepancies table:

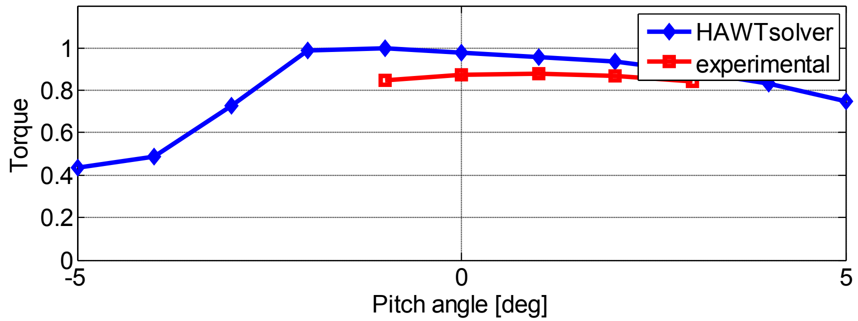
TSR	5	7	9	11
Thrust	-16.6 %	-5.0 %	-4.0%	-2.1%
Torque	-1.0 %	+12.1%	+6.6 %	+3.3 %

Results – Simulation vs experimental data

TSR 7

Pitch angle [deg]	-5	-4	-3	-2	-1	0	1	2	3	4	5





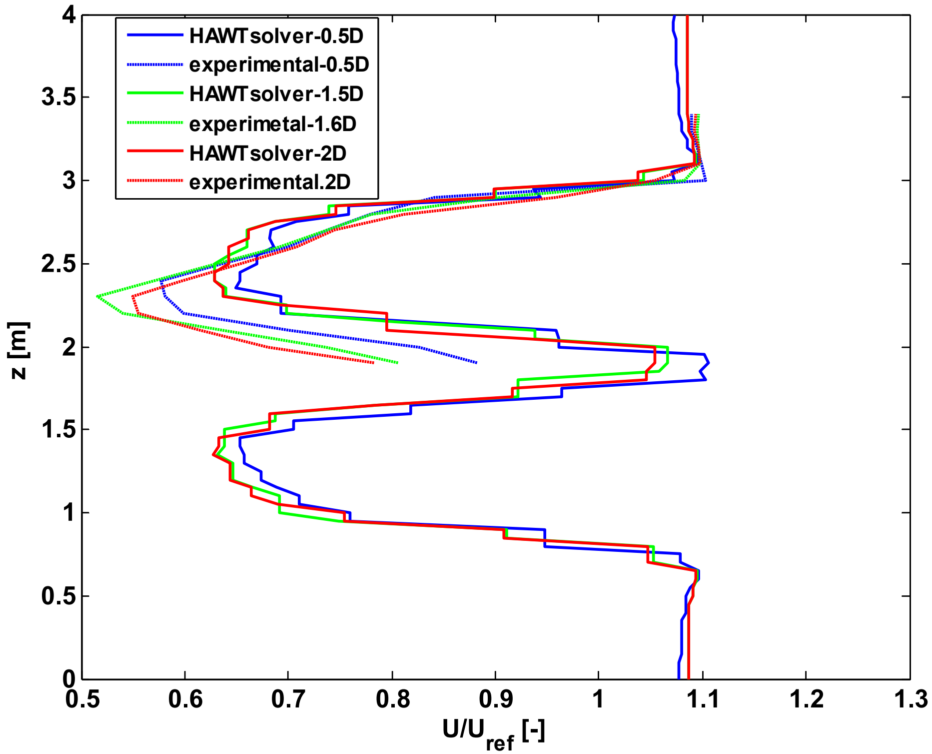
Discrepancies table:

Pitch angle [deg]	-1	0	1	2	3
Thrust	-0.4 %	-5.0 %	-6.9 %	-7.3 %	-7.7 %
Torque	+17.6 %	+12.1%	+8.9 %	+7.8 %	+5.8 %

Results – Simulation vs experimental data

TSR 7

For TSR7 the wake velocity deficit is plotted



Near the root the wake isn't reproduced with accuracy, this can be due to the not modelled turbine hub.

A root-correction factor for correctly model the flow can be take in consideration.

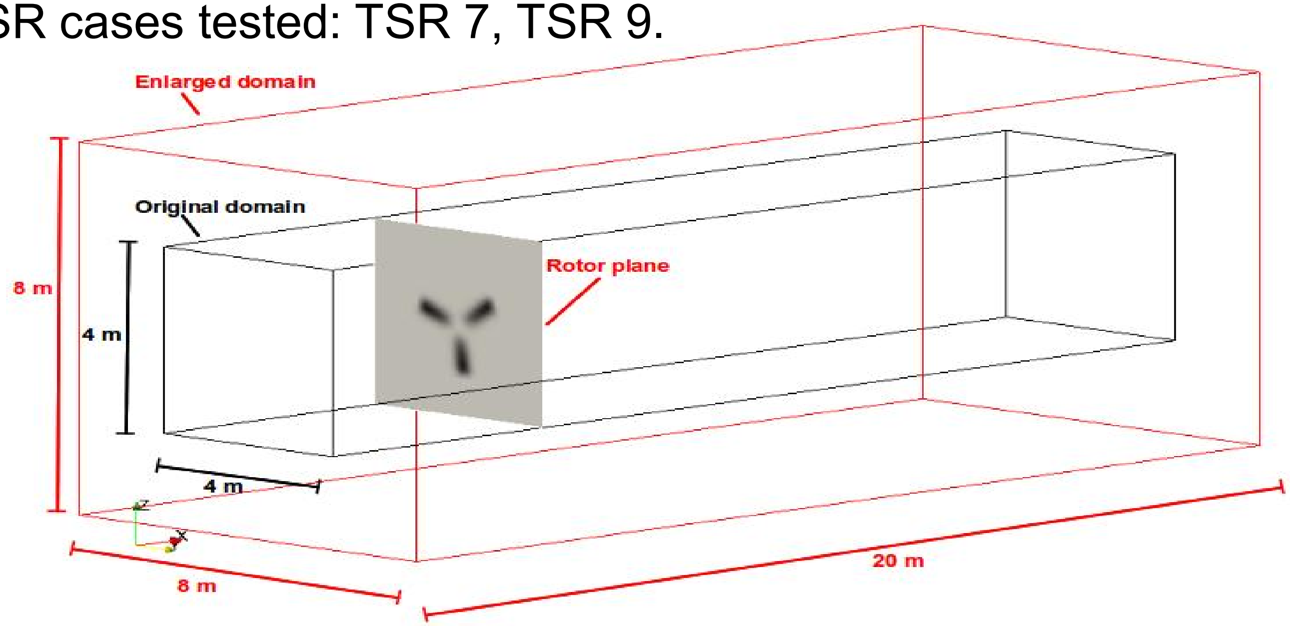
BEM comparison

To better validate the WT simulation via AL and EVM, some other test cases have been compared with a classical BEM approach:

-Enlarged computational domain in order to limit the blockage ratio and making this condition more consistent to the BEM hypothesis of infinite domain.

Duct section [m]	4 x 4	8 x 8
Rotor diameter [m]	2	2
Blockage ratio	≈ 20 %	≈ 5 %

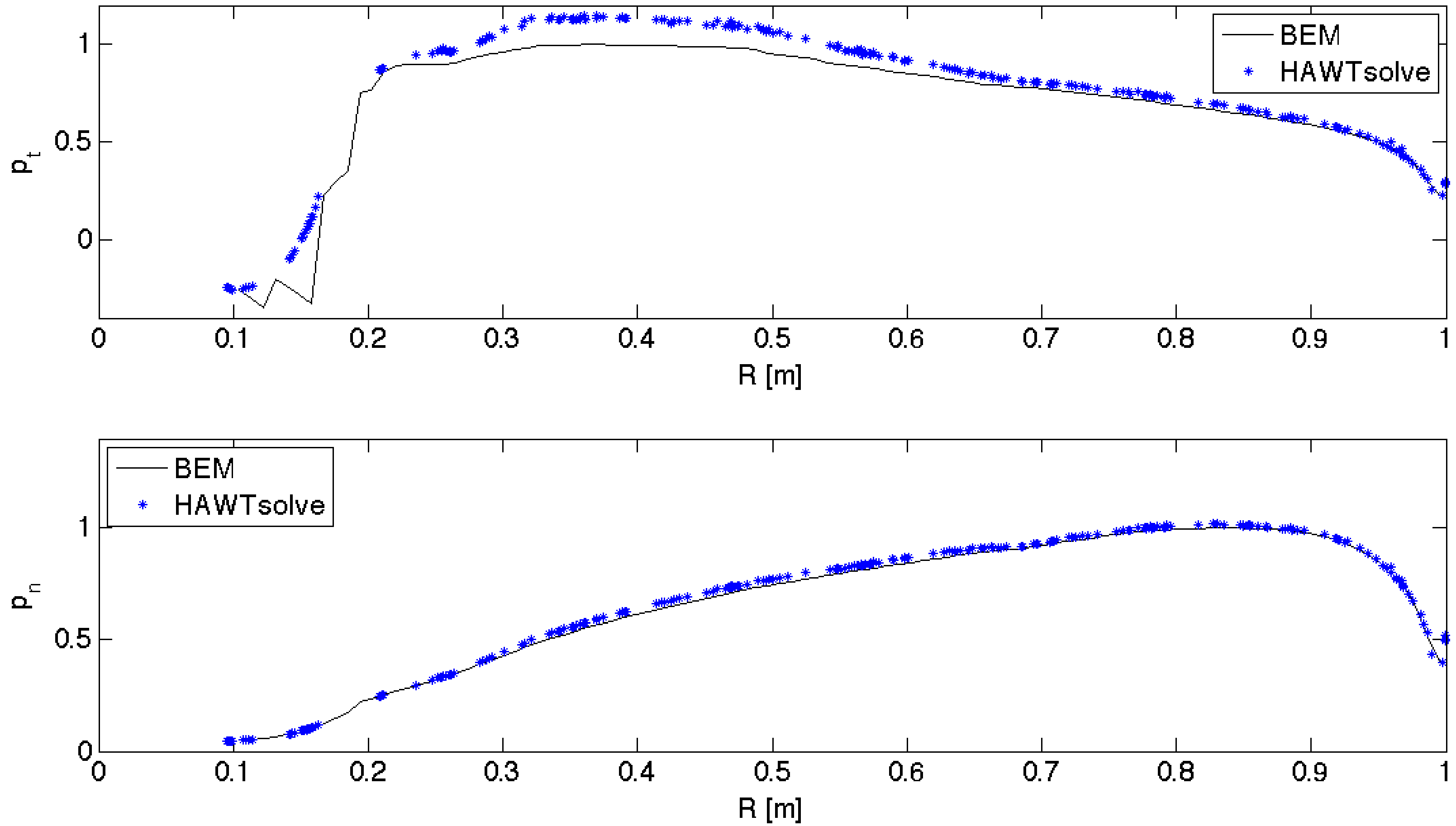
- Different TSR cases tested: TSR 7, TSR 9.



Results – Simulation vs BEM data

Data from simulations agree very well with the data coming from BEM theory.

