Three-Dimensional Viscous-Inviscid Coupling Method for Wind Turbine Simulations

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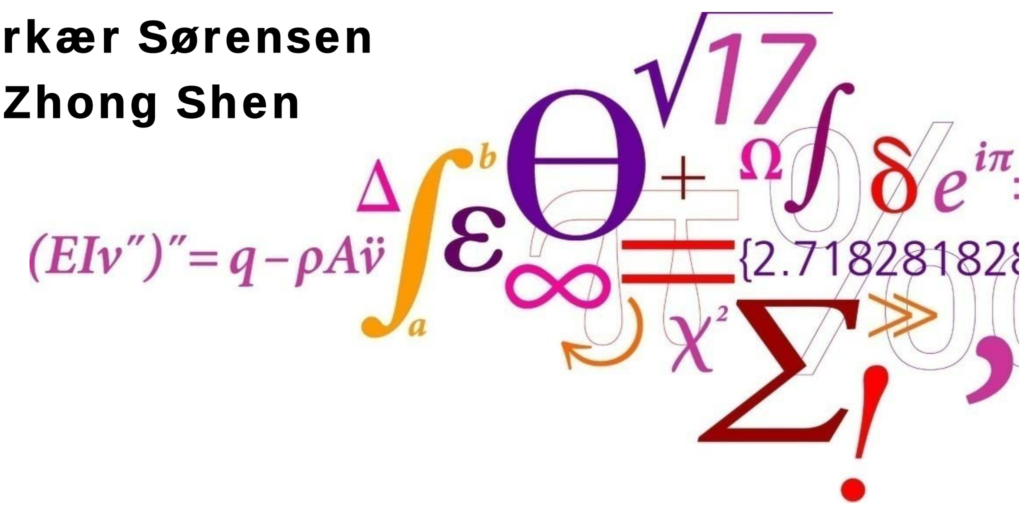


DTU *WIND ENERGY*

PRESENTATION LAYOUT

- INTRODUCTION
- 3D PANEL METHOD + FREE WAKE
- VISCOUS-INVISCID COUPLING WITH Q^3UIC
- CODE VALIDATION :
    - NON-ROTATING CASE
    - WIND TURBINE ROTOR (MEXICO EXPERIMENT).
        - MESH INDEPENDENCE STUDY.
        - BLADE AoA CALCULATION.
        - BLADE AERODYNAMIC COEFFICIENTS.
        - BLADE SURFACE PRESSURE DISTRIBUTION.
        - ROTOR GLOBAL PERFORMANCE.
        - WAKE VELOCITIES.
- CONCLUSIONS & FUTURE WORK

INTRODUCTION

1. Unlike Euler and Navier-Stokes codes that need to solve the entire flow domain, the panel method can solve the flow around a complex geometry by distribution of singularity elements on the body surface. In principle a faster solution can be obtained, making possible to use this solver iteratively during the design stage.
2. Computations can be performed in steady and unsteady manner using a free wake model formed by vortex filaments and clustered in vortex elements that will carry on the vorticity shed by the body. The rotor wake is key element in the blade aerodynamic performance.
3. The method becomes even more attractive by the possibility of taking into account the viscosity inside the boundary layer via the transpiration velocity through the integral boundary layer equations. The viscosity plays a very important role in the blade aerodynamics.

3D PANEL METHOD + FREE WAKE

The solution to the flow problem is reached by distribution of quadrilateral sources (σ) and doublets (μ) on the body surface. The wake is formed by vortex filaments (μ) clustered in vortex elements.

$$\nabla\Phi = \frac{-1}{4\pi}\int_{body+wake}\mu\left[n\cdot\nabla\left(\frac{1}{r}\right)\right]ds + \frac{1}{4\pi}\int_{body}\sigma\nabla\left(\frac{1}{r}\right)ds$$

In a discrete fashion the Neumann condition of no penetration can be written:

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

The sources strength is fixed to:

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

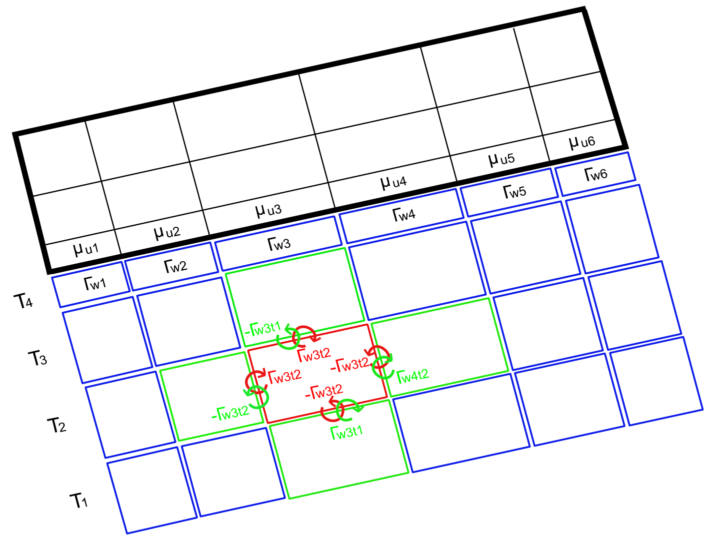
The local perturbation velocities are determined by the variations of the dipole distribution in the body surface. The unsteady Bernoulli equation is used to compute the surface pressure coefficient distribution:

$$C_{Pi} = 1 - \frac{Q_i^2}{Q_\infty^2} - \frac{2}{Q_\infty^2}\frac{\partial\Phi}{\partial t}$$

3D PANEL METHOD + FREE WAKE

• The Kutta condition reads:

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



• A fourth order **Adams Bashfourth Moulton** predictor-corrector time scheme is used for the vortex filament position updating.

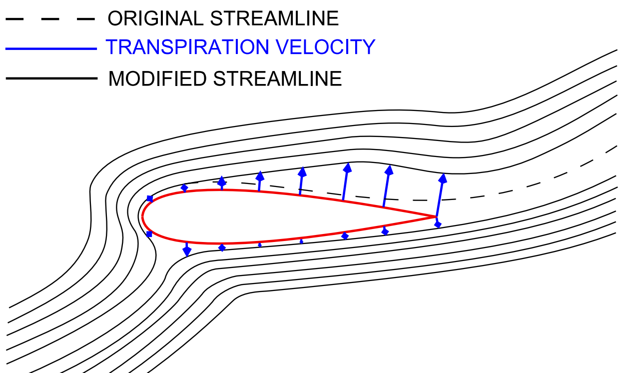
• **Scully** profile is used in the viscous core model.

• **Squire** apparent turbulent eddy viscosity parameter, δ, is included to take into account the vortex core growth rate with vortex age.

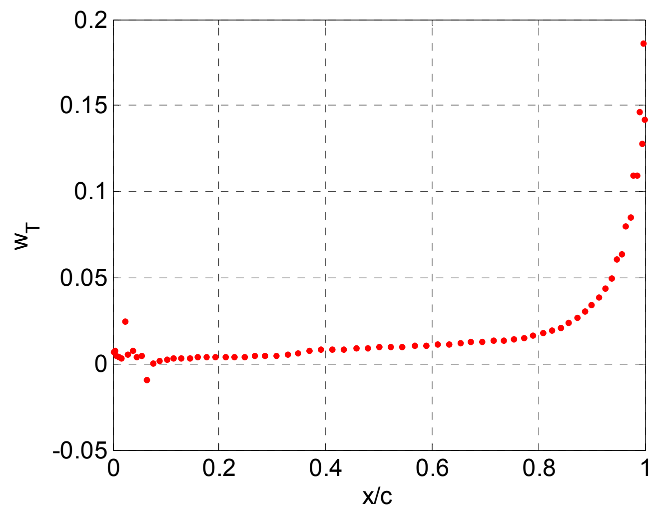
• **Leishman** straining model is included to account for changes in vortex filament radius due to stretching and squeezing.

