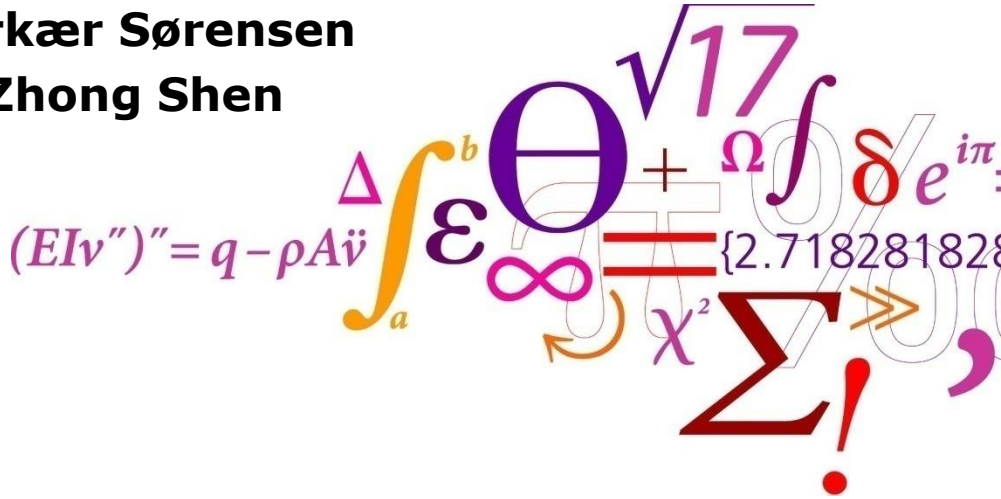
Validation of the 3D viscous-inviscid interaction model MIRAS

Néstor Ramos García
Jens Nørkær Sørensen
Wen Zhong Shen



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PRESENTATION LAYOUT

- MIRAS, Method for Interactive Rotor Aerodynamic Simulations
  - Inviscid body modelling.
  - Free wake modelling.
  - Viscous boundary layer solver, Q^3UIC.
  - Viscous-inviscid coupling.

- MIRAS validation for different scale rotor cases
  - NTNU ROTOR, (R0.4m).
  - DELFT ROTOR, (R0.6m).
  - MEXICO ROTOR, (R2.25m).
  - NM80 ROTOR, (R40.04m).
  - NREL 5MW ROTOR, (R62.9898m).

- Conclusions

MIRAS inviscid body modelling

The solution to the flow problem is reached by distribution of:

- Body quadrilateral **sources** (σ_p) .
- Body quadrilateral **doublets** (μ_p).
- Released wake **vortex filaments** (μ_w).

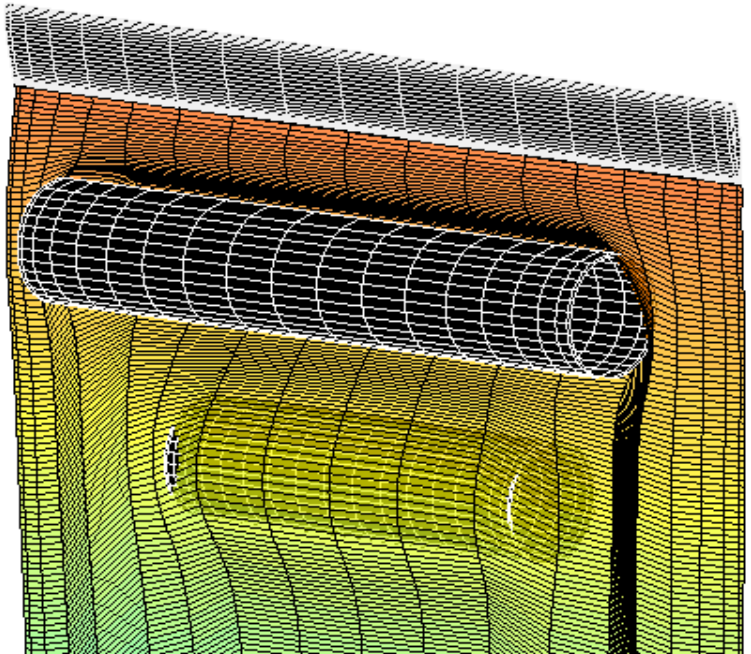
The Neumann condition of no penetration is applied at the solid surfaces:

$$\sum_{p=1}^{N} A_p \mu_p + \sum_{w=1}^{Nw} A_w \mu_w + \sum_{p=1}^{N} B_p \sigma_p = -Q_\infty \cdot n_i$$

The sources strength is fixed to:

$$\sigma_j = Q_\infty \cdot n_j$$

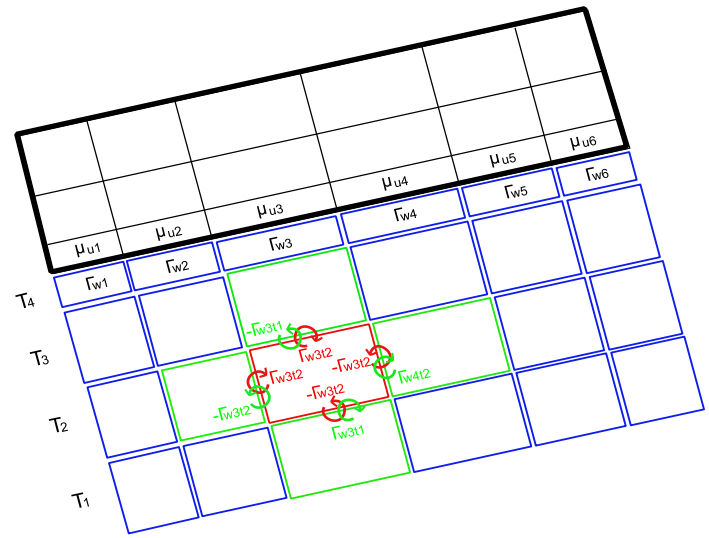
The unsteady Bernoulli eq. is used to compute C_P



MIRAS wake modelling

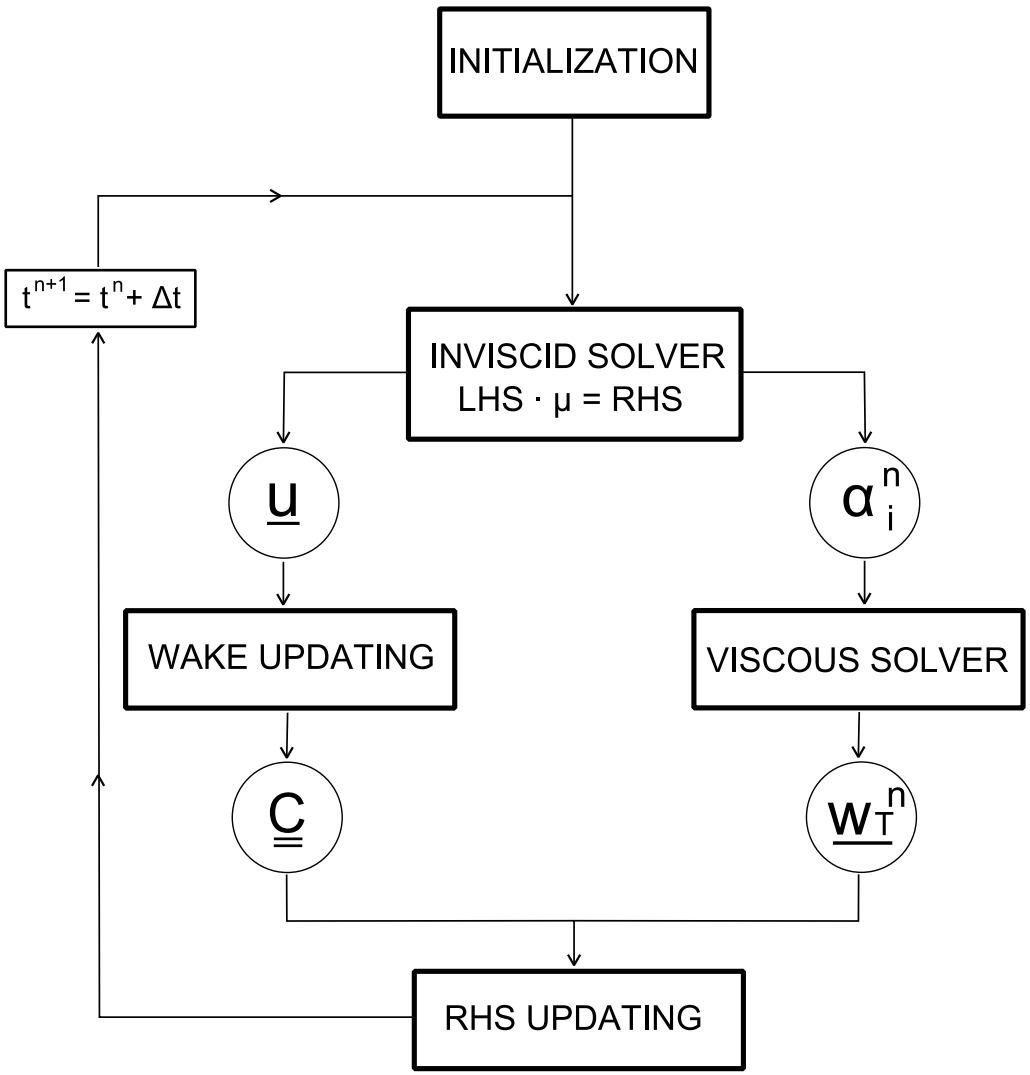
- The Kutta condition reads:

$$\Gamma_w = \mu_u - \mu_l$$



- **Time scheme** for the vortex filament position updating:
  - 1st to 4th order Adams Bashfourth
  - 4th order Adams Bashfourth Moulton predictor-corrector
- **Scully** profile is used in the viscous core model.
- **Initial vortex core**, S_C, is set to be equal to a 10% of the local chord.
- **Squire** apparent turbulent eddy viscosity parameter, δ, is included to take into account the vortex core growth rate with vortex age.
- **Leishman** straining model is included to account for changes in vortex filament radius due to stretching and squeezing.

MIRAS V-I coupling diagrame



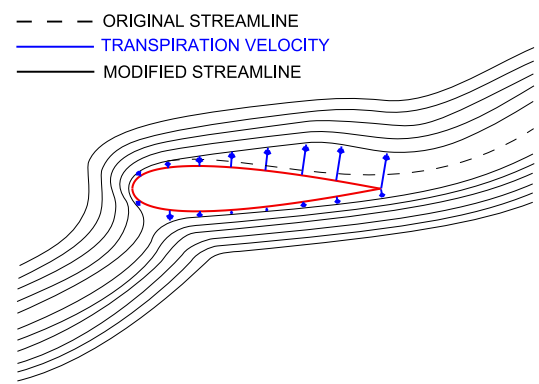
MIRAS boundary layer solver Q³UIC

- **Q³UIC** is used to introduce viscous effects into the 3D panel method.

$$\frac{\partial \theta_1}{\partial s} = -\frac{\theta_1}{u_e}\frac{\partial u_e}{\partial s}(2+H) + \frac{C_f}{2} + s_w p_r \frac{2Ro \cdot ls}{u_{2D} c}\delta_2 - \frac{1}{u_e}\frac{\partial u_e}{\partial s}(2\theta_2 - \delta_2) - \frac{ls}{c}(2\theta_2 - \delta_2)$$

$$\frac{\partial \theta_2}{\partial s} = -\frac{2\theta_2}{u_e}\frac{\partial u_e}{\partial s} + \tan\beta_w \frac{C_f}{2} + \frac{ls}{c}\left(\theta_1 + \delta_1 - \delta - \delta_3 + s_w p_r \frac{2Ro}{u_{2D}}(\delta - \delta_1)\right) - \frac{1}{u_e}\frac{\partial u_e}{\partial r}(2\delta_3 + \delta)$$

- **Q³UIC** solves the boundary layer at each span station given:
  - Airfoil Geometry.
  - Reynolds number.
  - Rotational parameters (R_O & l).
  - Angle of attack.



- Transpiration velocities **Q3UIC** → Extra source distribution in RHS vector.

NTNU MODEL ROTOR

Airfoil = S826

R = 0.4 m.