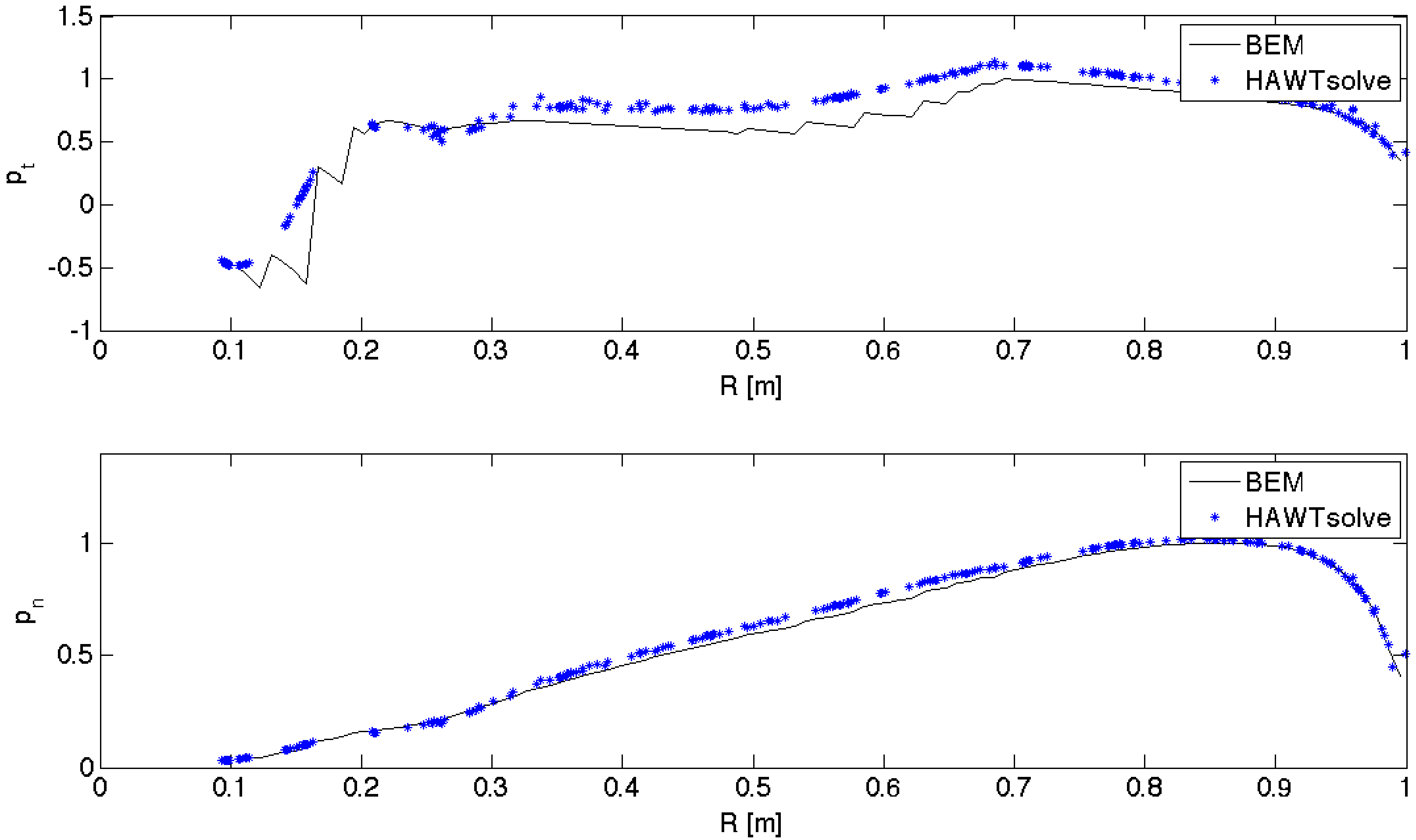
TSR 7



Results – Simulation vs BEM data

Data from simulations agree very well with the data coming from BEM theory.

TSR 9



Wind turbines

VAWTs:

- independent from flow direction; C_P = 0.2 – 0.4;
- drive trains are near the ground;
- blades with easier shape;
- low TSR and sound emission;
- can be packed much closer together in wind farms;

Savonius:

- low efficiency

  C_P = 0.15 – 0.3;
- drag devices;
- self-start ability;
- low startup wind speed;
- low cost

Darrieus:

- higher efficiency;

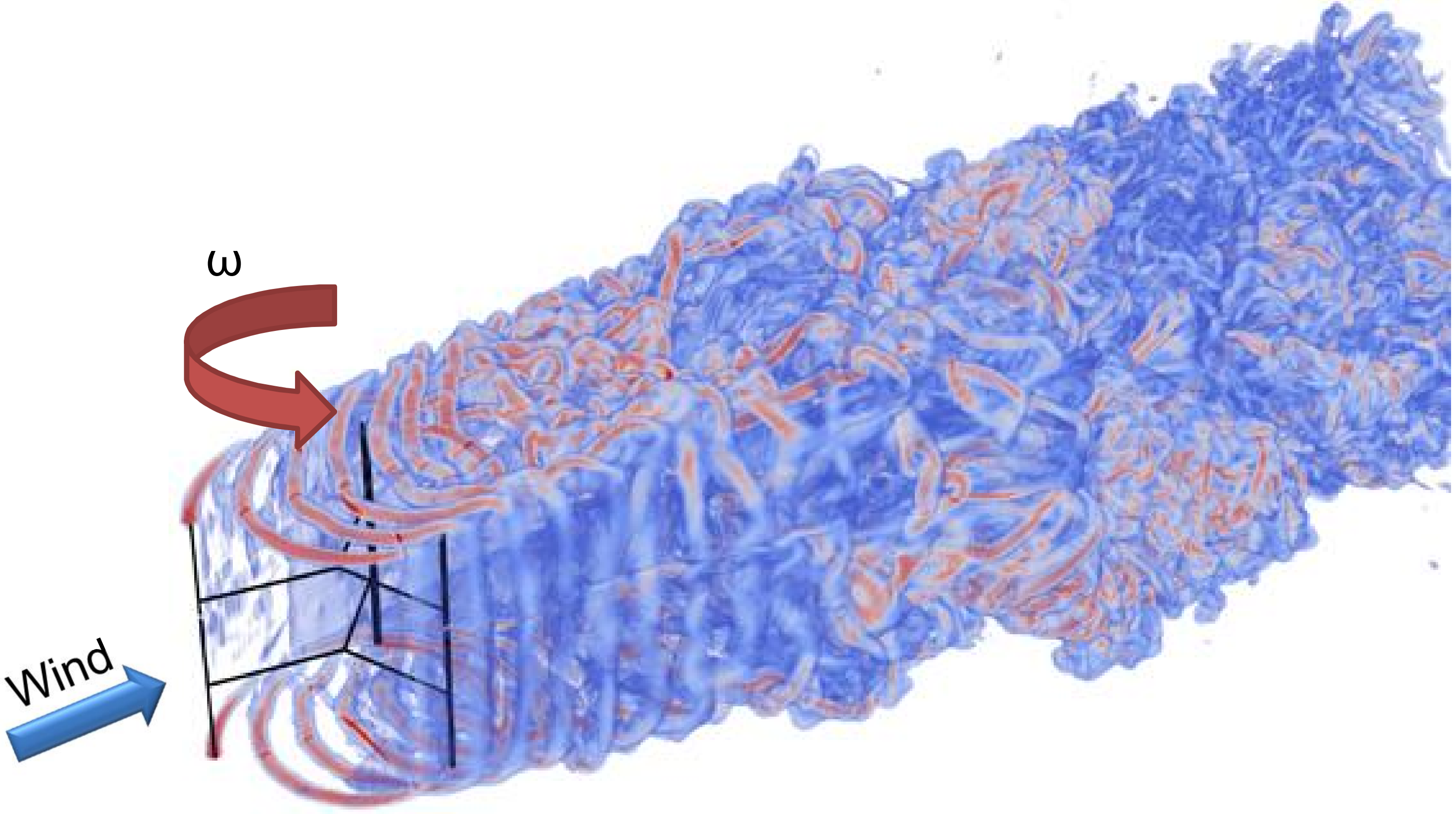
  C_P = 0.3 – 0.4;
- lift devices;
- no self starting
- low wind speed;

H-Darrieus wind turbine

H-Darrieus turbine

Straight-blade Darrieus turbine has a very simple structure.
This simplicity, however, does not extend to the aerodynamics of the rotor, characterized by:

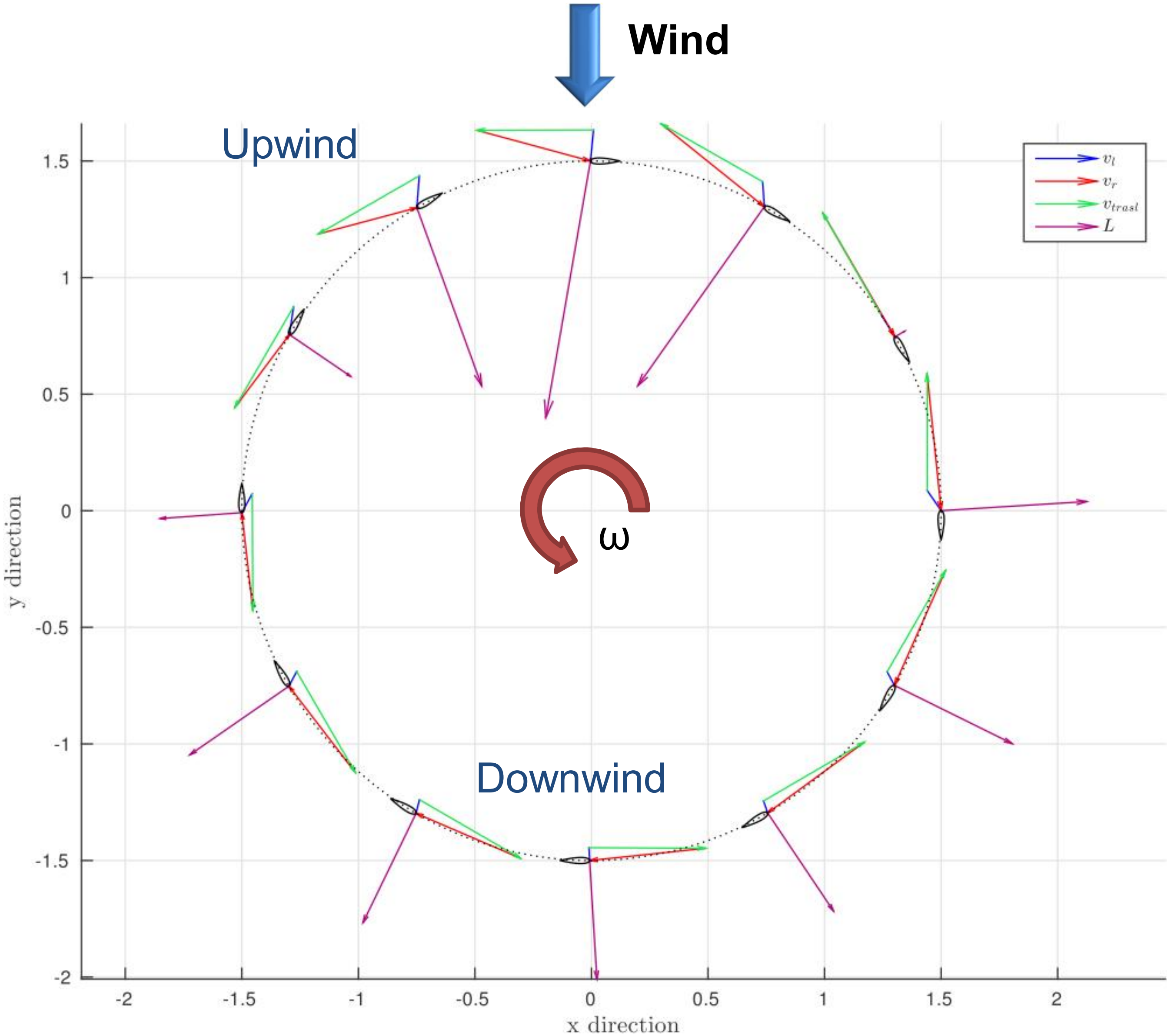
- Static and dynamic stall;
- High turbulence level;
- Interference with wakes generated by other blades;



According to Klimas [1], the interaction between the blades and the wakes is considered to be one of the most critical problems in the numerical modeling of the aerodynamics of vertical-axis wind turbines.