Q3D-3D VISCOUS-INVISCID COUPLING

- **Q³UIC** computations are used to introduce viscous effects into the 3D potential panel method.
- **Q³UIC** inputs at each spanwise location:
  - Airfoil Geometry.
  - Reynolds number.
  - Rotational parameters (R_O & l).
  - Angle of attack.
- Transpiration velocities (w_T) computed with **Q³UIC** at each of the blade stations are used to add an extra source distribution in **RPM**.

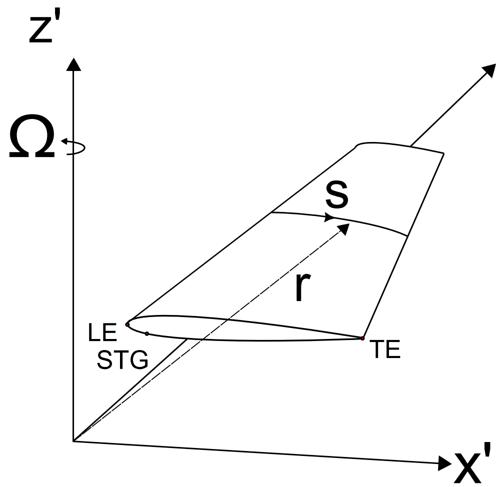


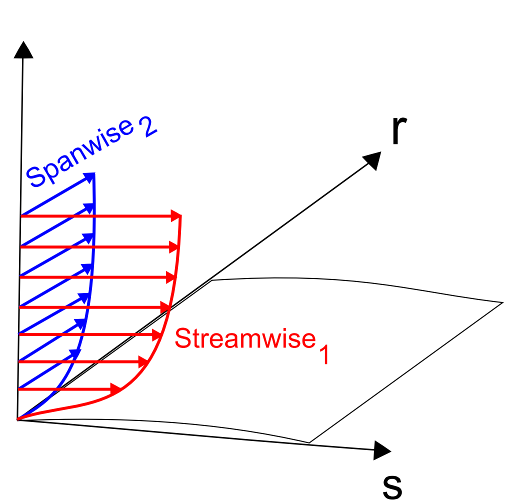
$$w_T = \frac{d}{dx}\int_0^{\infty}(u_e - u)dz = \frac{d}{dx}(u_e\delta_1)$$



Q3D VISCOUS SOLVER, Q³UIC

- The three-dimensional boundary layer equations are used with all the necessary assumptions in order to reduce them into the integral quasi-3D ones.





Integral θ -momentum

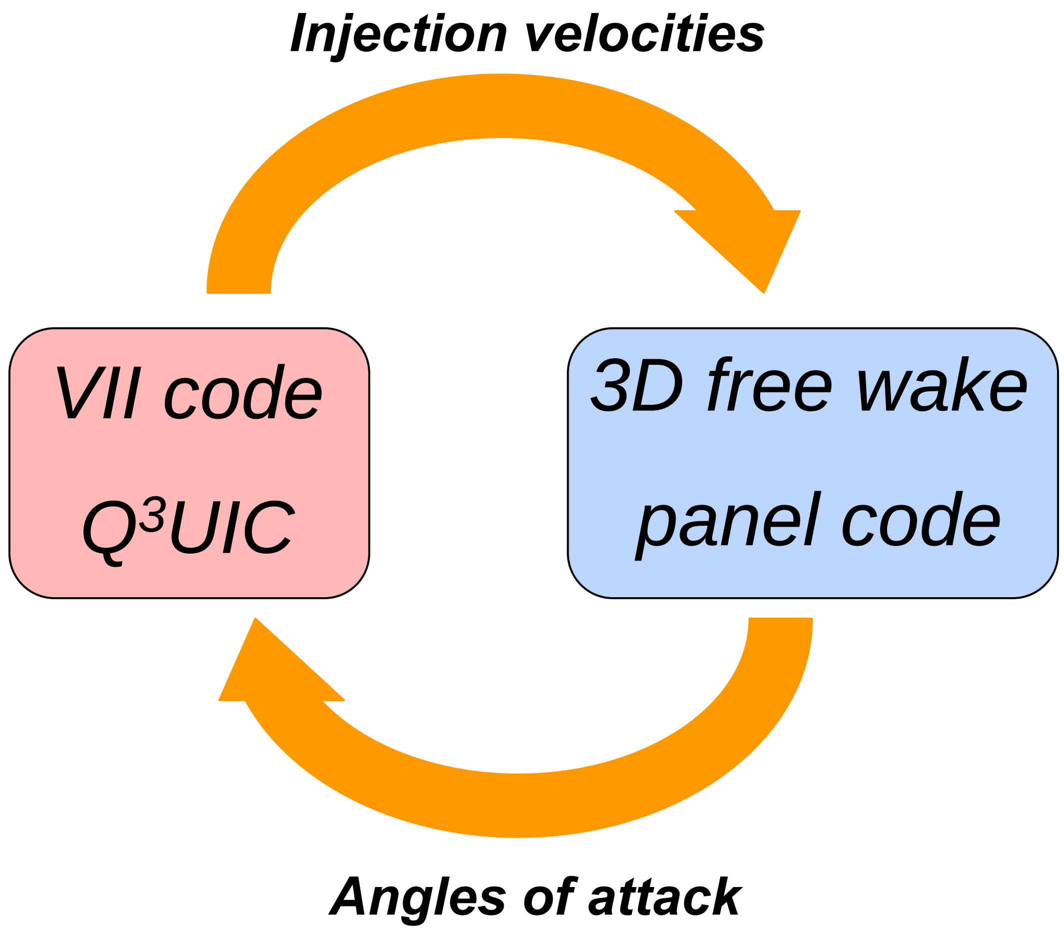
$$\frac{\partial \theta_1}{\partial s} = -\frac{\theta_1}{u_e}\frac{\partial u_e}{\partial s}(2+H) + \frac{C_f}{2} + s_w p_r \frac{2Ro \cdot ls}{u_{2D} c}\delta_2 - \frac{1}{u_e}\frac{\partial u_e}{\partial s}(2\theta_2 - \delta_2) - \frac{ls}{c}(2\theta_2 - \delta_2)$$

Integral r-momentum

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

A set of 3D turbulent closure equations are used in order to close the system (semi-empirical)