Root chord = 0.08 m

Tip chord = 0.0258 m

SURFACE MESH

Spanwise cells = 19

Chorwise cells = 160

Wake revolutions = 25

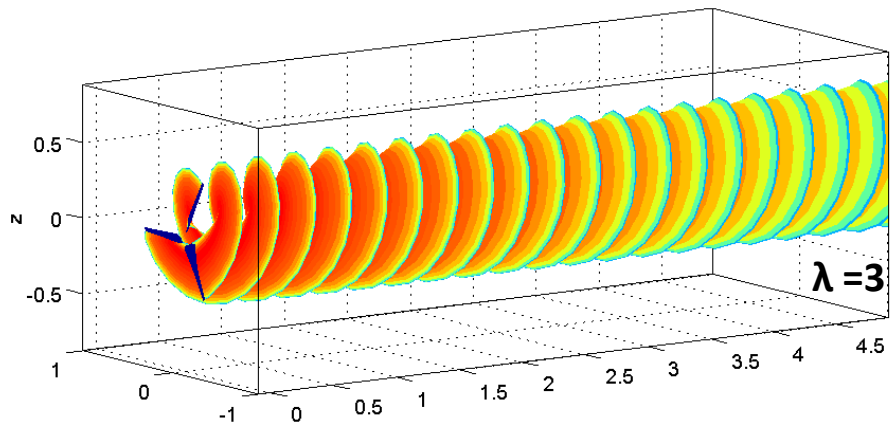
Angular discret. = 20°

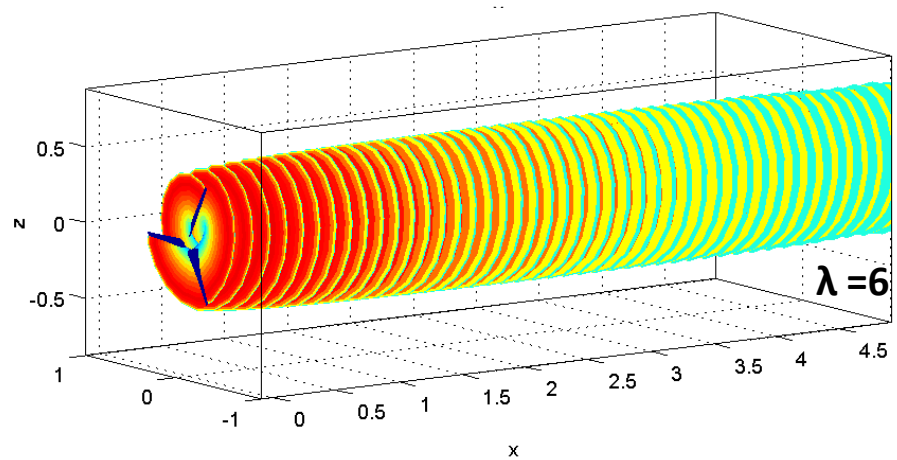
Qw = 10 m s^{-1}

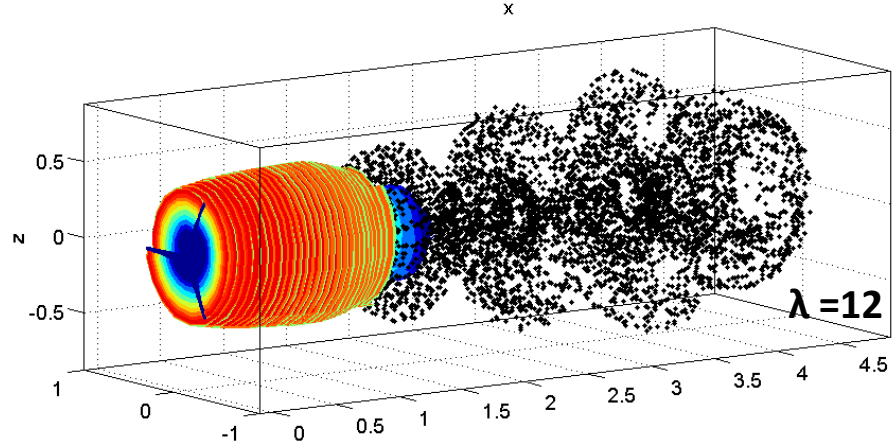
TSR = 1 to 12

Reynolds number = 5·10^4 to 2·10^5

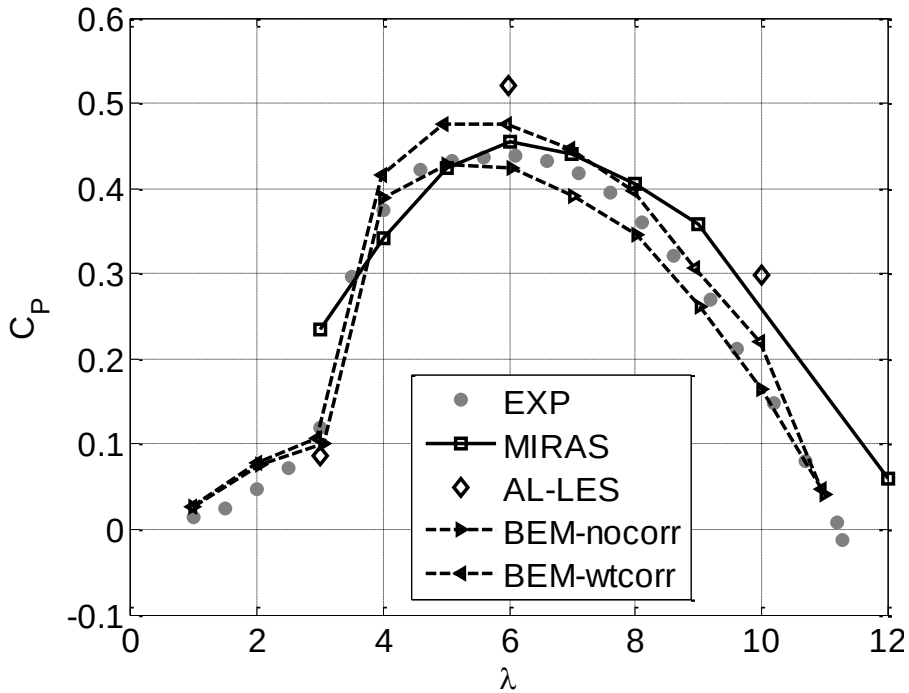
BL free transition

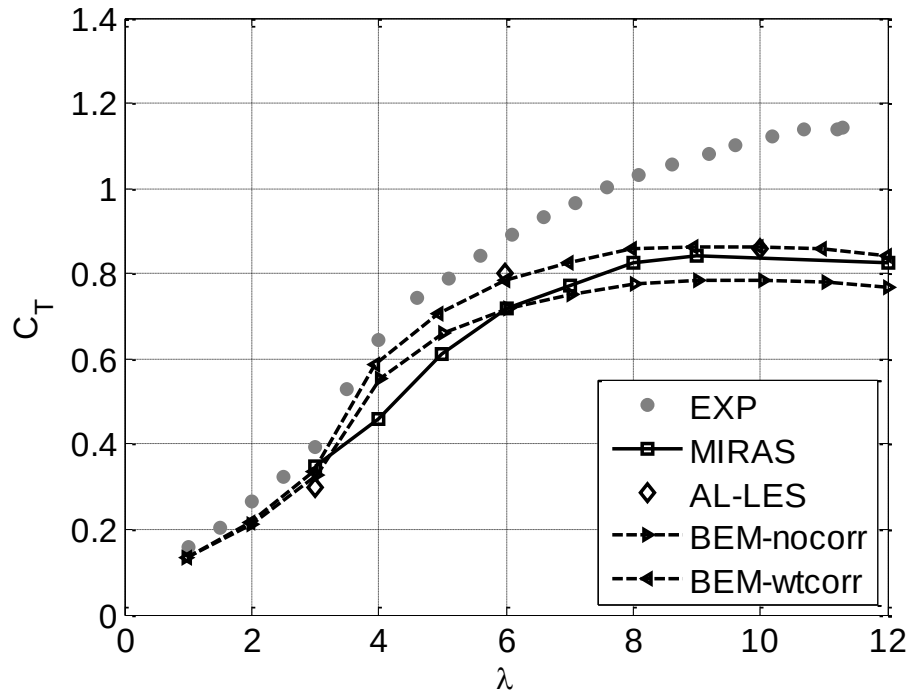






NTNU MODEL ROTOR





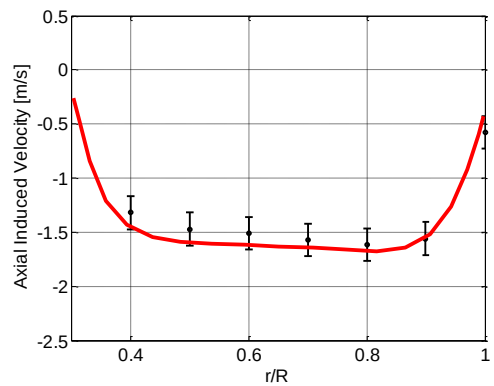
DELFT MODEL ROTOR

Airfoil = naca 0012

R = 0.6 m.

Chord = 0.08 m.

β_{tip} = 2°



λ =7.96

SURFACE MESH

Spanwise cells = 19

Chordwise cells = 50 (wake study)