[1] P.C. Klimas. Darrieus rotor aerodynamics. 1982

H-Darrieus turbine



Relative-velocity direction and the angle of attack change during rotation.

These variations affect the directions of the aerodynamic forces and increase the simulation complexity.

VAWT simulations

According to Ferreira et al. [2], the most important aerodynamic models for VAWT analysis are:

- Multiple Streamtube model (MST); Only turbine performances
- **Double-Multiple Streamtube model (DMST);** Only turbine performances
- Vortex model (VM); Both turbine performances and wake
- **Panel method (PM);** Both turbine performances and wake

➢ CFD simulations
- Actuator Disk (AD)
- Actuator Line (AL) — Chosen method
- Fully-resolved airfoil simulations (FRA)

minutes

hours

day

weeks

Computational cost

[2] M. Barone C.S. Ferreira H.A. Madsen and B. Roscher. “Comparison of aerodynamic models for Vertical Axis Wind Turbines”.

DMST and PM

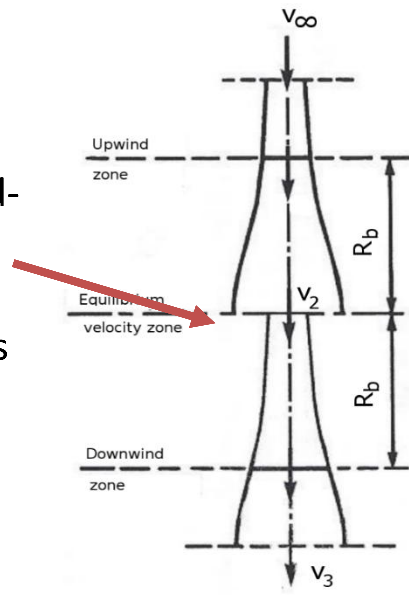
BENEFITS

DMST : Fast convergence of the iterative procedure [5].

[5] Paraschivoiu I., Double-multiple streamtube model for Darrieus wind turbine, 1983

DISAVANTAGES

- Rely on airfoil tabulated data
- The wake, generated by the wind-blade interactions in the upwind zone, is considered as <u>fully expanded</u> before the interactions in the downwind zone.



PM : Assumptions Potential Flow theory :

Irrotational flow;
Inviscid flow;
High Reynolds number

Key aspect of PM is the solution of the Laplace Equation by the singular solutions.

BENEFITS

- accurate wake reproduction
- low computational costs

DISAVANTAGES

- no stall model
- overestimation of the performances
- require low rotor solidity

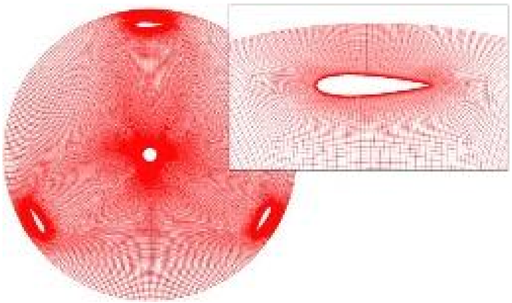
FRA versus AL simulations

Fully-resolved airfoil simulations :

- Geometry model of the turbine in the computational mesh.
- Resolution of the discretized Navier-Stokes equations.
- The aerodynamic forces on blades are computed from the pressure field as a post-processing analysis.

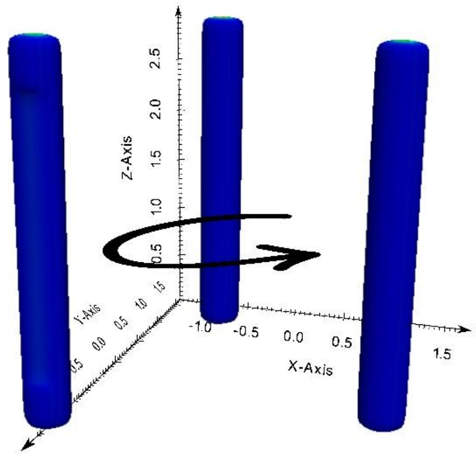
Actuator Line simulations:

- The computational domain does not contain the turbine profile.
- Aerodynamic forces are computed analytically from the tabulated aerodynamic coefficients.
- Resolution of the modified discretized Navier-Stokes equations.



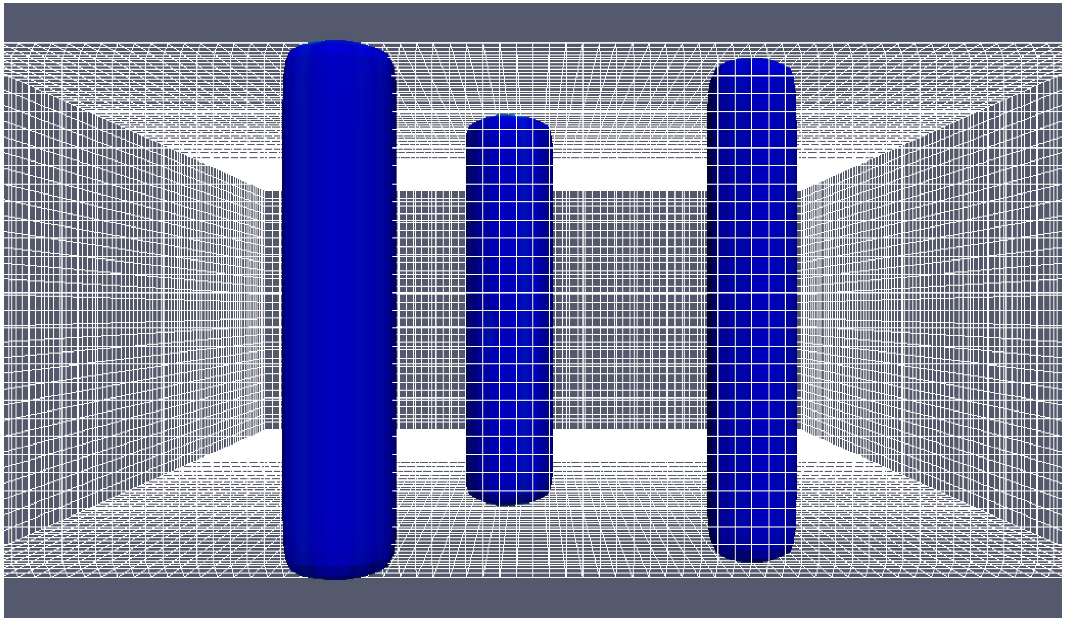
$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho\, \mathbf{u}\, \mathbf{u}) - \nabla \cdot (\mu \nabla \mathbf{u}) + \mathbf{f} = -\nabla p$$

```
solve
  {
     fvm::ddt(U)
   + fvm::div(phi, U)
   + turbulence->divDevReff(U)
   + volumeForce
     ==
   - fvc::grad(p)
  };
```



$$\vec{F} = \frac{1}{2}\, \rho\, C\, t_h\, v_r^2\, (C_L(\alpha)\, \vec{l} + C_D(\alpha)\, \vec{d}\,)$$

AL simulations



The turbine blades are modelled by rotating *volumeForce* in the computational domain

$$\vec{F}_{2D} = \frac{1}{2}\,\rho\, C\, v_{rel}^2\, (C_L\,(\alpha, \mathrm{Re})\ \vec{l} + C_D(\alpha, \mathrm{Re})\ \vec{d}\ )$$

The magnitude of the relative velocity varies during the rotation requiring an interpolation, based on the Reynolds number, of the aerodynamic coefficients.

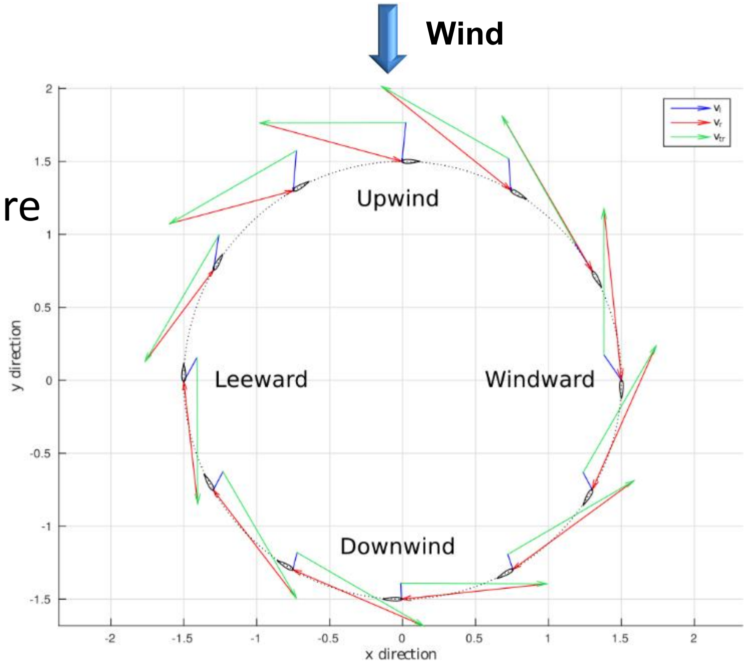
The evaluation of the incoming wind velocity is done thorough the ***Effective Velocity Model:*** an innovative method that samples the blade incoming wind characteristics on multiple point and after an average, it extrapolates the reference velocity to be used to evaluate the aerodynamic coefficients from table values.