Q3D-3D V-I COUPLING DIAGRAM



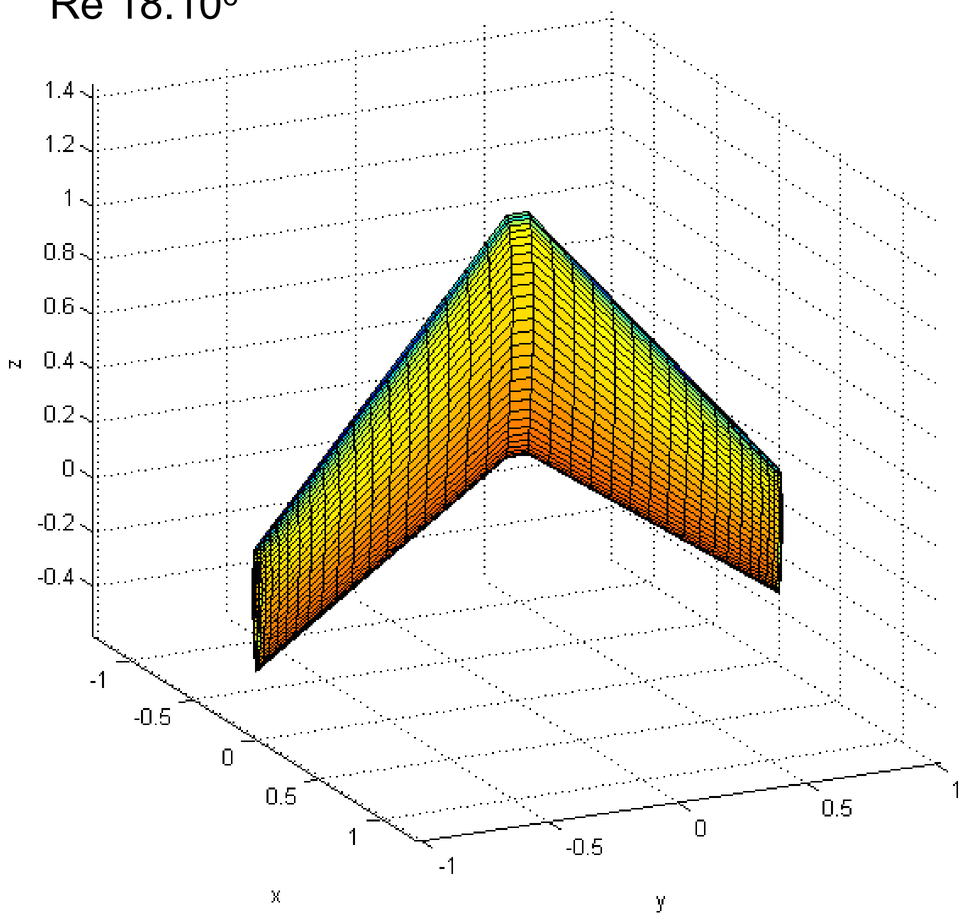
NON-ROTATING CASE

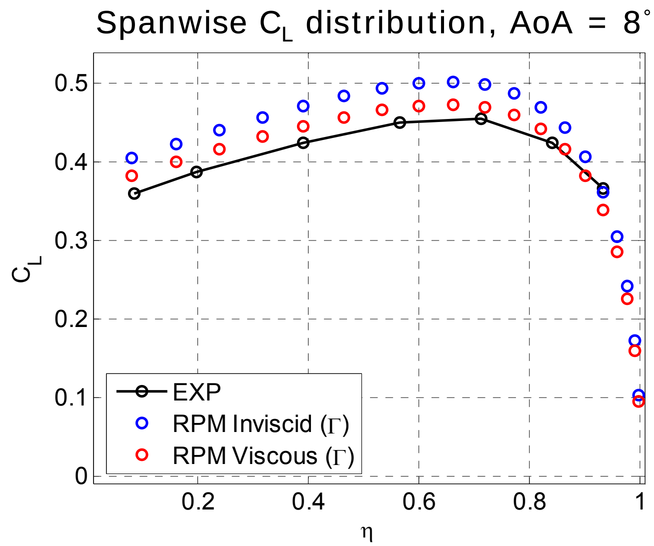
Boltz F.W. and Kolbe C.D.

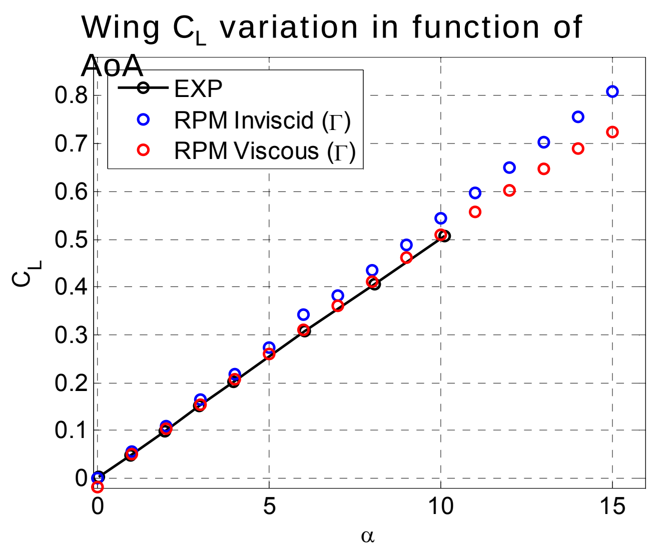
NACA RMA52D22 Wing

NACA 64A010 Airfoils

Re 18.10[6]







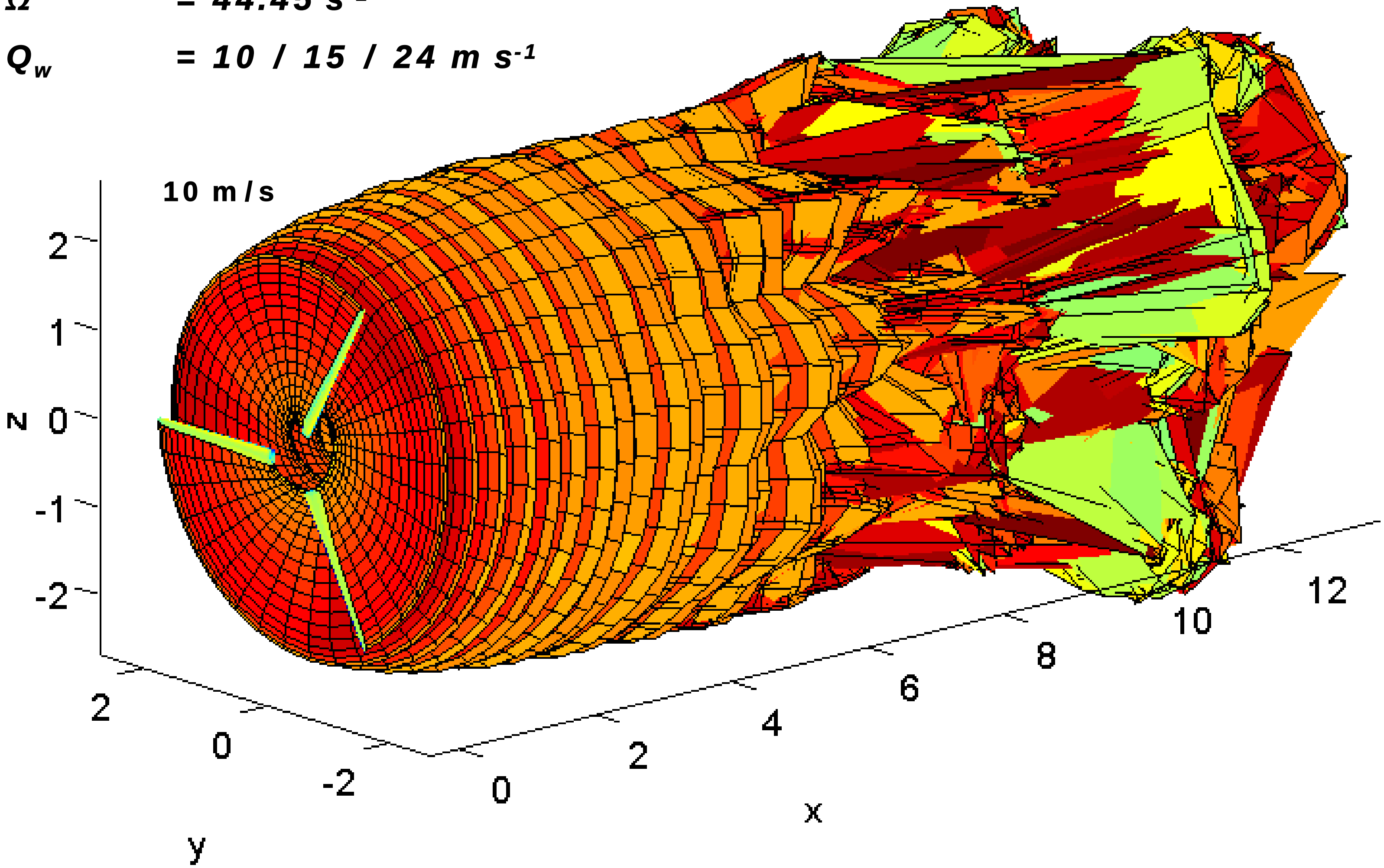
MEXICO ROTOR EXPERIMENT

R = 2.25 m.