Wake revolutions = 16

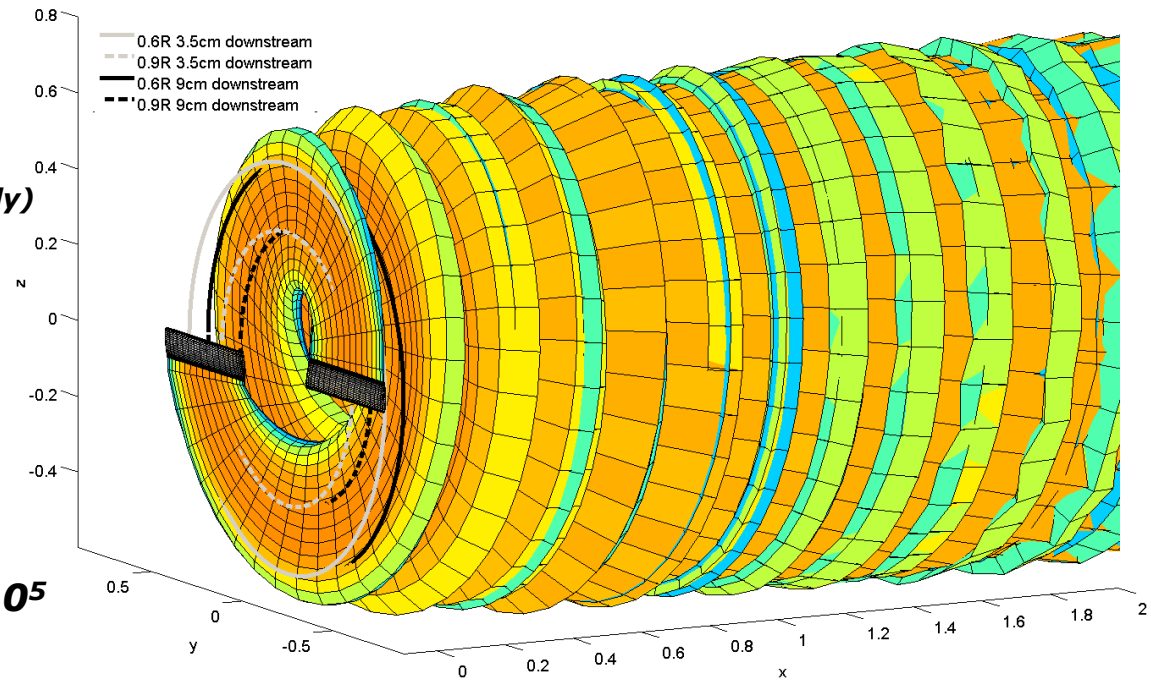
Angular discret. = 10°

Ω = 700 rpm

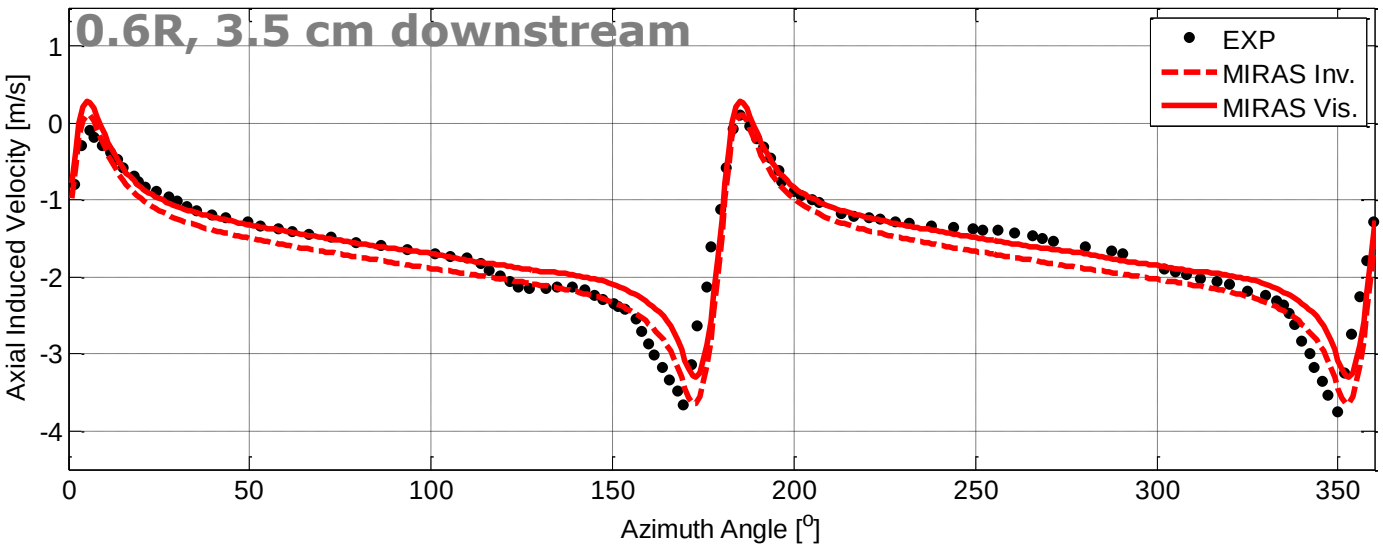
Q_w = 5.5 m s^{-1}

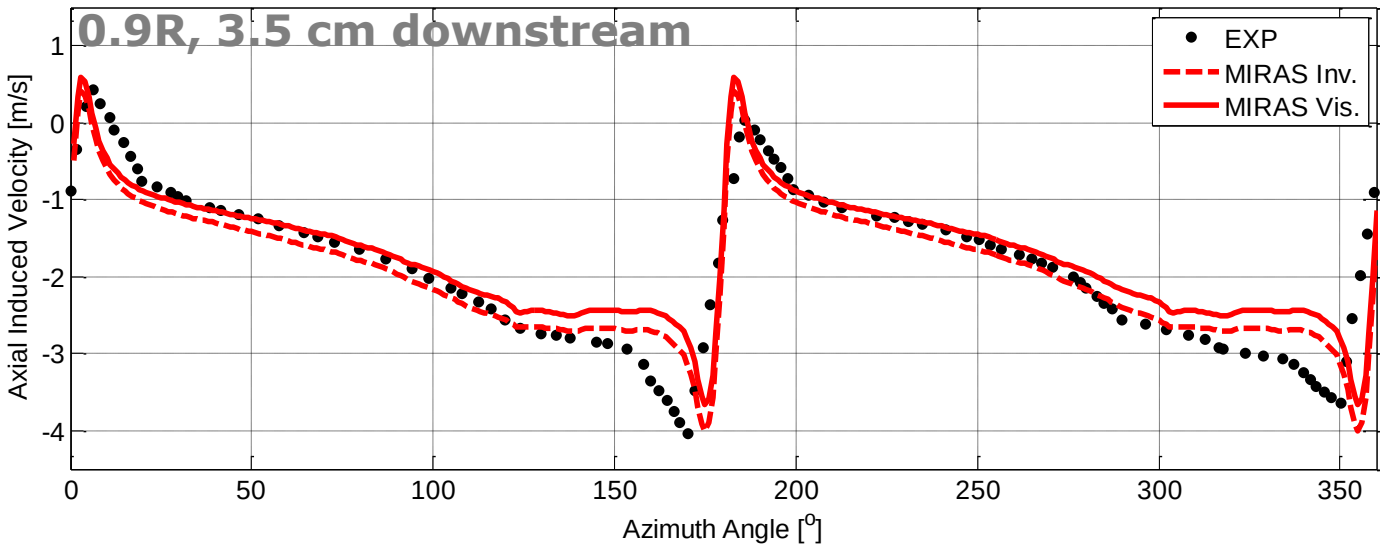
Reynolds number = $1 \cdot 10^5$ to $2 \cdot 10^5$