AL simulations: EVM direction

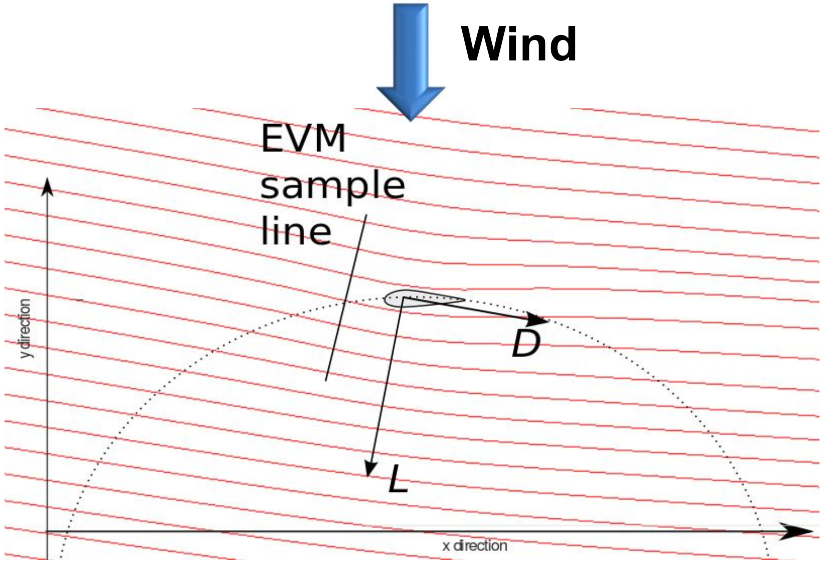
This work starts from the master thesis of Bernini and Caccialanza [3] and P. Schito PhD thesis [4]. The aim is to extend the AL model to simulation of VAWTs.

[3] Bernini and Caccialanza. "Development of the Effective Velocity Model for wind turbines aerodynamics numerical simulation through an Actuator Line approach." Master Thesis in Mechanical Engineering.

[4] P. Schito. "Large Eddy Simulation of wind turbines: interaction with turbulent flow". Doctoral Dissertation.



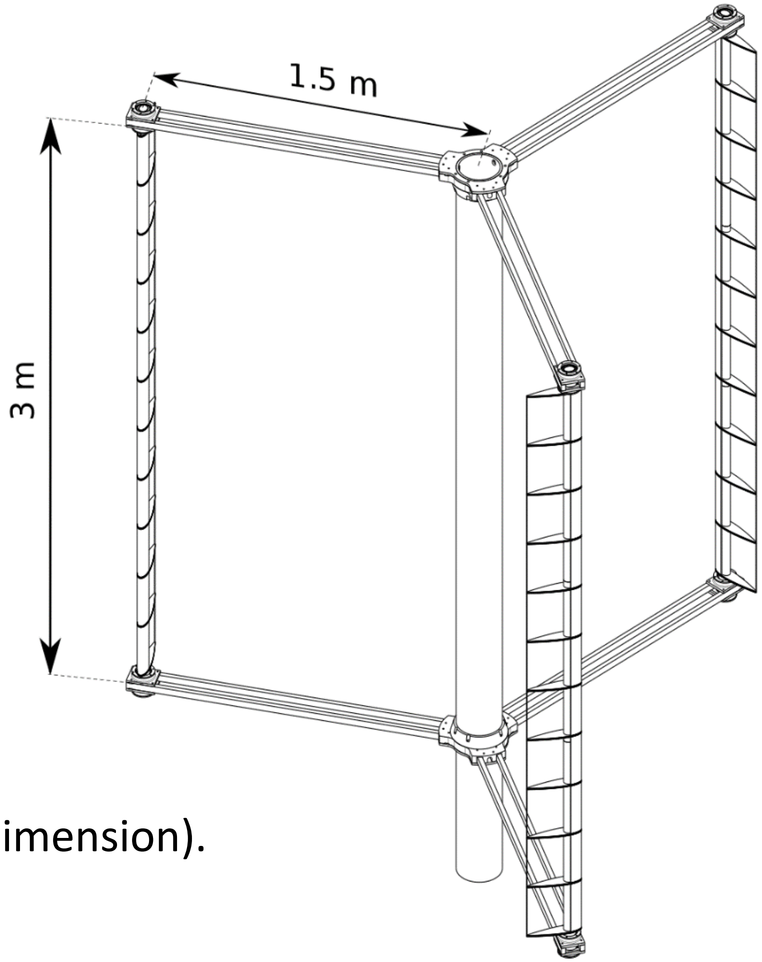
The fast variations of the relative-velocity direction require the addition of a function called *EVMDirection*



H-Darrieus turbine

Turbine characteristics:

Blade profile	h_b	R_b	C	σ
NACA 0021	3m	1.5 m	0.25 m	0.25



DMST and PM do not consider neither
3D effects nor blockage effects

Computational domain

-Section: 48 x 3 m.

-Length: 13 m.

-Structured mesh adopted: cubic cells (0.05 m side dimension).

Boundary conditions:

-Lateral sides (sky, ground, sides) → symmetry plane.

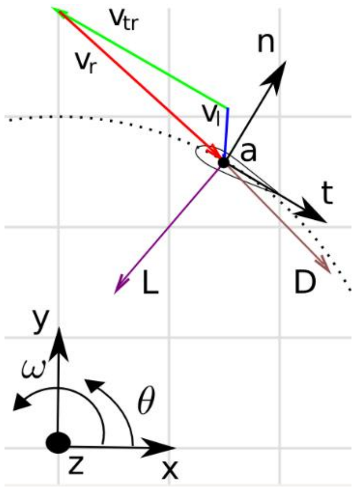
-Inlet and outlet sections.

AL - DMST comparison

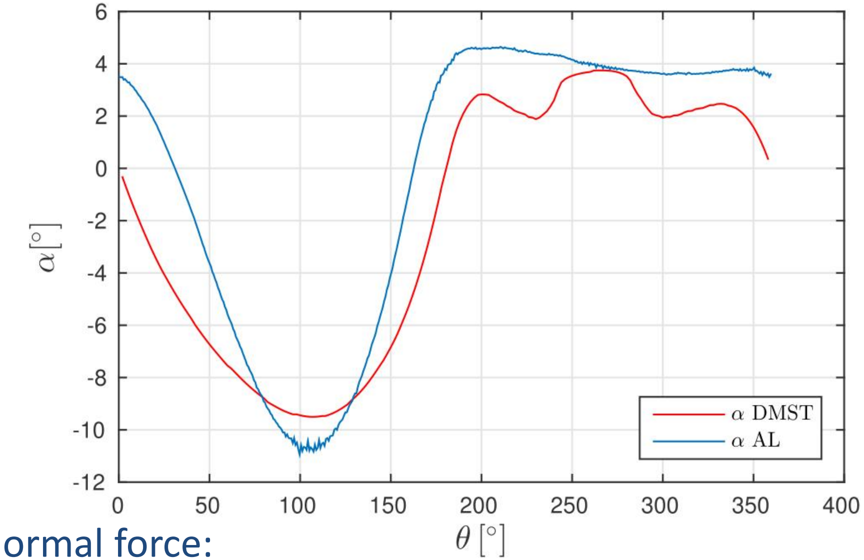
Wind and turbine are chosen in order not to cause stall effects.

v_∞ $[\frac{m}{s}]$	TSR
5	4

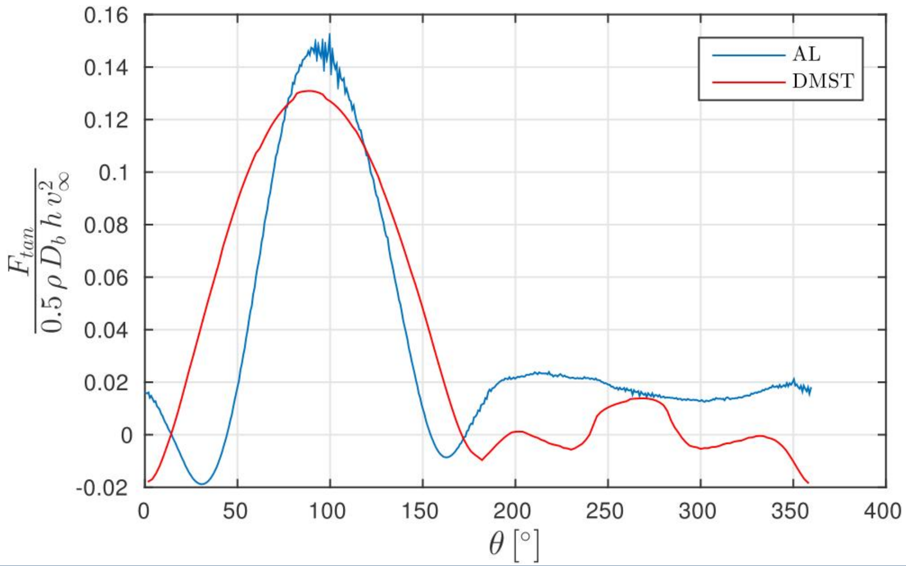
Agreements:



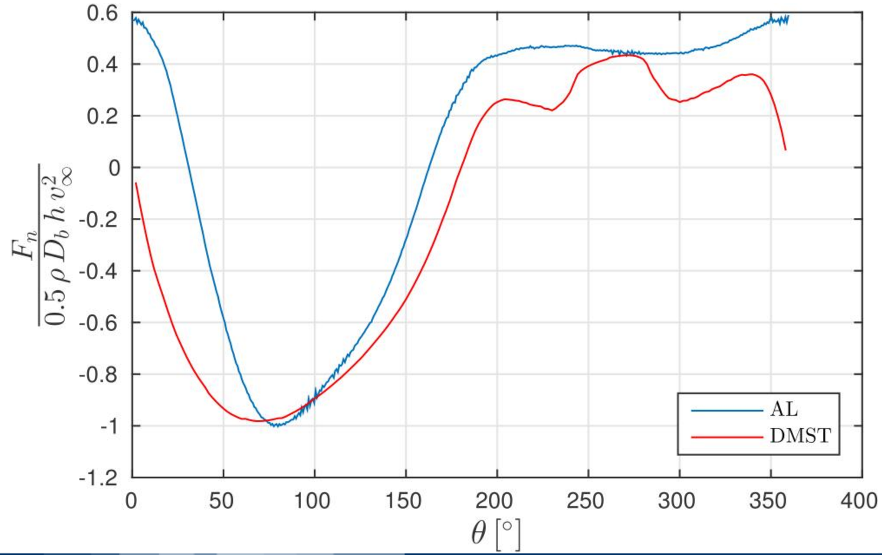
Angle of attack:



Tangential force:



Normal force:

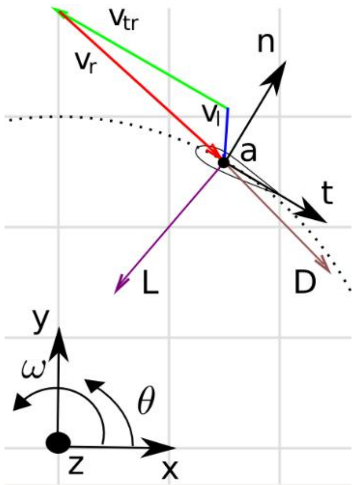


AL - DMST comparison

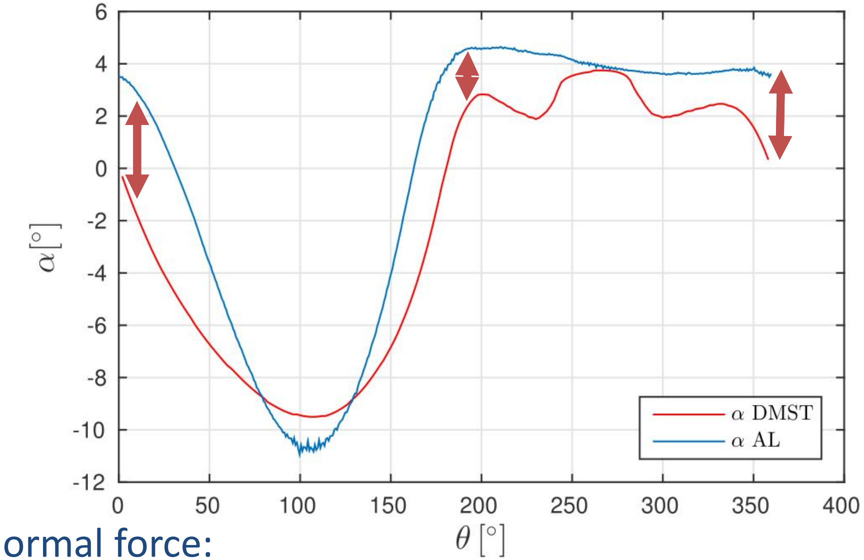
Wind and turbine are chosen in order not to cause stall effects.

v_∞ $[\frac{m}{s}]$	TSR
5	4

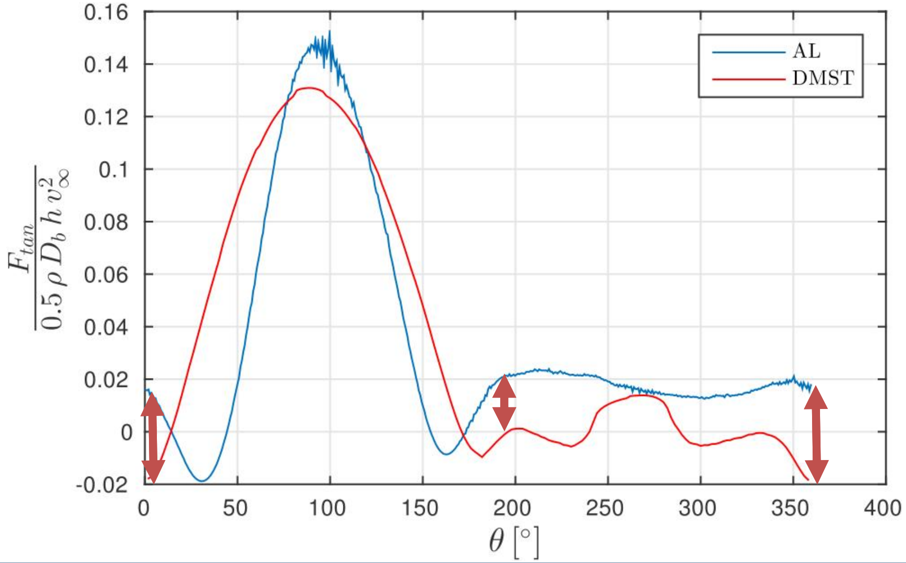
Agreements:



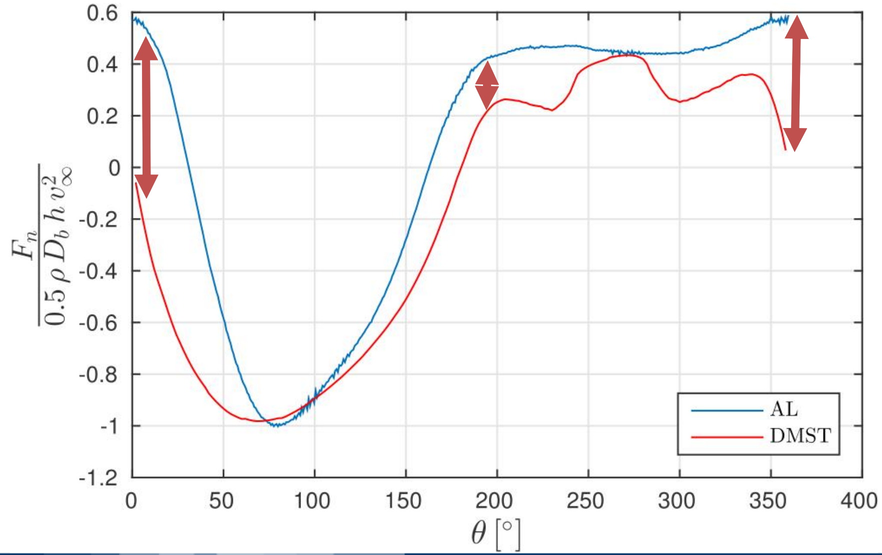
Angle of attack:



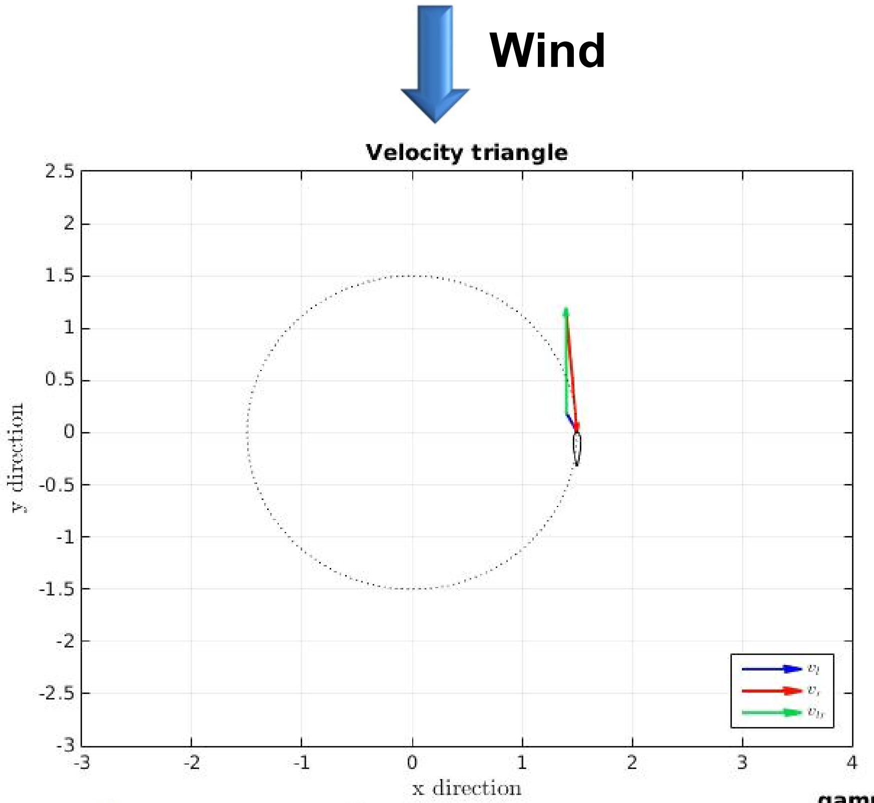
Tangential force:

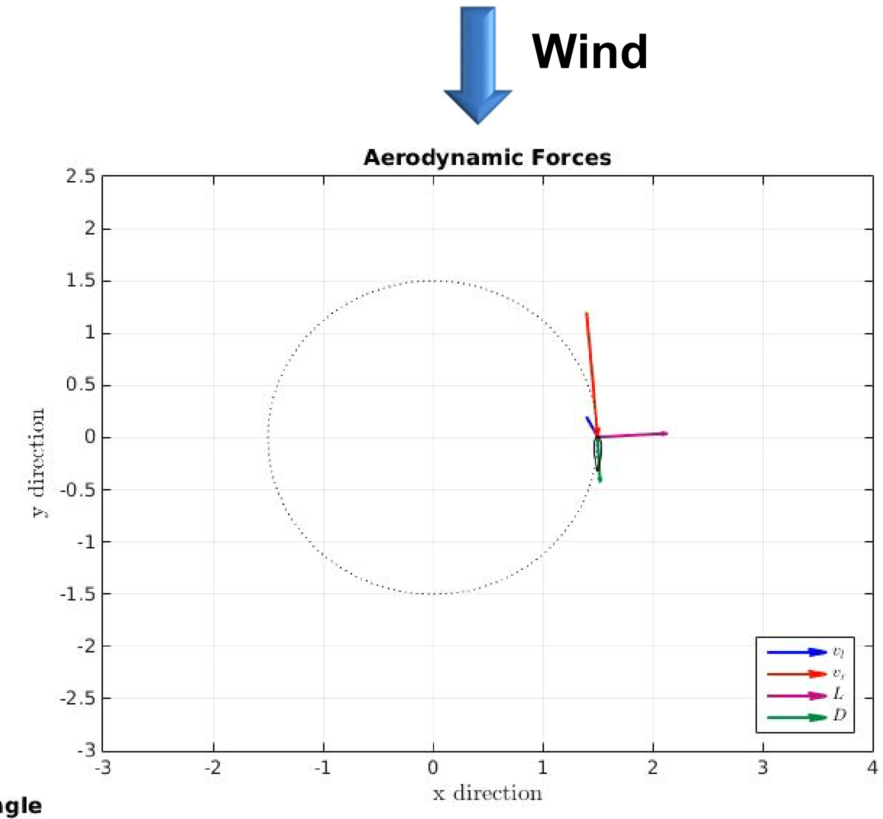


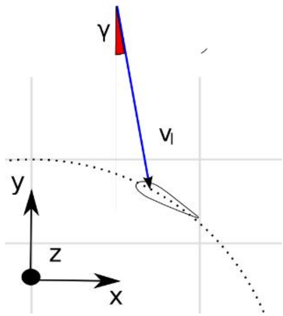
Normal force:

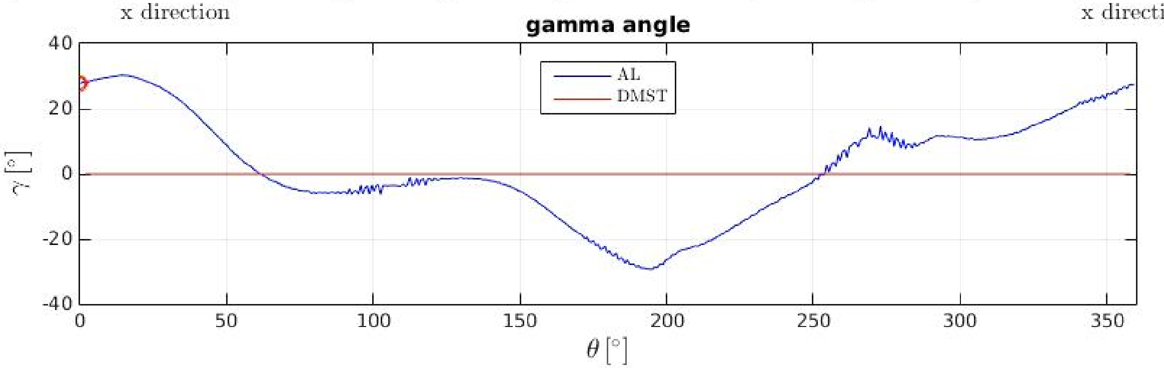


AL - DMST comparison







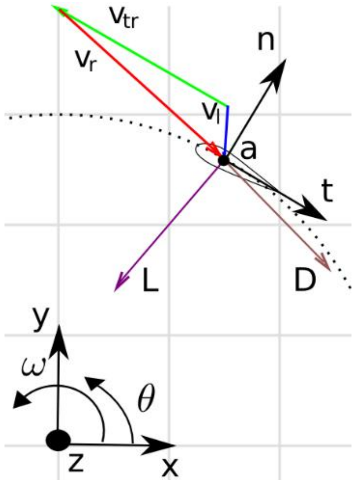


AL - DMST comparison

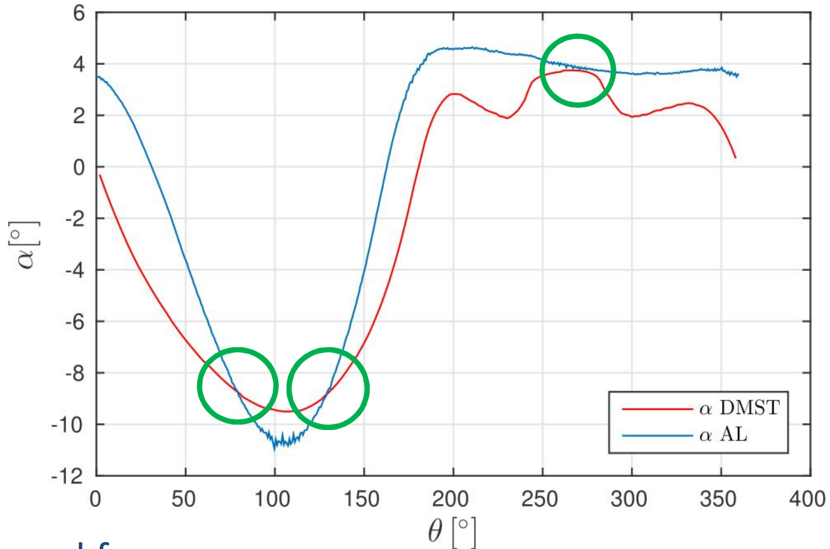
Wind and turbine are chosen in order not to cause stall effects.

v_∞ $[\frac{m}{s}]$	TSR
5	4

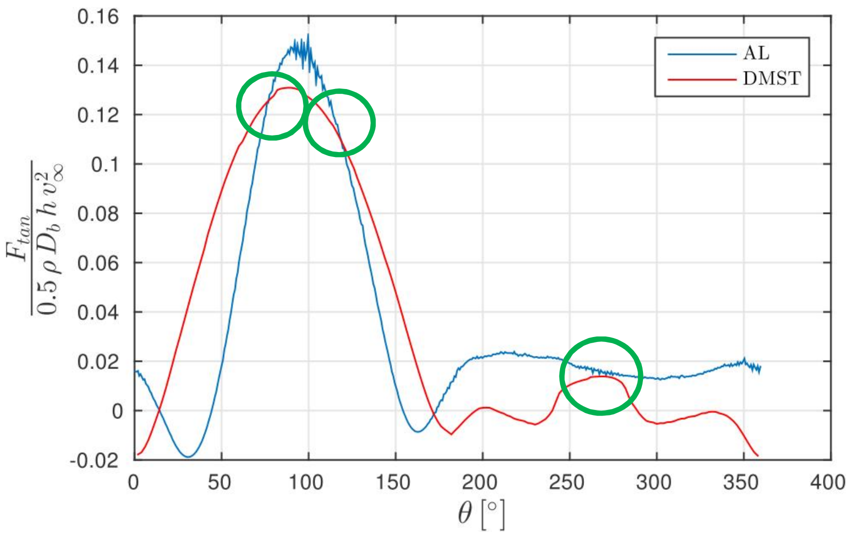
Agreements:



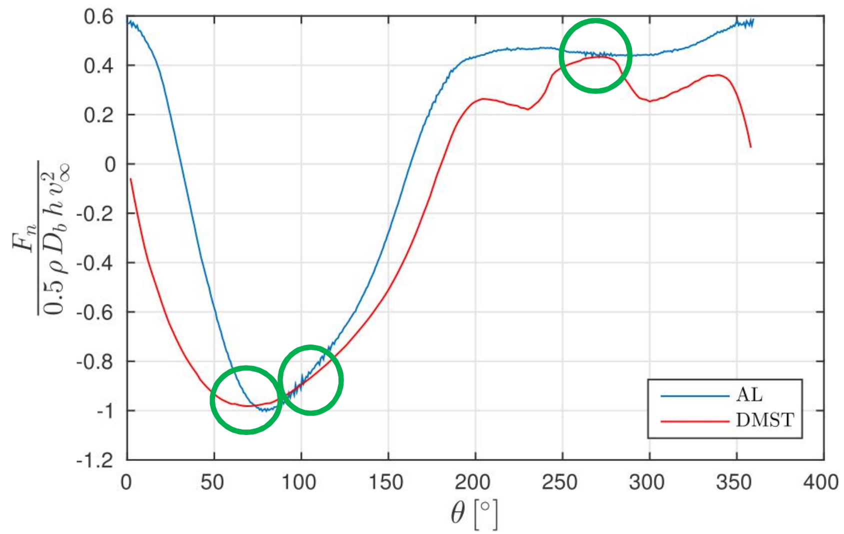
Angle of attack:



Tangential force:



Normal force:

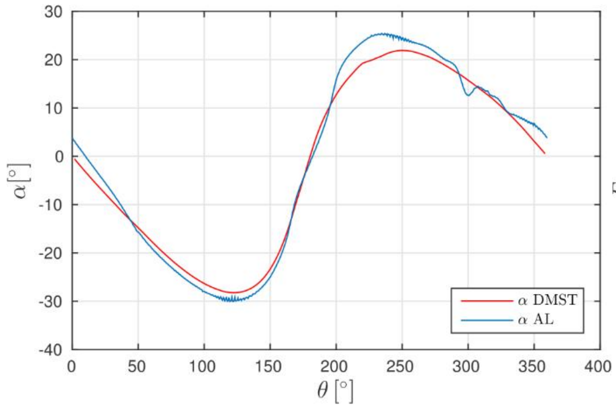


AL - DMST comparison

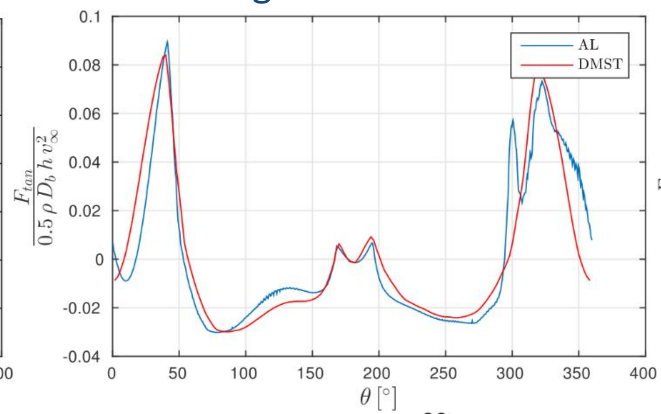
v_∞ [$\frac{m}{s}$]	TSR
5	2

At low TSR the DMST assumption is more accurate physically

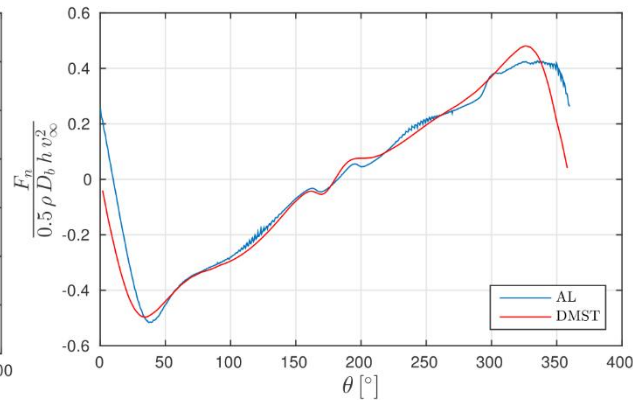
Angle of attack:



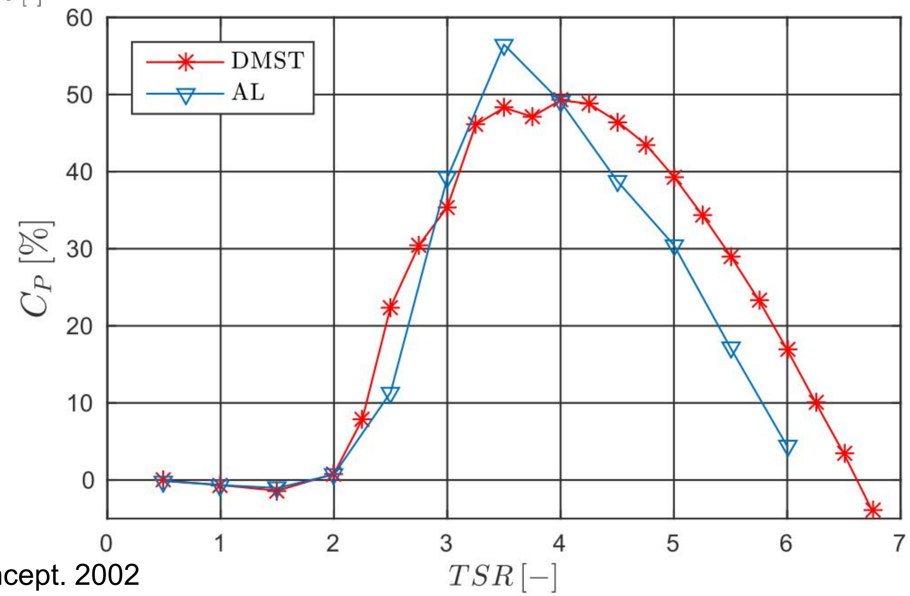
Tangential force:



Normal force:



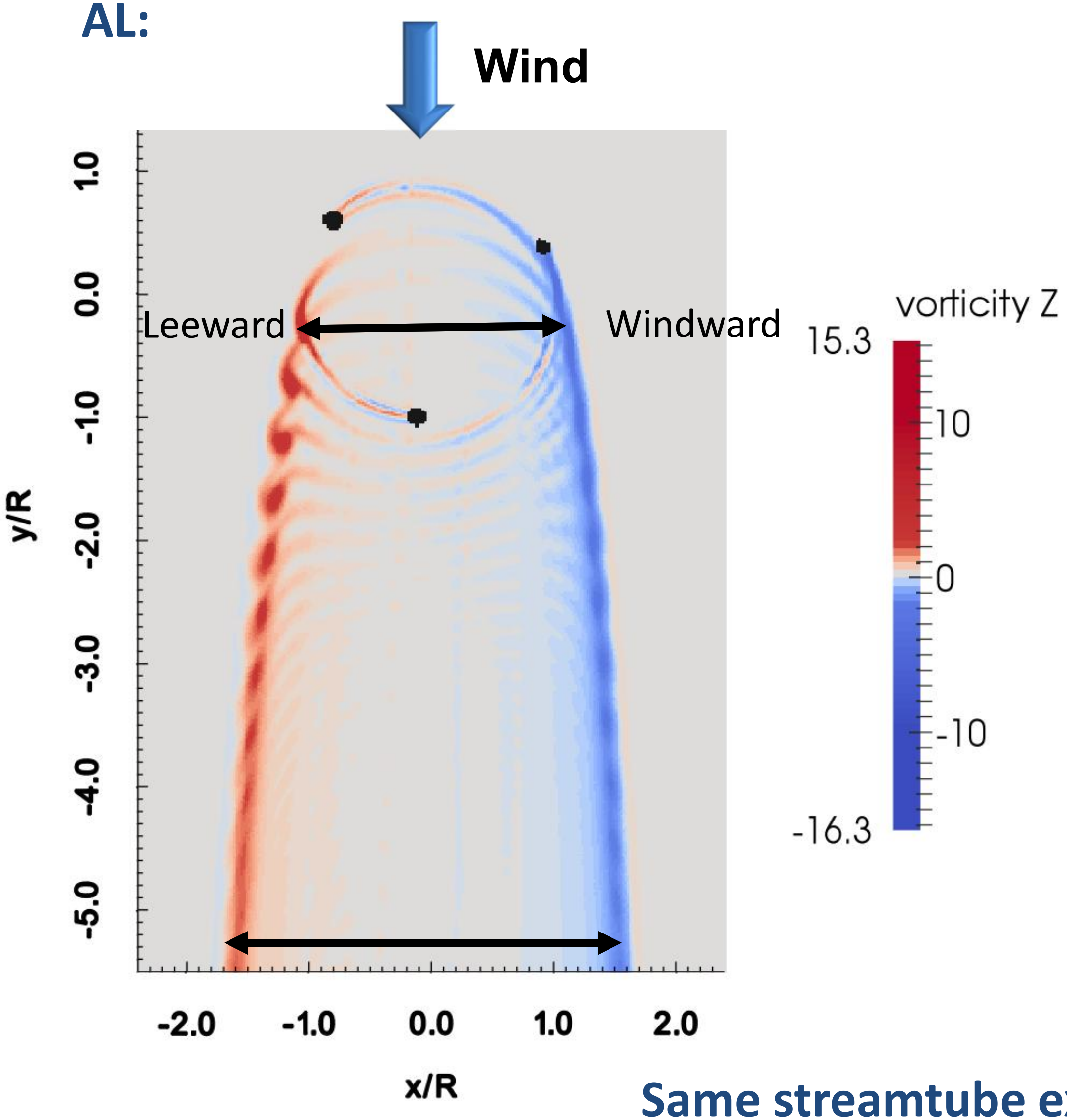
It has been proved that DMST model works well at low TSR [6], this is a direct consequence of its hypothesis.



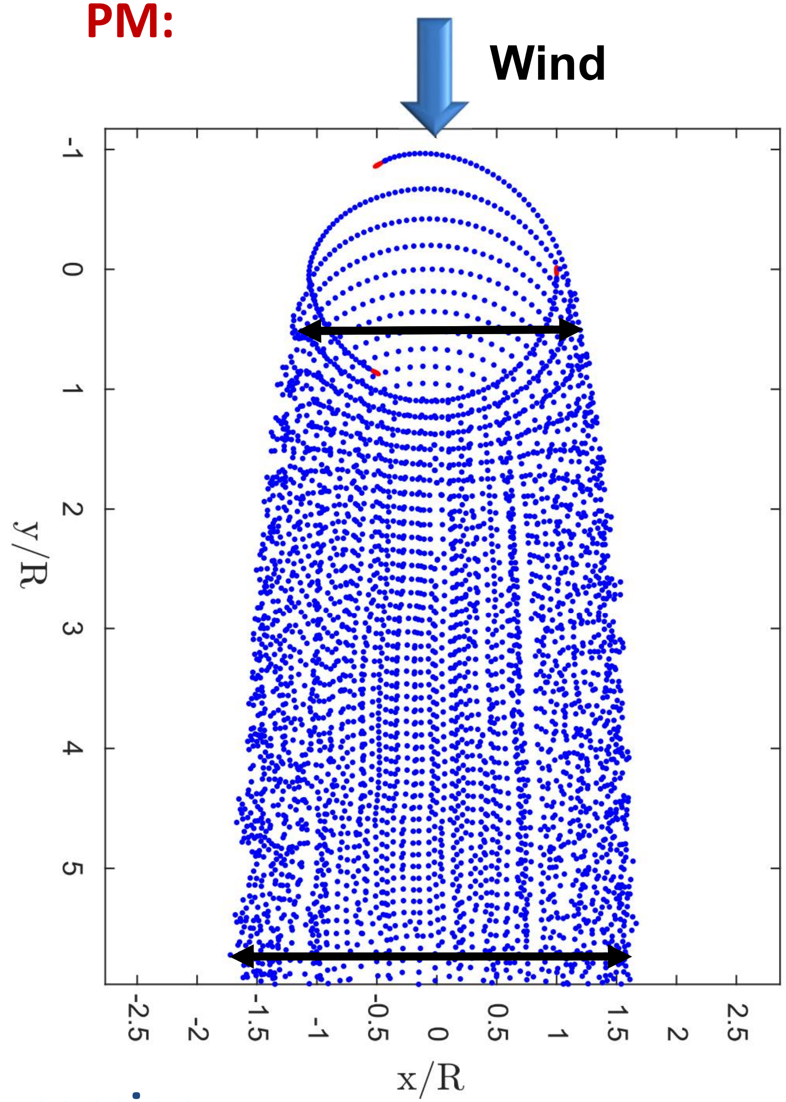
[6] I. Paraschivoiu. Wind Turbine Design: With Emphasis on Darrieus Concept. 2002

AL - PM comparison

AL:



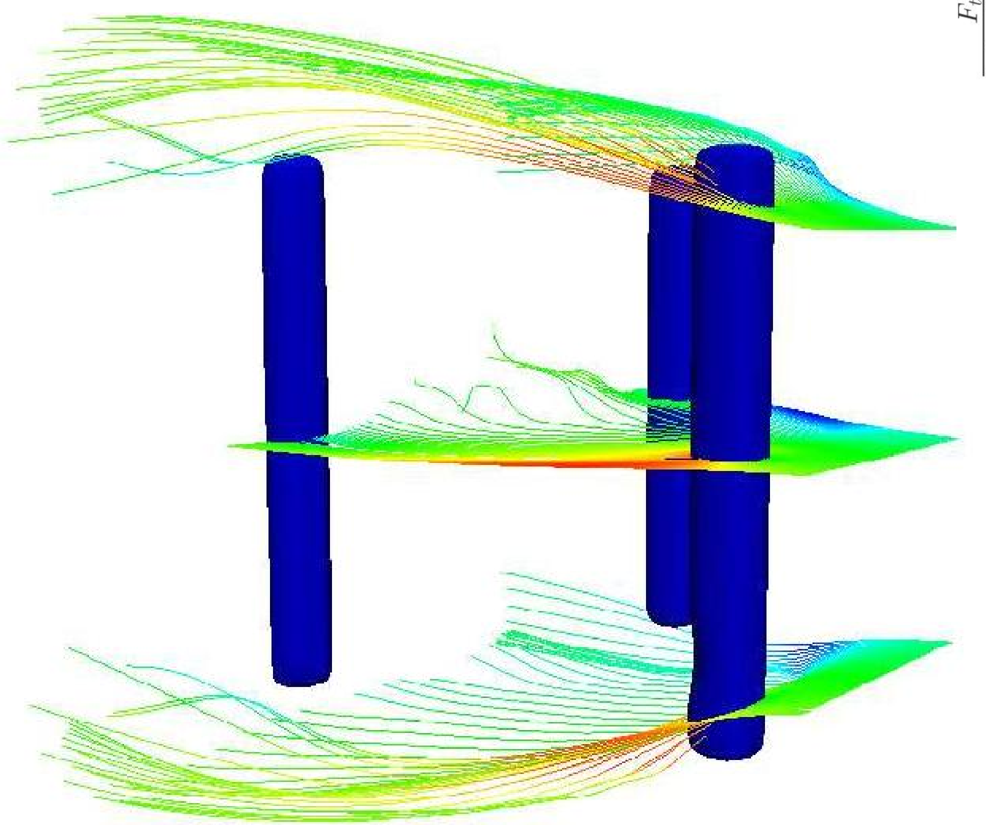
PM:

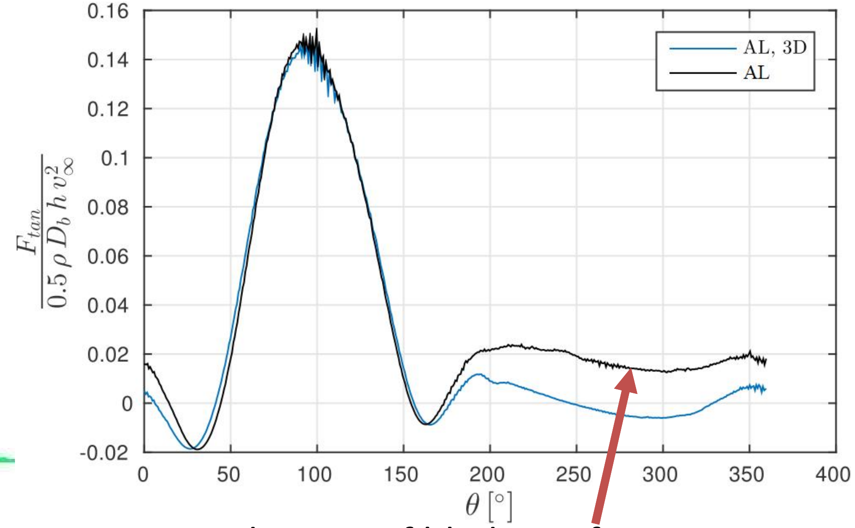


Same streamtube expansion

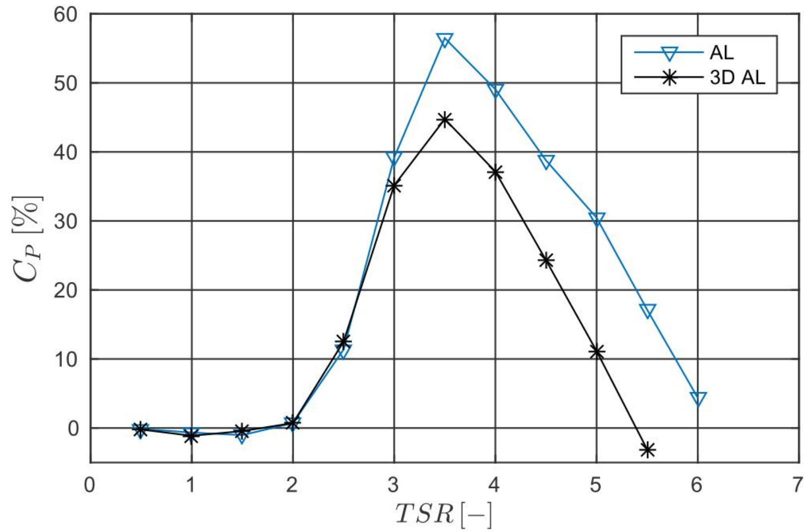
3D simulations

After the interaction with the first blade part of the flow deviates along the z-axis and avoid the interaction with the other blades.