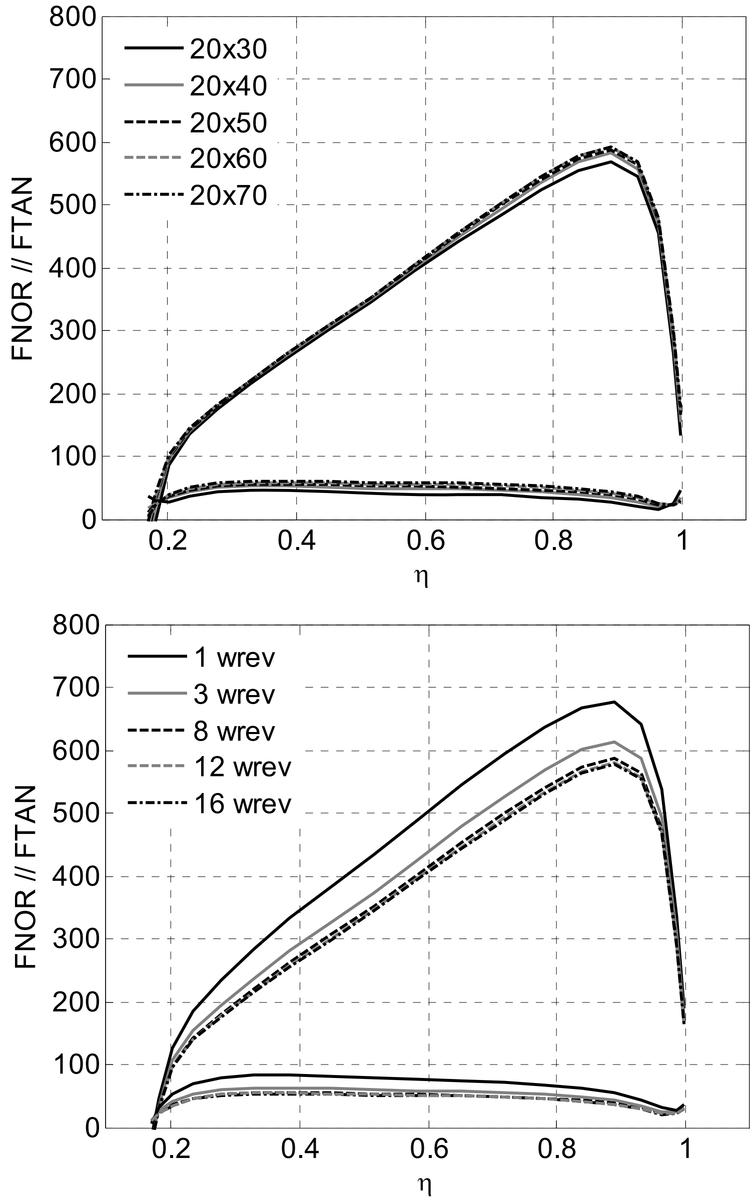
β_0 = -2.3°

Ω = 44.45 s^{-1}

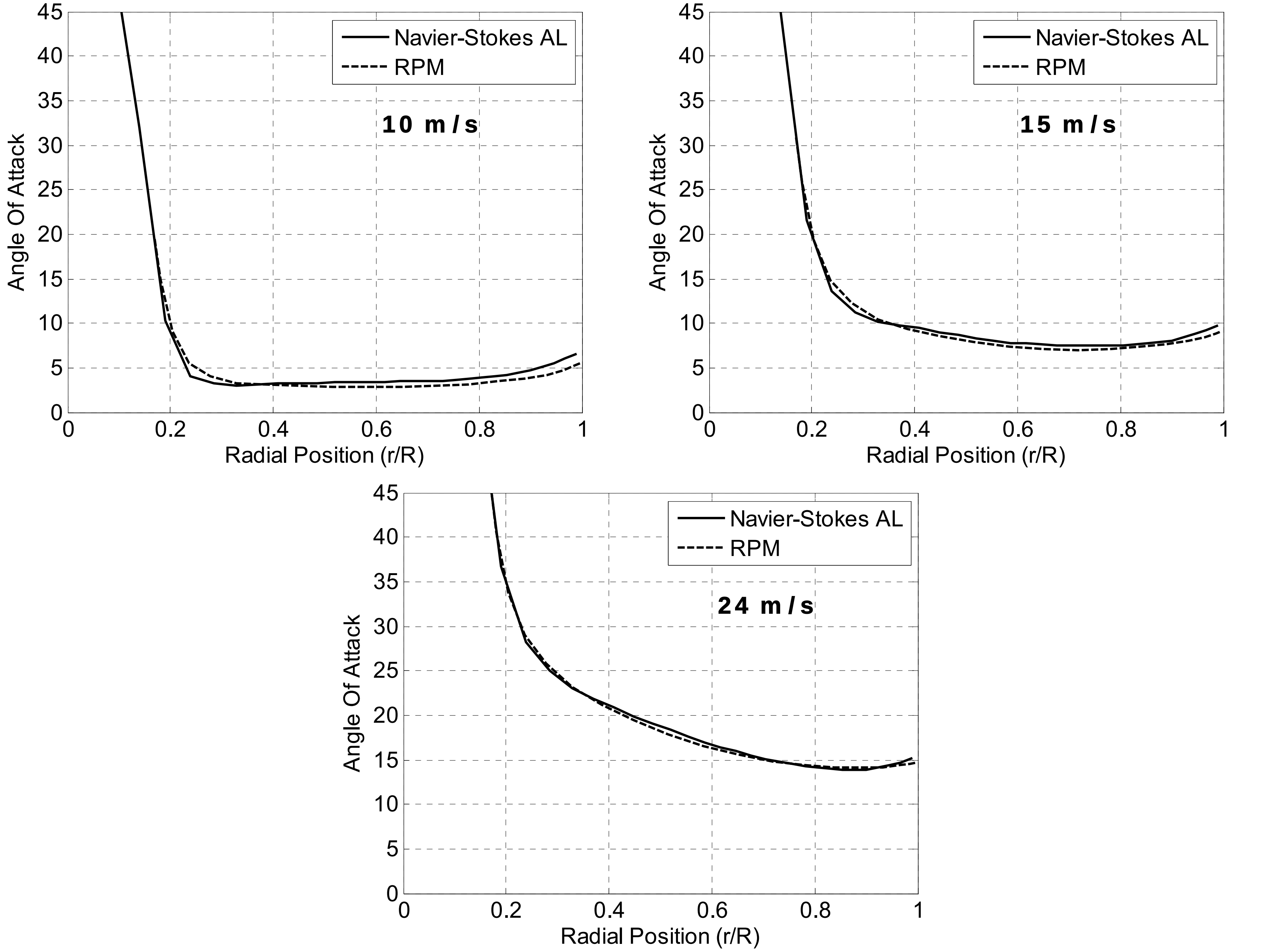
Q_w = 10 / 15 / 24 m s^{-1}



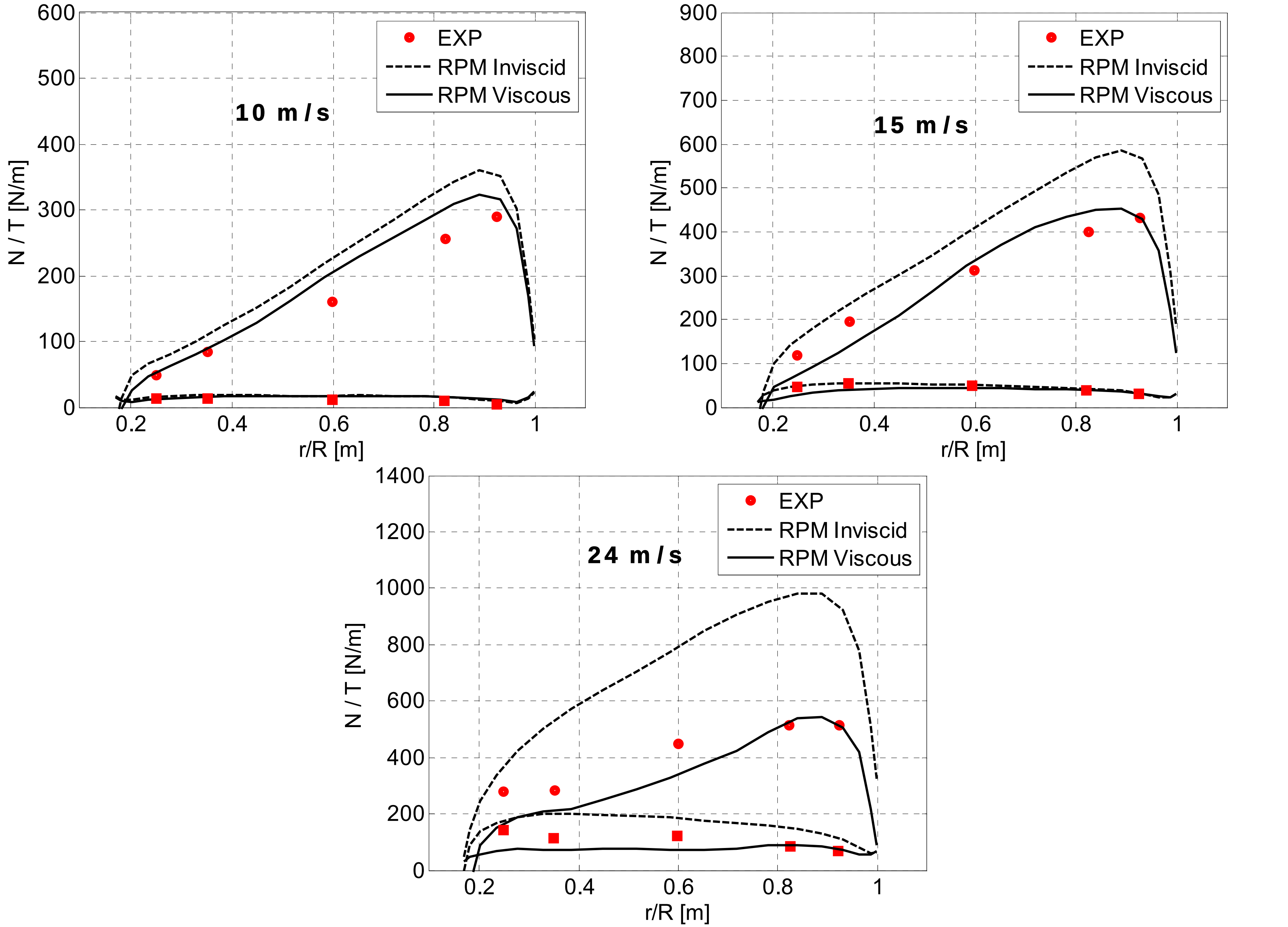
INDEPENDENCE STUDY (15 ms^{-1})