BL free transition



DELFT ROTOR EXPERIMENT





MEXICO MODEL ROTOR

Airfoils = ***DU 91-W2-250***

RISØ A1-21

NACA 63-418

R = ***2.25 m.***

β_0 = ***-2.3°***

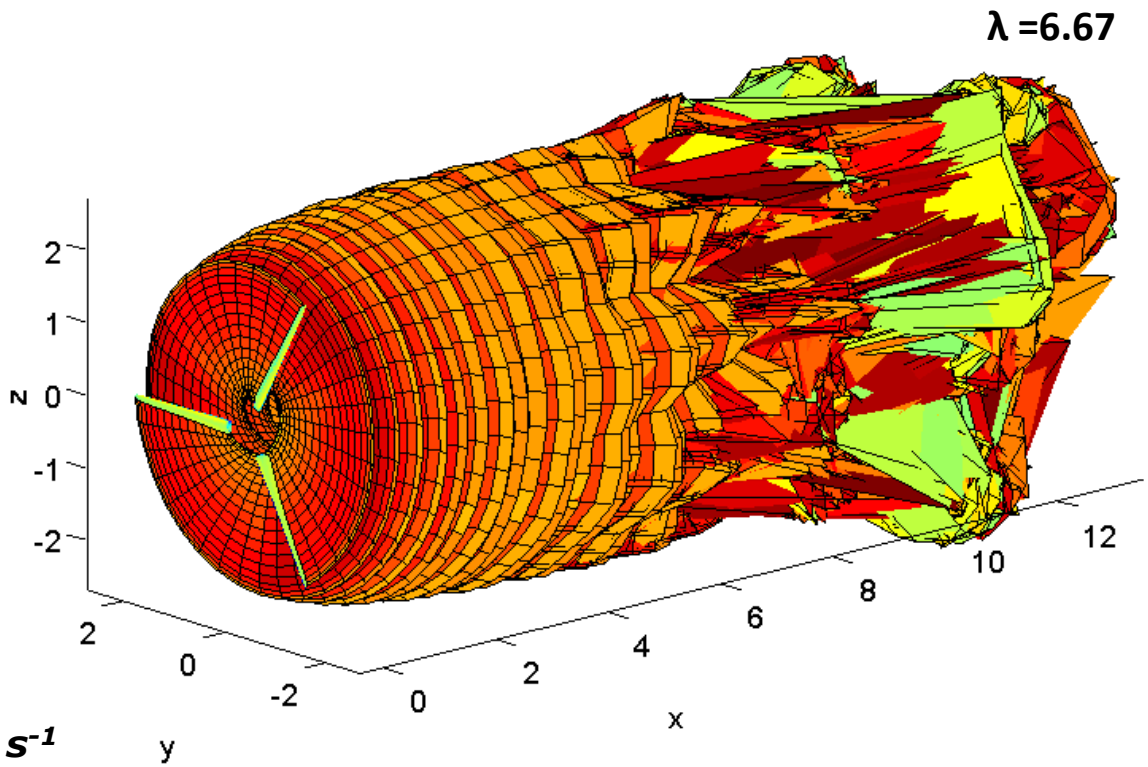
SURFACE MESH

Spanwise cells = 19

Chordwise cells = 50

Wake revolutions = 16

Angular discret. = 10°



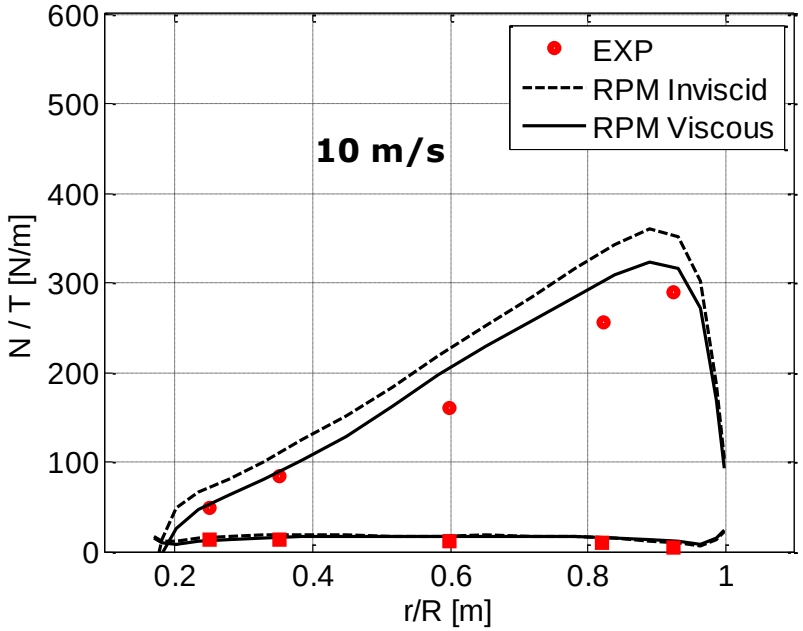
Ω = $44.45\ s^{-1}$

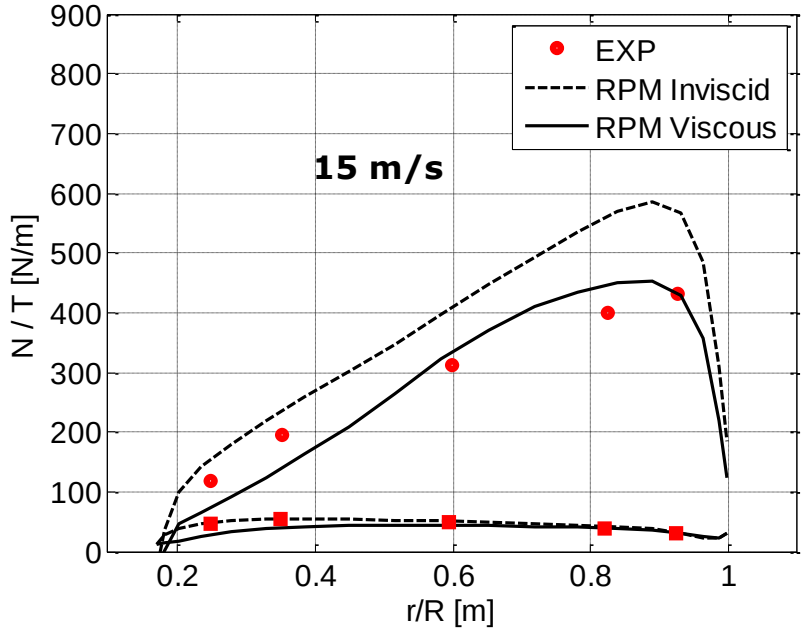
Q_w = $10 / 15 / 24\ m\ s^{-1}$

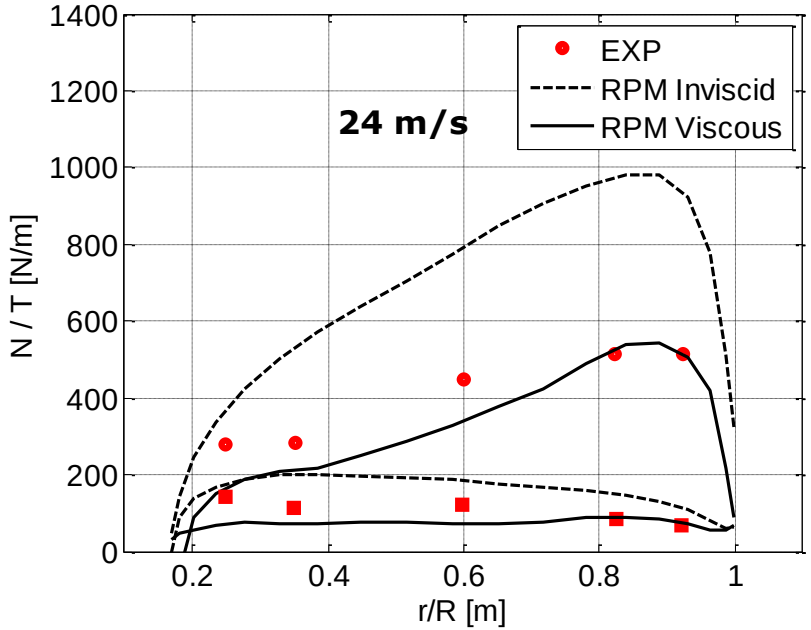
Reynolds numbers = $2 \cdot 10^5$ ***to*** $7 \cdot 10^5$