Strong reduction of blade performances in the downwind zone

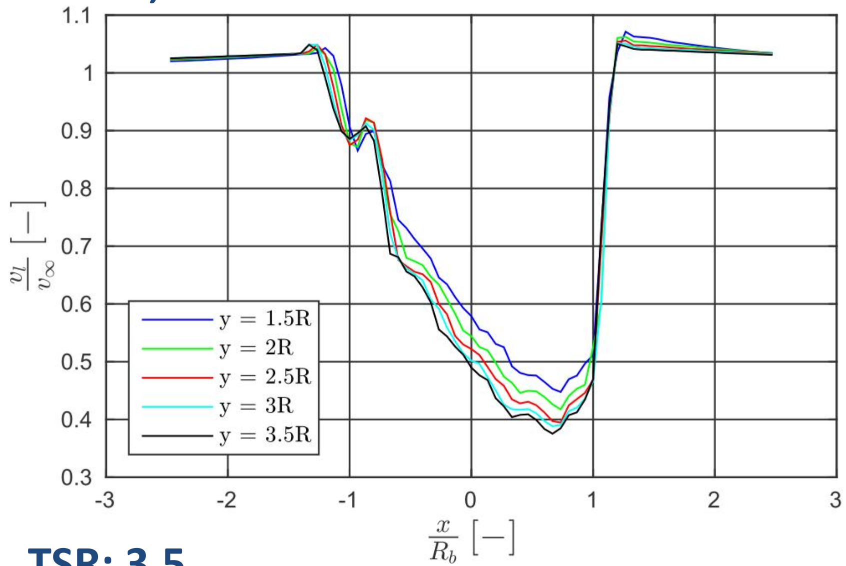


3D simulations

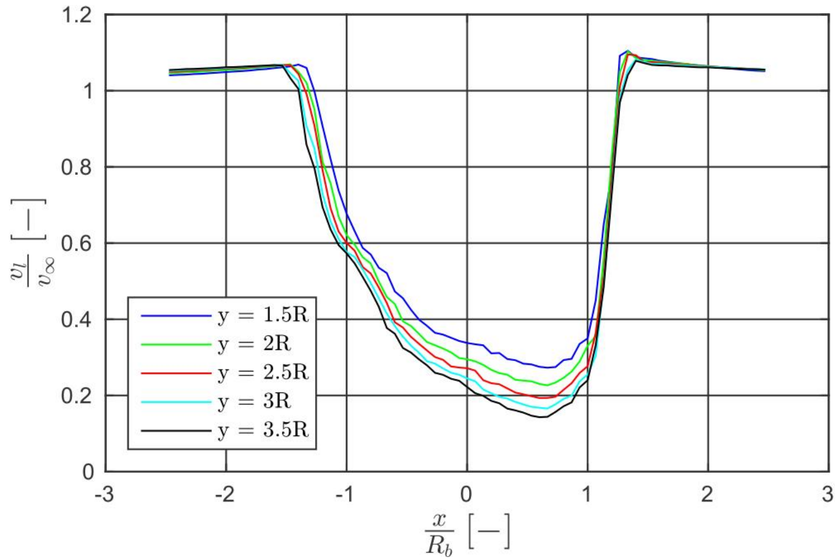
VAWT wake is slightly asymmetric in the XY plane (when viewed along its axis of rotation).

The XY asymmetry is inversely proportional to TSR

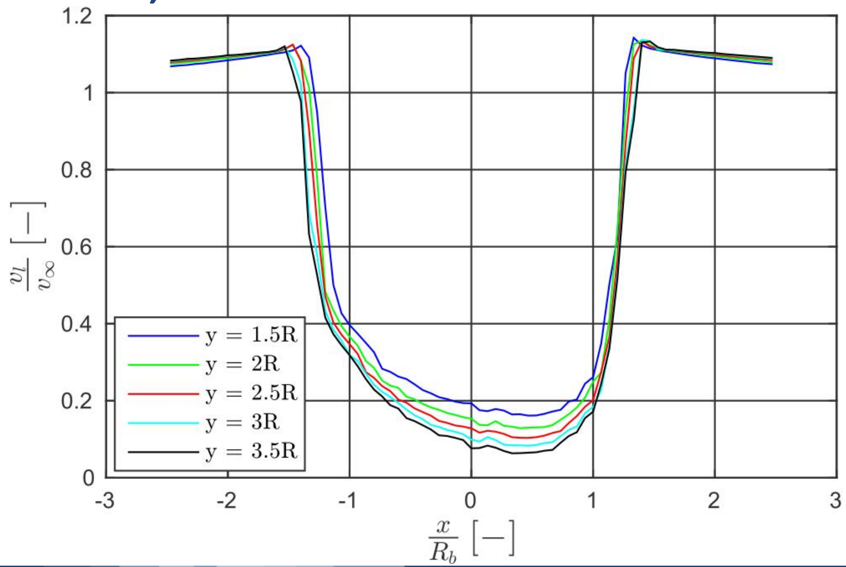
TSR: 2,5



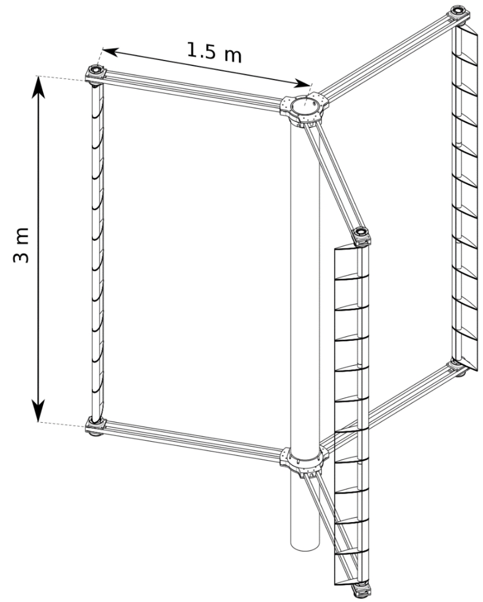
TSR: 3



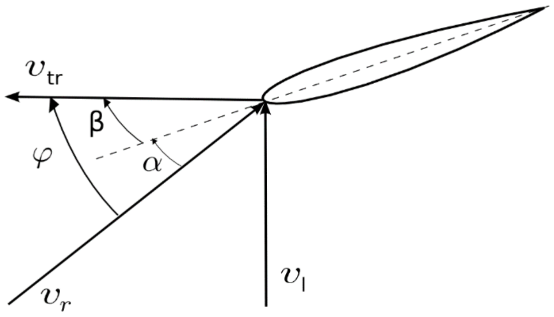
TSR: 3,5



Pitch-Angle effects

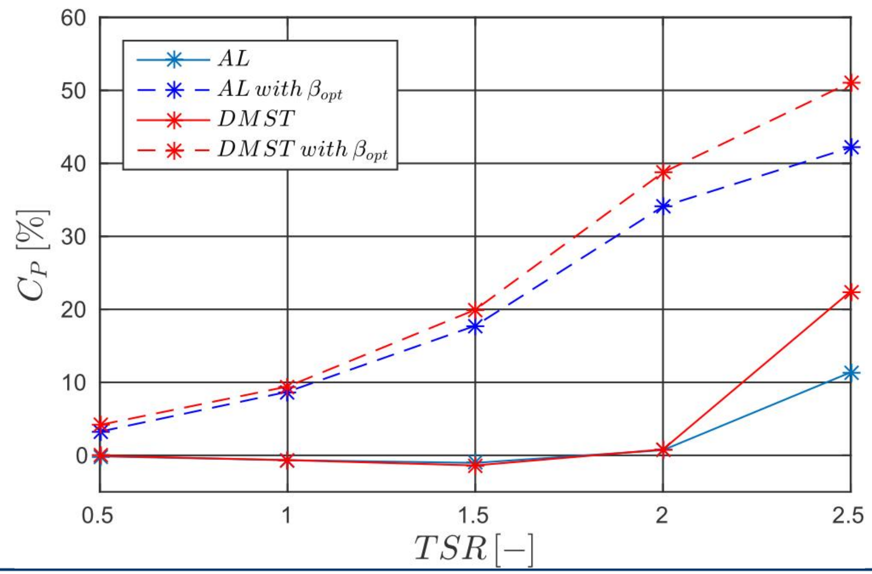


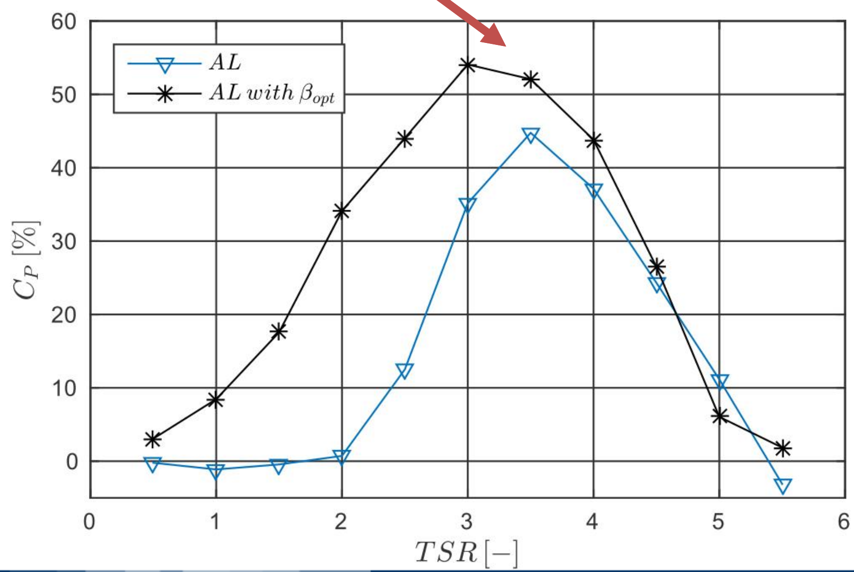
Variations of the pitch angle influence the angle of attack and so the blade performances.



The optimum pith angle are computed with an algorithm based on the DMST model.

The possibility to optimize the pith angle during rotation increase the turbine performances both <u>avoiding</u> and <u>considering</u> the 3D effects.





Conclusions and future efforts

A working CFD solver, based on Actuator Line and Effective Velocity Model, has been implemented in the open-source environment of OpenFOAM.

The comparisons with the DMST and PM models show good results both in turbine performances and the wake simulations.

The possibility to analyze turbine operations both including and avoiding 3D effects with low computational costs and to optimize the pitch angle during rotation can encourage future works.

Future efforts involve:

- Inclusion of a dynamic-stall model
- Comparison with experimental data provided by wind-tunnel proofs.
- Higher validation of the EVM model in simulation of incoming turbulent flows and code efficiency
- Deeper study in pitch-angle optimization