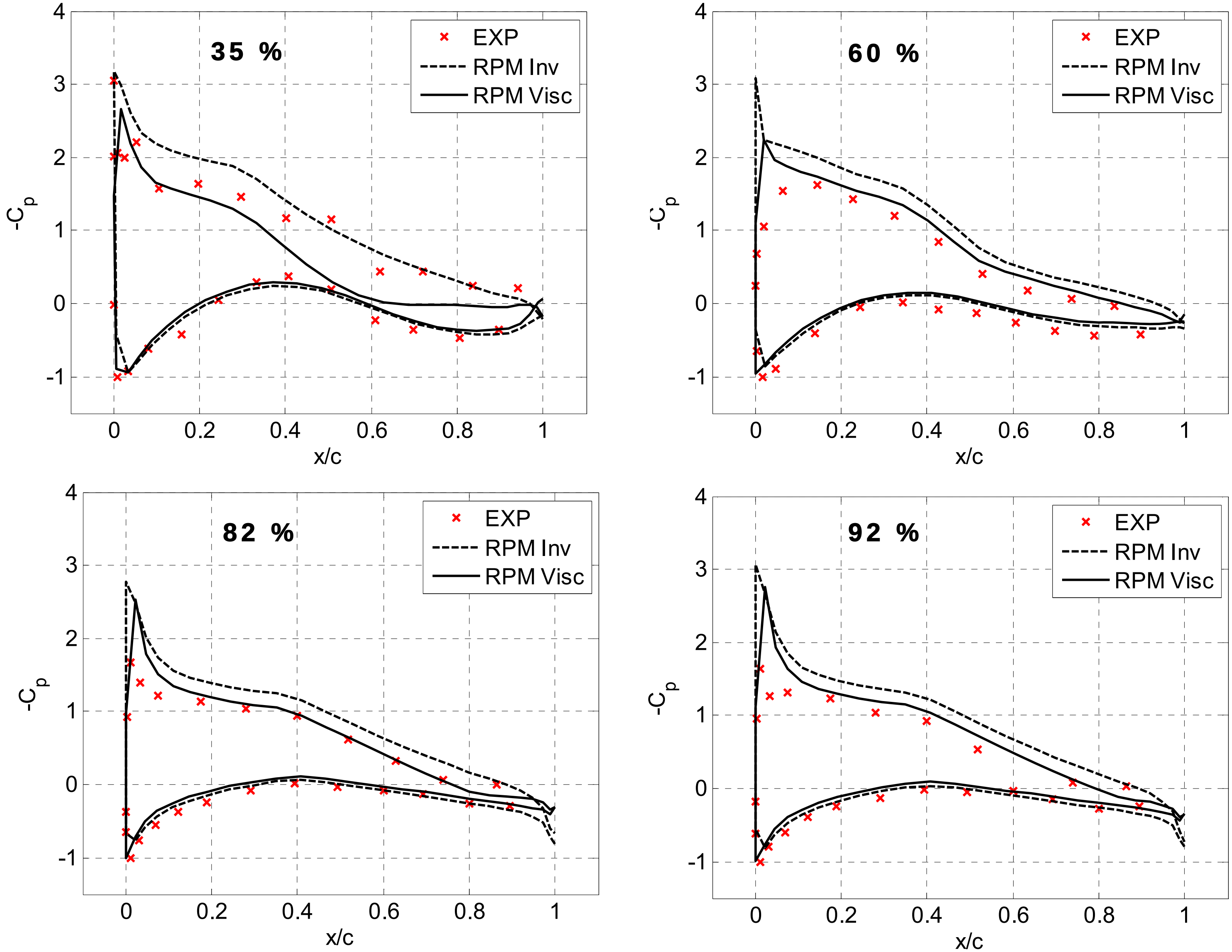
MEXICO BLADE AOA CALCULATIONS



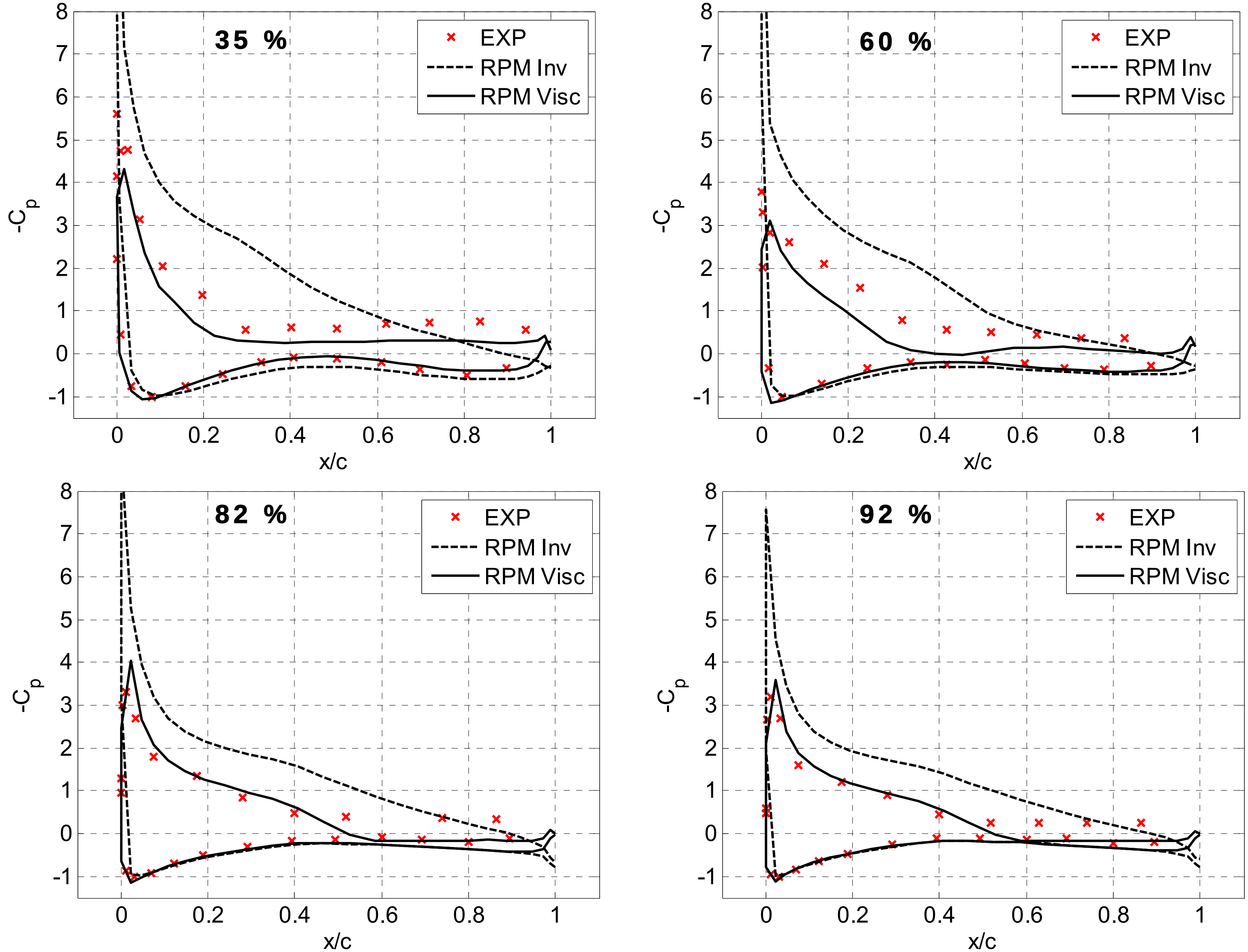
MEXICO BLADE AERODANYMICS, N / T



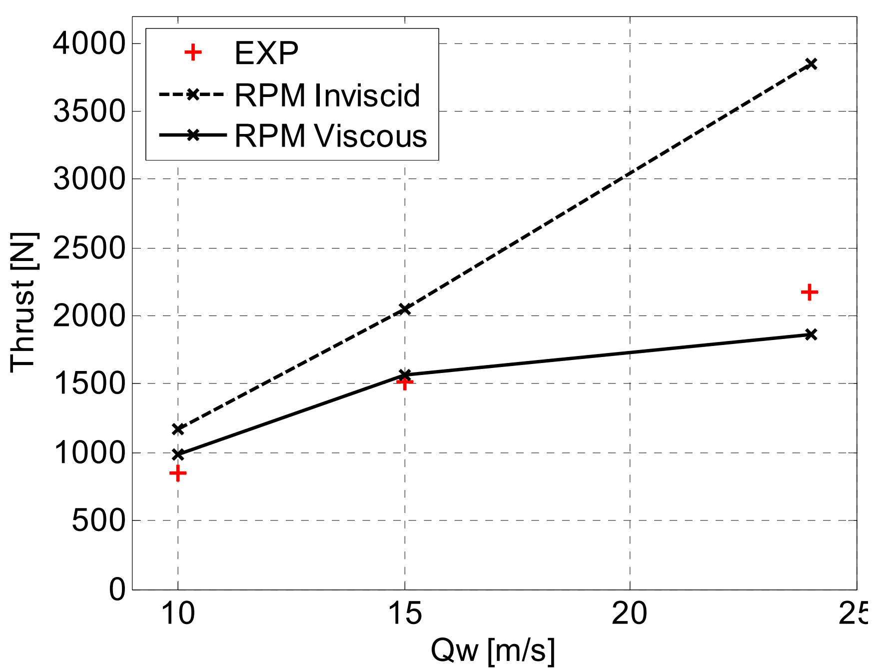
MEXICO BLADE, C_p , 15 m s^{-1}

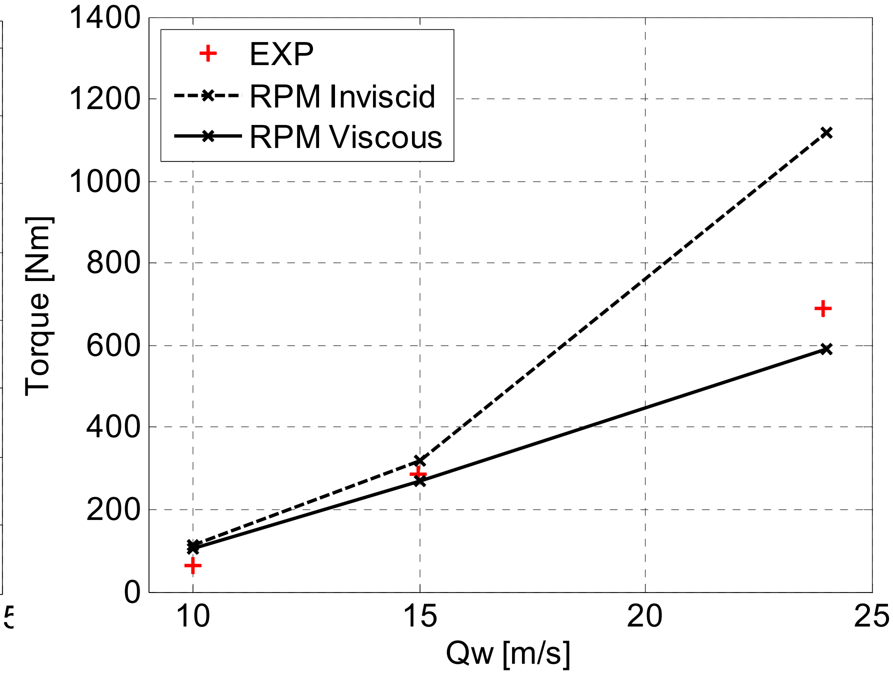


MEXICO BLADE, C_P , 24 m s^{-1}

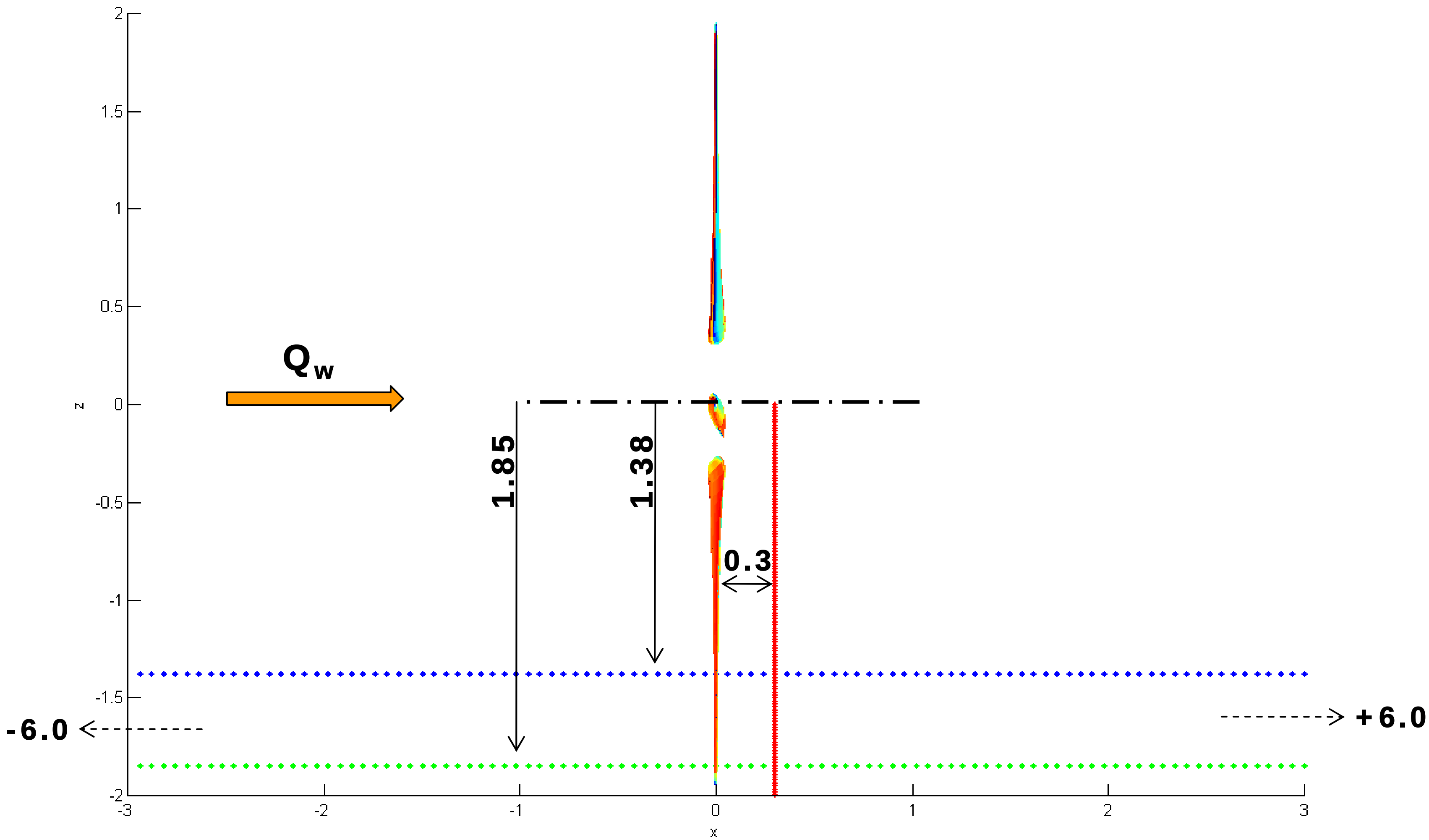


MEXICO ROTOR GLOBAL PERFORMANCE

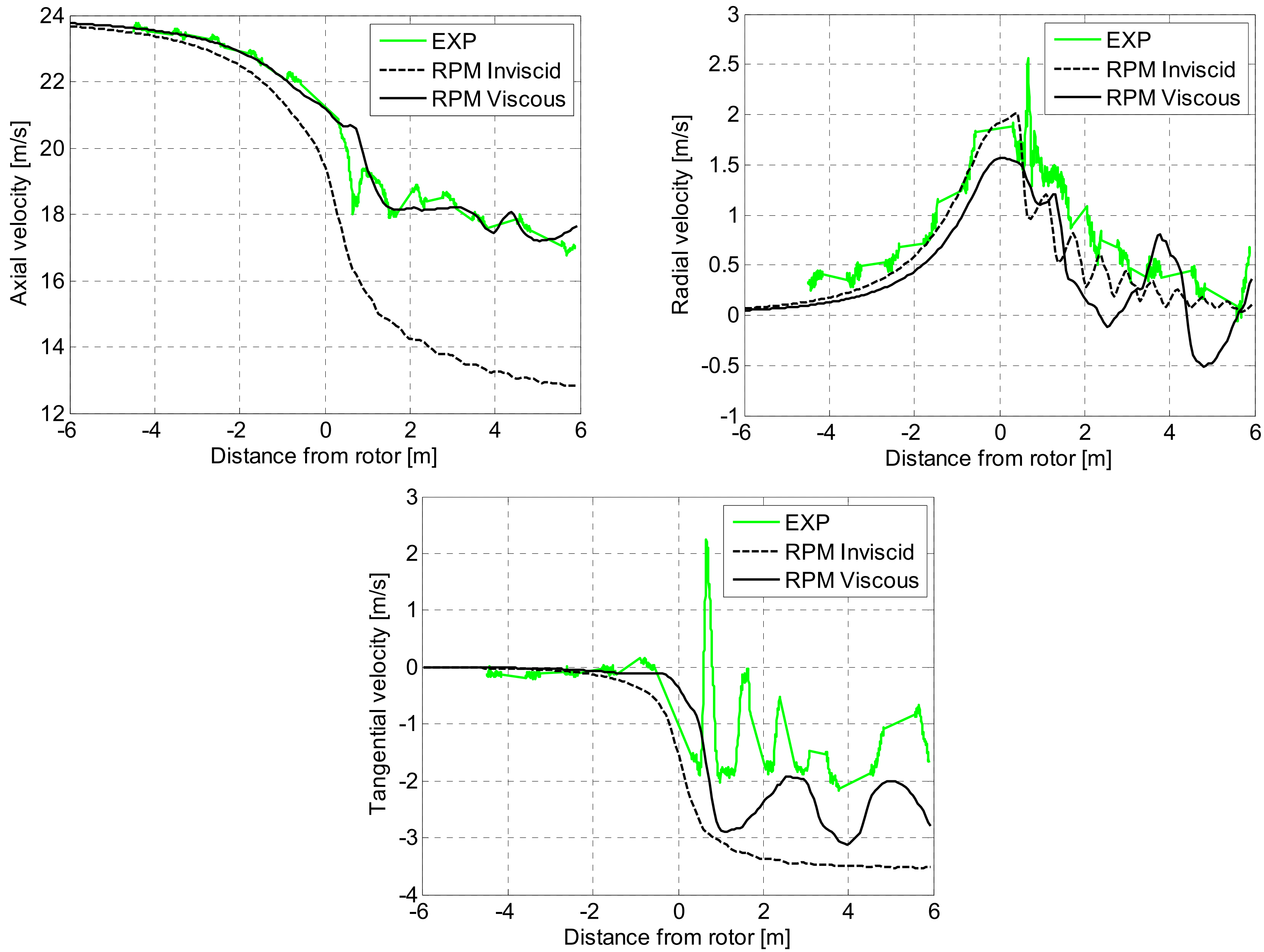