Boundary layer trip = 5% from LE

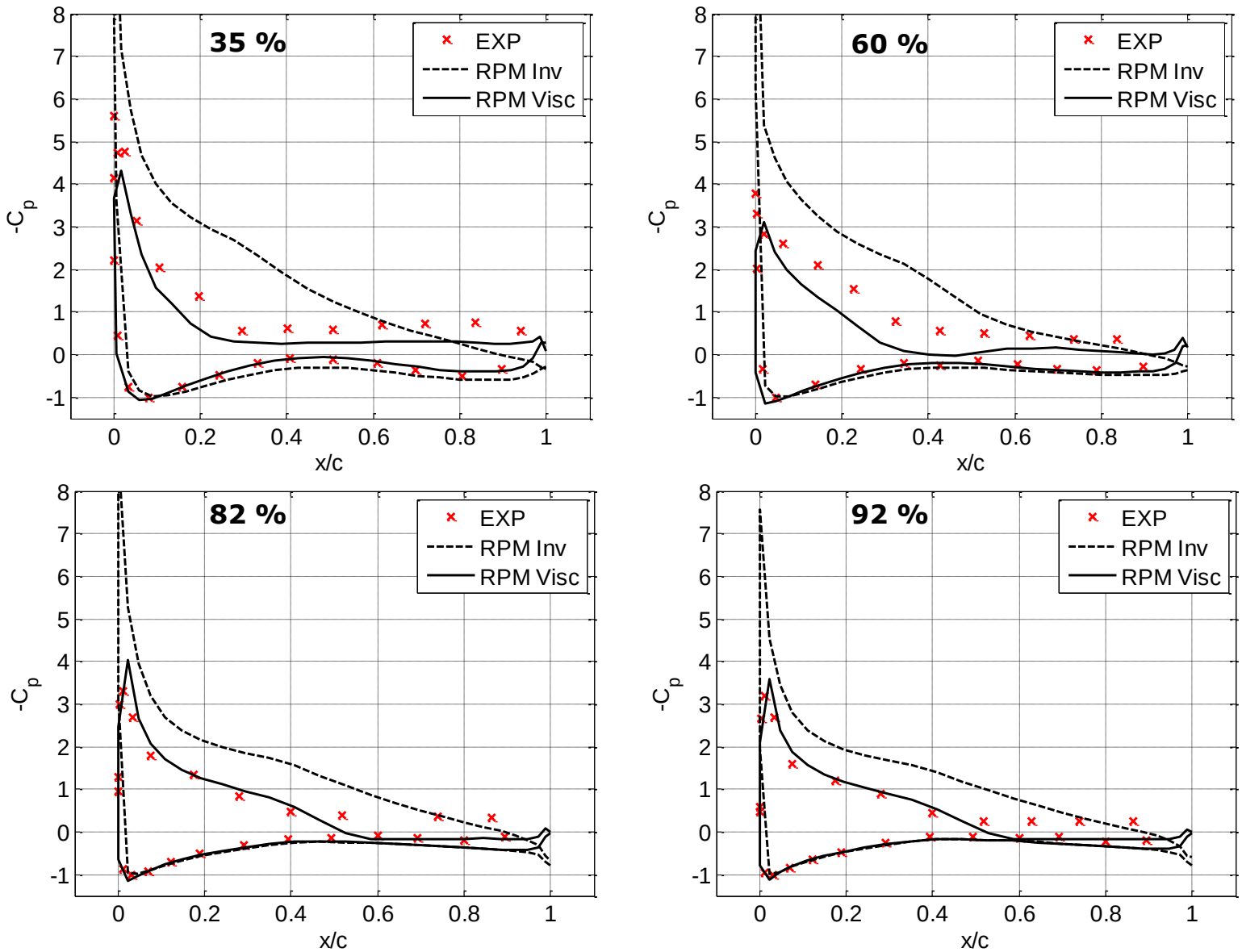
MEXICO BLADE AERODANYMICS, N / T



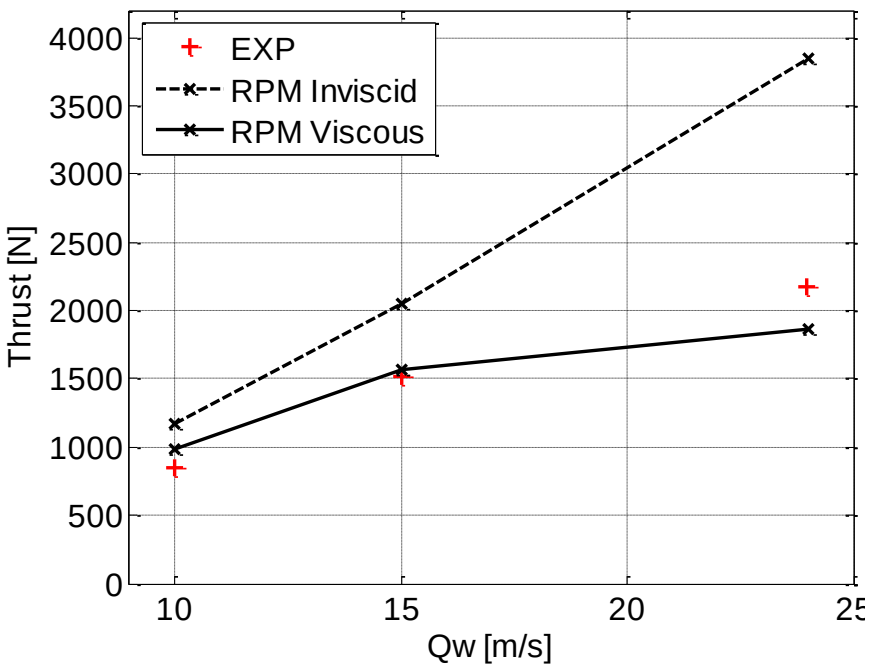


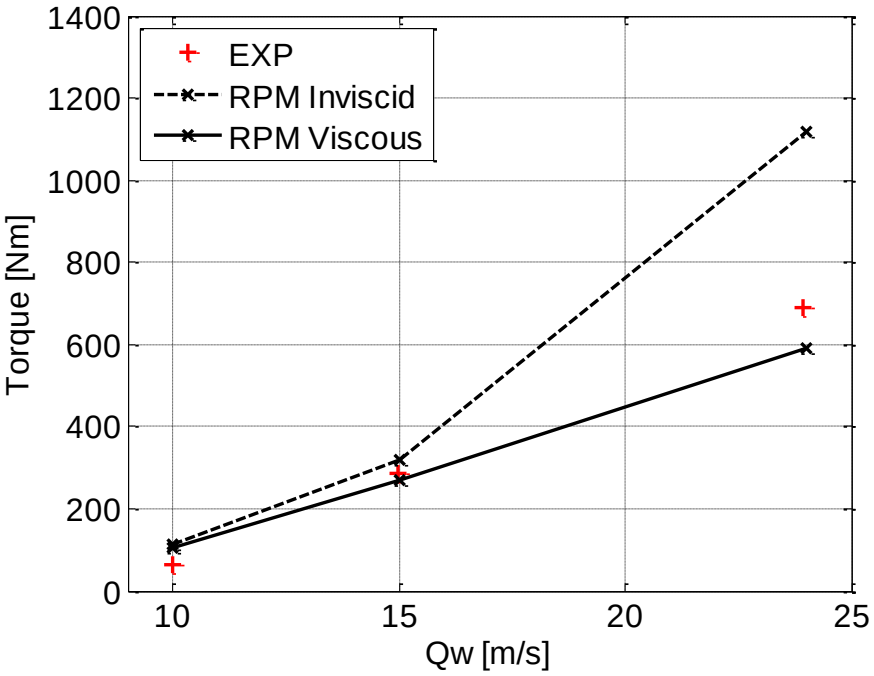


MEXICO BLADE, C_P , 24 m s^{-1}

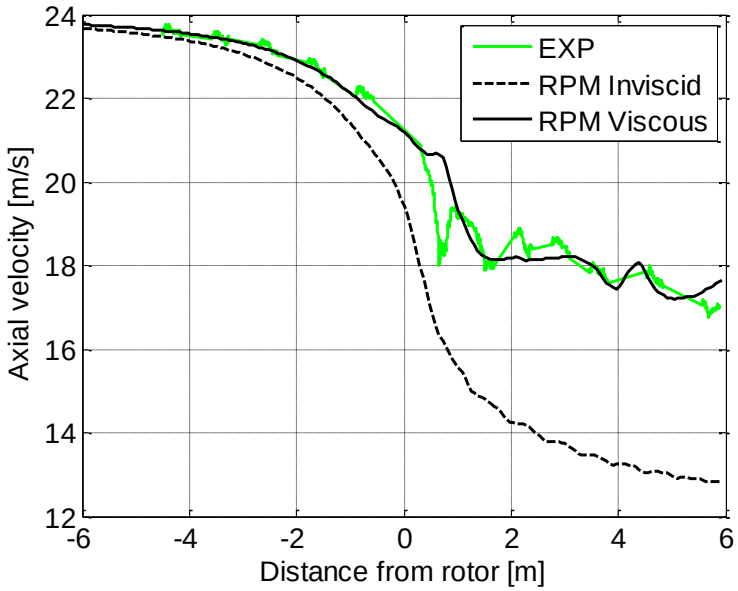


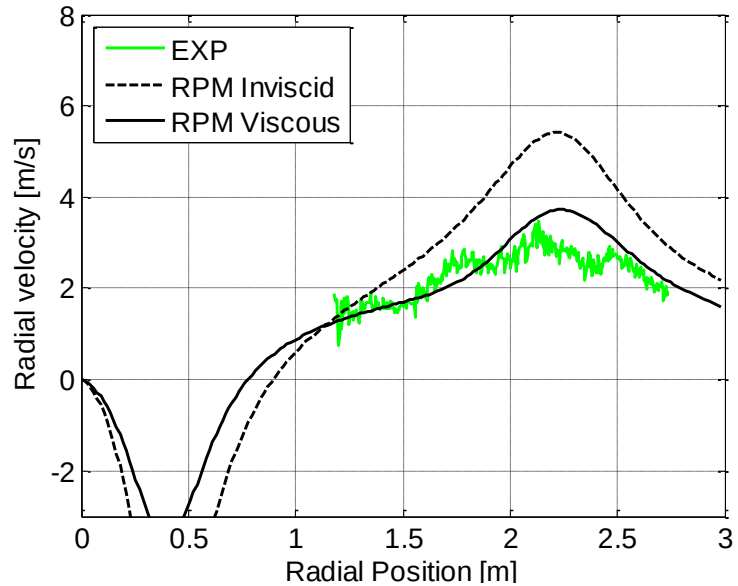
MEXICO ROTOR GLOBAL PERFORMANCE

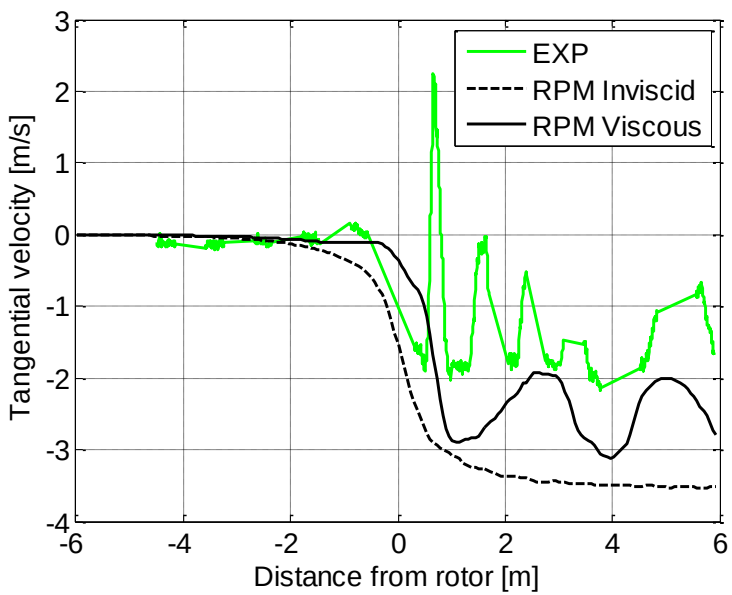


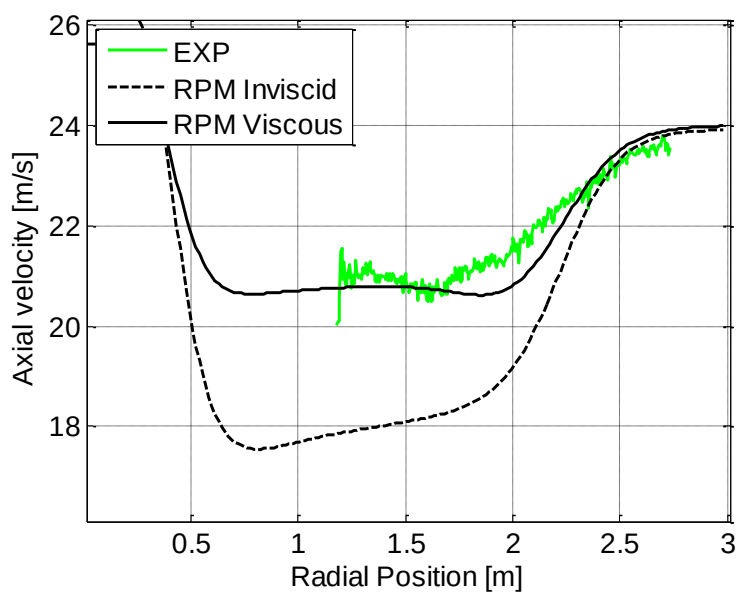


MEXICO ROTOR WAKE(24 ms^{-1})









2.5MW NM80 WIND TURBINE

Blades = LM 38.8 m

Airfoil = NACA 63-4xx

Pre-bend = 1.42 m.

D = 80.08 m.