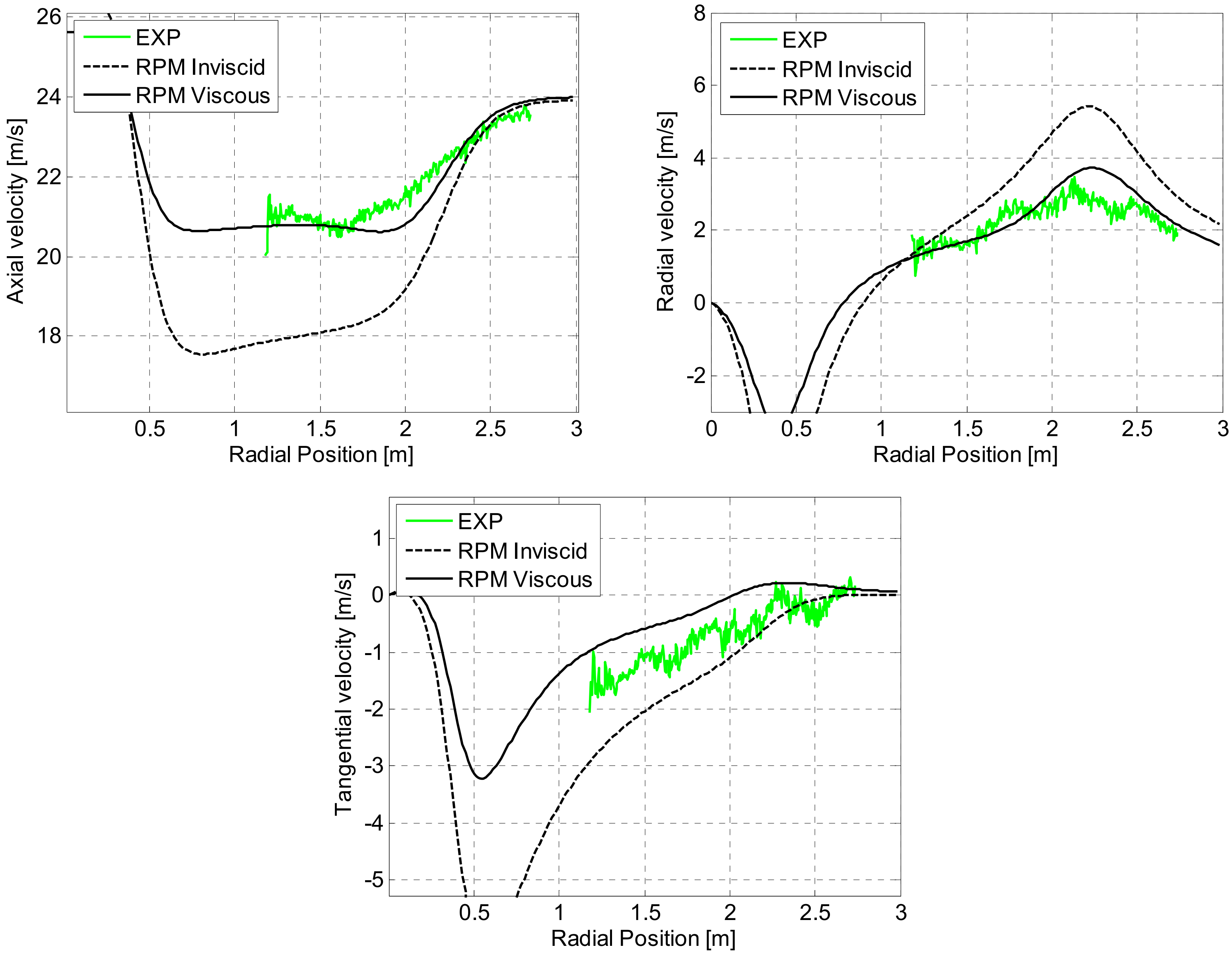
MEXICO ROTOR WAKE



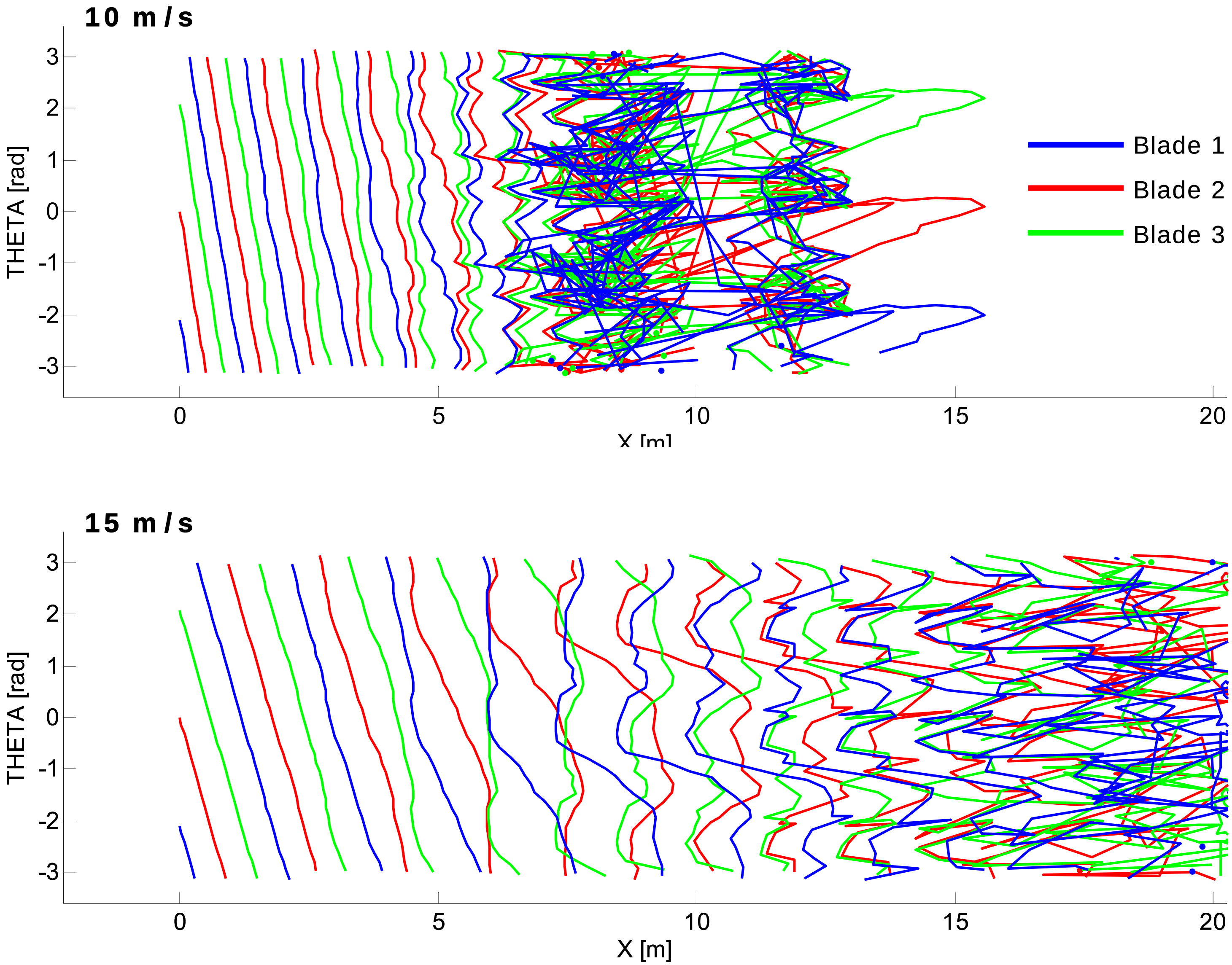
MEXICO ROTOR WAKE(24 ms^{-1}, 1.38 m)



MEXICO ROTOR WAKE (24 ms^{-1}, 0.30 m)



MEXICO ROTOR WAKE, VP



CONCLUSIONS

- THE RPM CODE HAS BEEN VALIDATED FOR **NON-ROTATIONAL CASES.**

- IT HAS BEEN PROVEN THAT THE RPM CODE CAN BE USED TO SUCCESFULLY SIMULATE A **WIND TURBINE