Pitch controlled

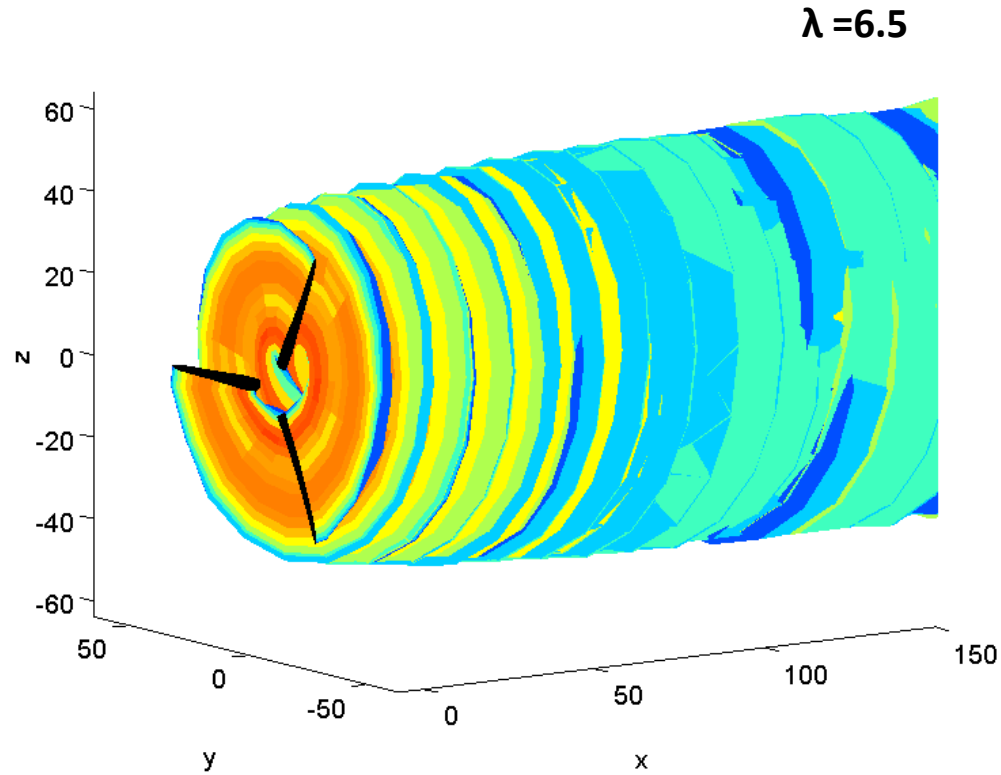
SURFACE MESH

Spanwise cells = 19

Chordwise cells = 160

Wake revolutions = 25

Angular discret. = 20°



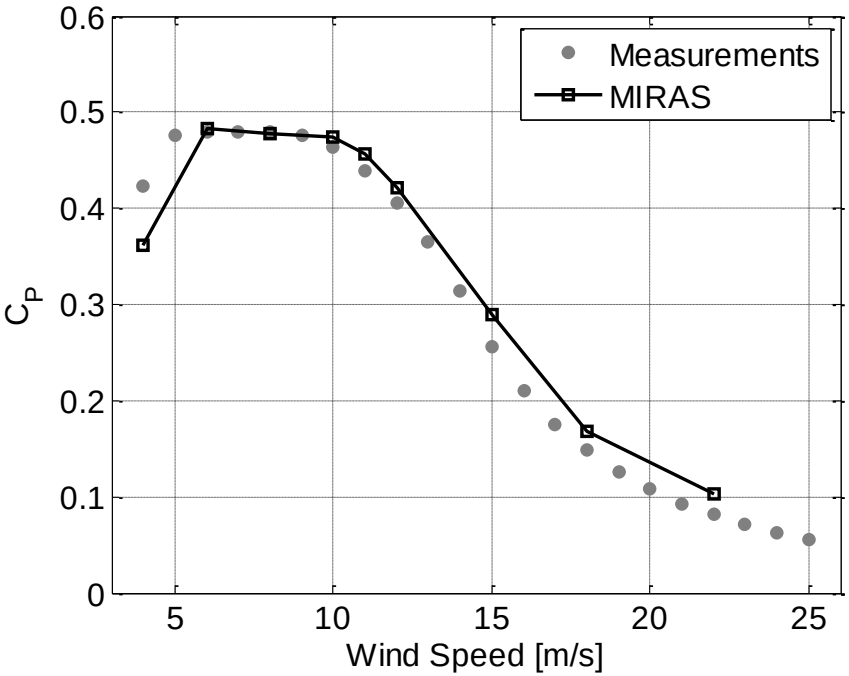
Ω = 10.90 to 16.80 rpm

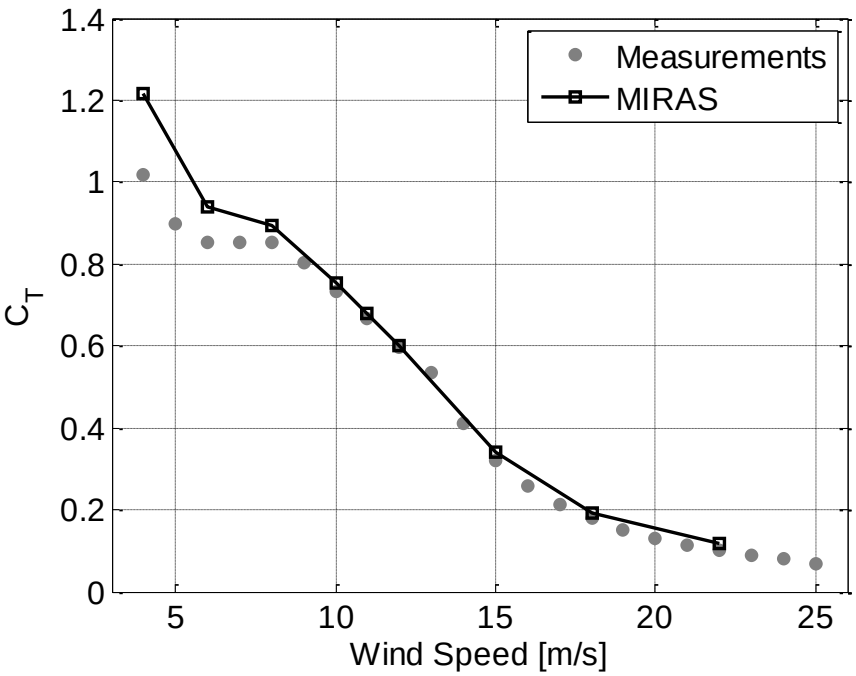
Q_w = 4 to 22 m s^{-1}

Reynolds numbers = $1.7 \cdot 10^6$ to $7 \cdot 10^6$

Boundary layer trip = 5% from LE

2.5MW NM80 WIND TURBINE





NREL 5MW VIRTUAL ROTOR

Airfoil = DU XX

NACA64418

R = 62.9898 m.

Pitch controlled

SURFACE MESH

Spanwise cells = 19

Chordwise cells = 160

Wake revolutions = 16

Angular discret. = 10°

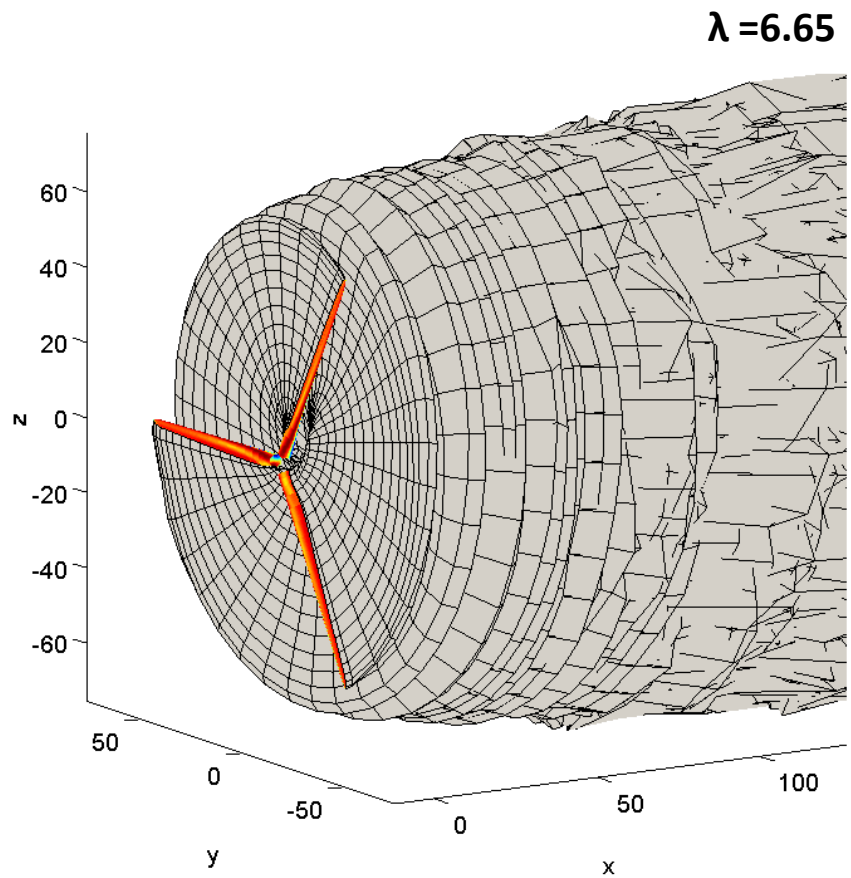
Ω = 7.92 to 12.10 rpm

Q_w = 6 to 12 m s^{-1}

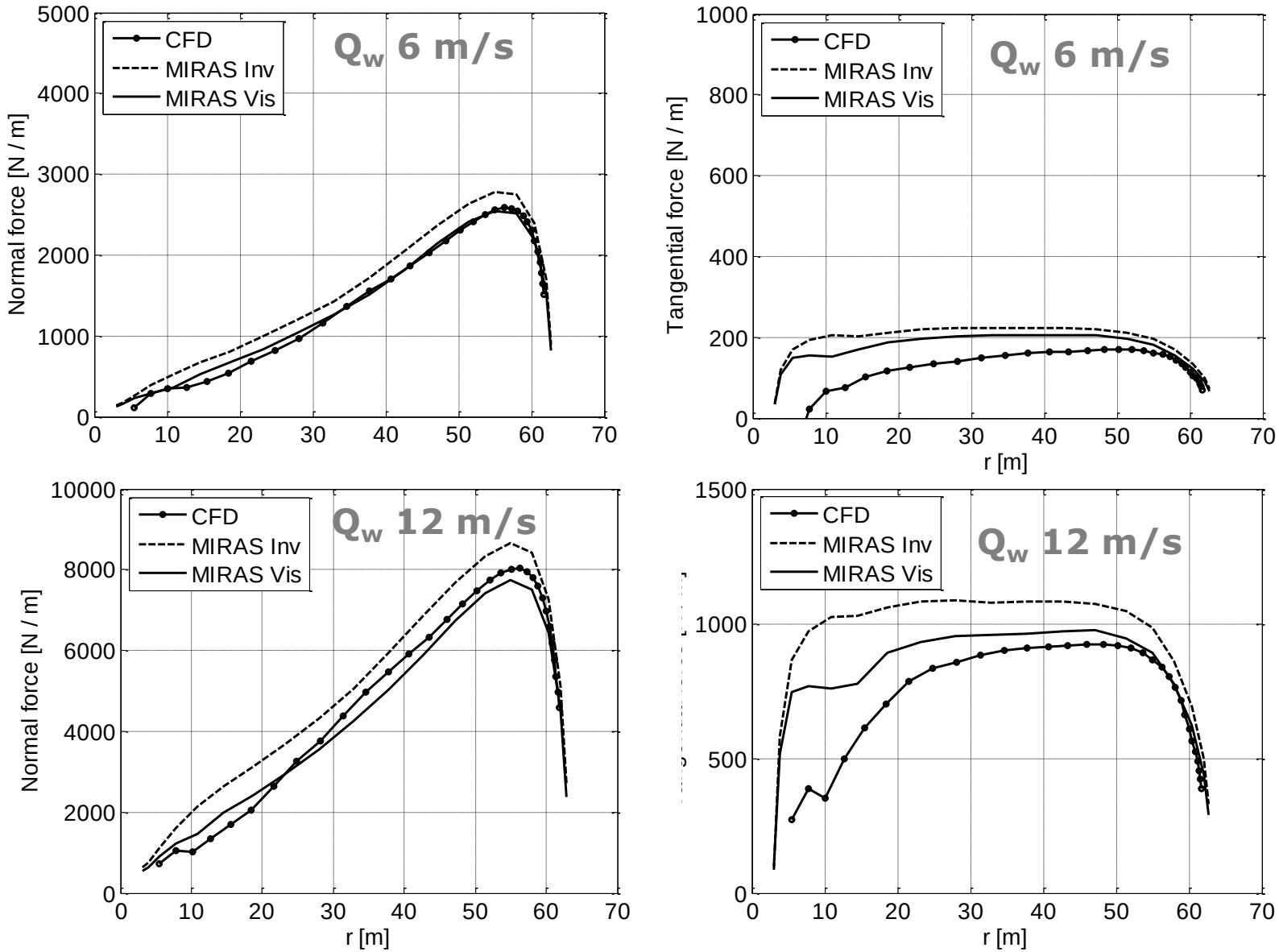
Reynolds numbers = $1.5 \cdot 10^6$ to $1.2 \cdot 10^7$

TI = 0.1%

BL free transition



NREL 5MW VIRTUAL ROTOR



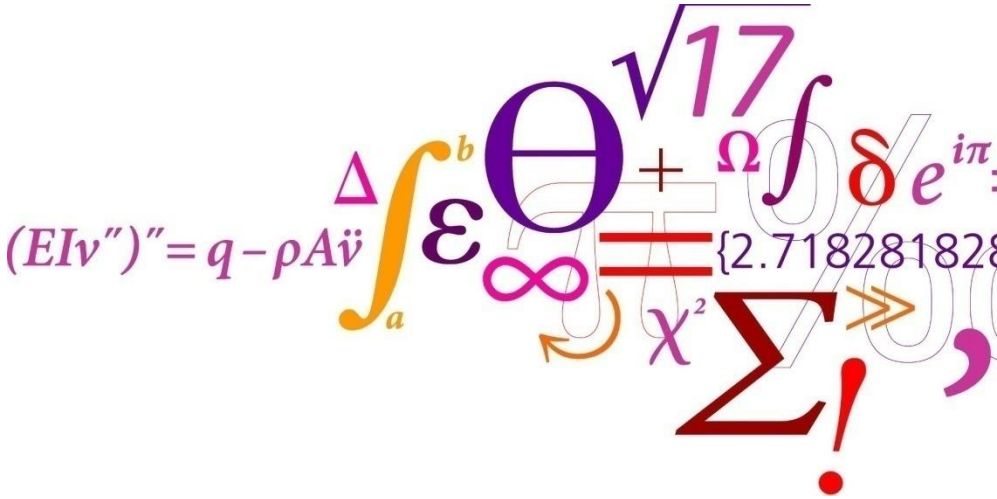
CONCLUSIONS

- IT HAS BEEN PROVEN THAT THE **MIRAS** CODE CAN BE USED TO **SUCCESFULLY SIMULATE WIND TURBINE ROTORS** UNDER AXIAL INFLOW CONDITIONS.
    - VALIDATIONS HAVE BEEN CARRIED OUT FOR FIVE DIFFERENT ROTOR GEOMETRIES RANGING FROM MODEL ROTORS TO LARGE SCALE WIND TURBINES.
- THE **VISCOUS-INVISCID COUPLING WITH Q^3UIC IMPROVES** GENERALLY THE PREDICTION OF BLADE AERODYNAMICS AND WAKE CHARACTERISTICS. ESPECIALLY AT HIGH WIND SPEEDS WHERE LARGER FLOW SEPARATION REGIONS EXIST.
- THE MODEL **SLIGHTLY OVERPREDICTS C_P AT HIGH TIP SPEED RATIOS**, PROFILE DRAG SEEMS TO PLAY AN IMPORTANT ROLE AT SUCH HIGH TSR.
- A **FINE CHORDWISE BLADE DISCRETIZATION** IS IMPORTANT TO CAPTURE THE CORRECT POWER COEFFICIENT AT HIGH TIP SPEED RATIOS.

FUTURE WORK

- A DOUBLE WAKE MODEL WILL BE IMPLEMENTED FOR ROTOR SIMULATIONS UNDER DEEP STALL CONDITIONS (ongoing work).
- YAW SIMULATIONS WILL BE PERFORMED AND COMPARED AGAINST EXPERIMENTAL DATA (ongoing work).
- THE VORTEX FILAMENTS IN THE WAKE WILL BE TRANSFORMED INTO VORTEX PARTICLES (Master project starting in Januar-February, collaboration with Delft).
- GPU, MPI AND FAST MULTIPOLE EXPANSION FOR SPEEDING UP THE SIMULATIONS (Collaboration with Delft, Emmanuel?).

THANK YOU FOR YOUR ATTENTION.



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