ROTOR**. VALIDATIONS HAVE BEEN CARRIED OUT FOR BOTH BLADE AERODYNAMICS AND WAKE DYNAMICS.

- THE VISCOUS COUPLING WITH **Q^{3}UIC IMPROVES** GENERALLY THE PREDICTION OF BLADE AERODYNAMIC AND WAKE CHARACTERISTICS. ESPECIALLY AT HIGH WIND SPEEDS.

FUTURE WORK

- ❑ DECREASE CPU TIME (MPI AND/OR MULTIPOLE EXPANSION).
- ❑ COUPLE RPM WITH A ROTOR DESIGN ALGORITHM.
- ❑ PERFORM TANDEM TURBINES SIMULATIONS.
- ❑ IMPLEMENTATION OF FLAP/SLUT GEOMETRIES IN RPM.
- ❑ INCLUDE NON-LIFTING BODIES IN RPM (TOWER & HUB). -> DONE
- ❑ VORTEX FILAMENTS TO VORTEX POINTS IN MEDIUM-FAR WAKE FOR A BETTER WAKE/BODY INTERACTION. -> IN PROCESS
- ❑RPM COMPARISON AGAINST PIV MEASUREMENTS BEHIND GLAUERT, BETZ & JOUKOWSKI ROTORS, DTU WATER FLUME. -> IN PROCESS

THANK YOU FOR YOUR ATTENTION.

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