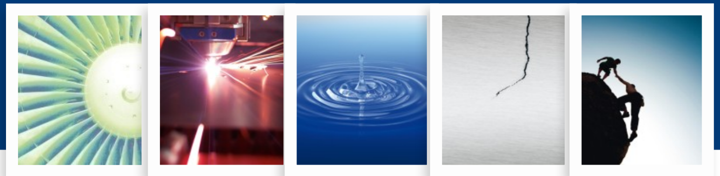

Turbulence Characterization in Compressor Tandem Blades Aerodynamics

ETMM 2025

Dubrovnik,Croatia – 22 September 2025

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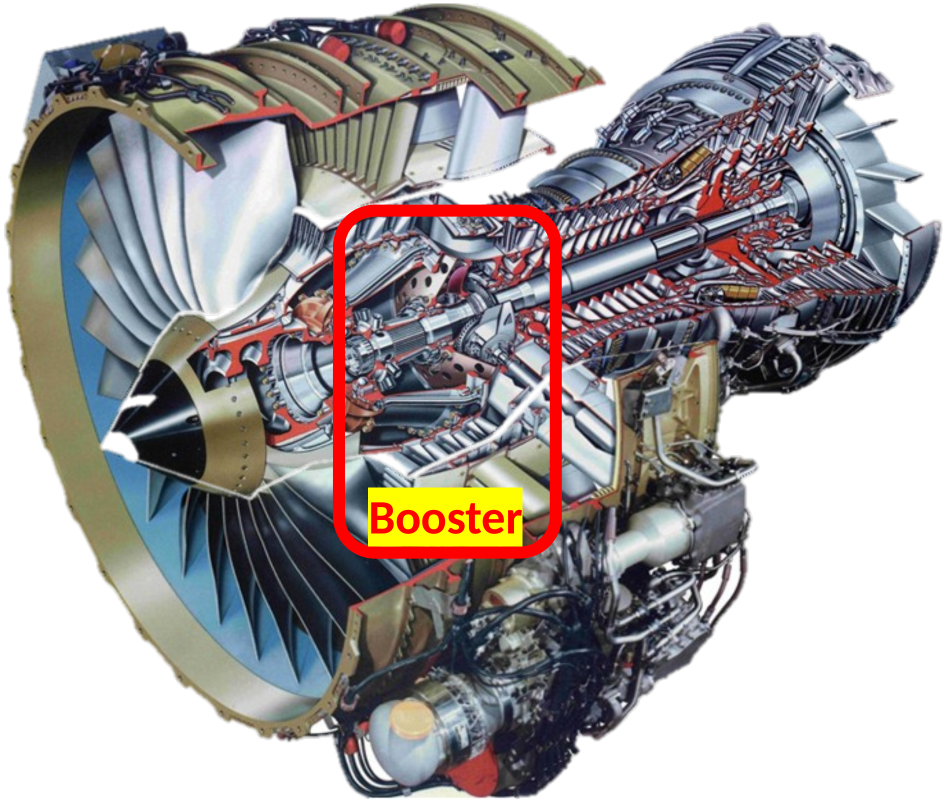

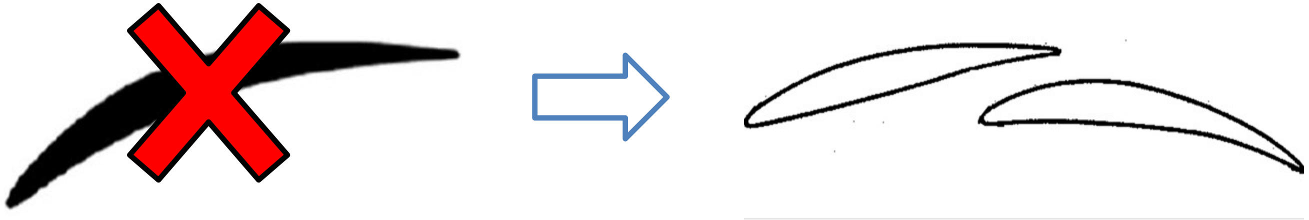

- **Outlet guide vane**
  - **High turning**
    - High losses
    - Increased risk of flow separation
  - **Alternative to standard blades: tandem**
    - More resilient to flow separation
    - Complex flow phenomena

- **Challenging flow conditions for standard RANS-based design tools**

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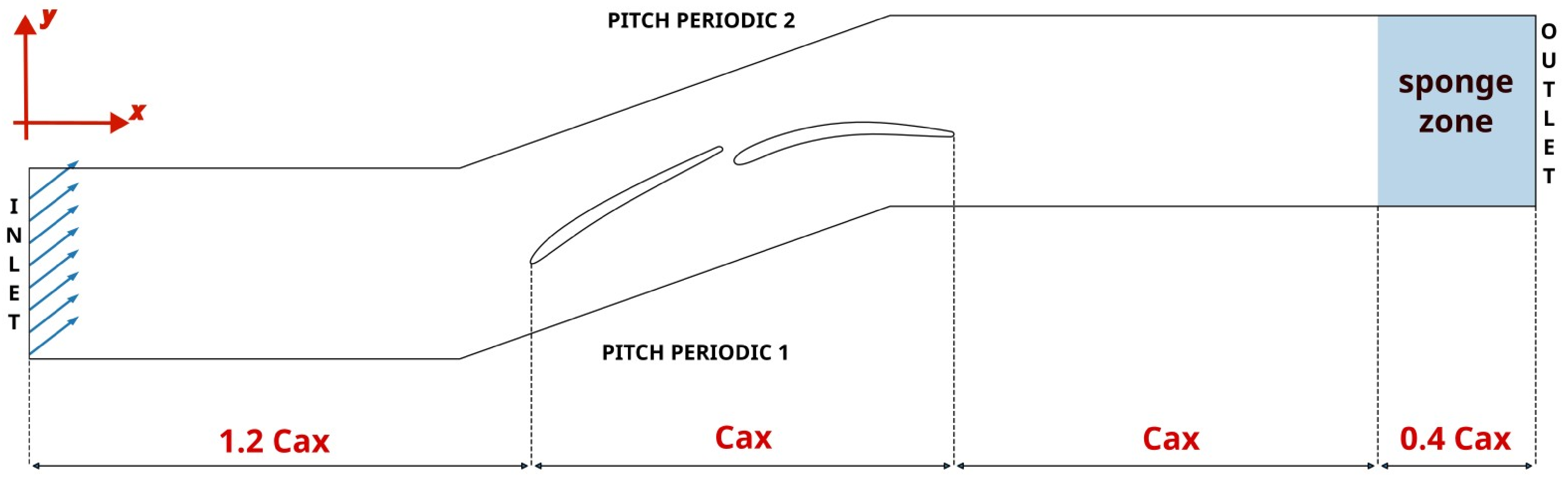
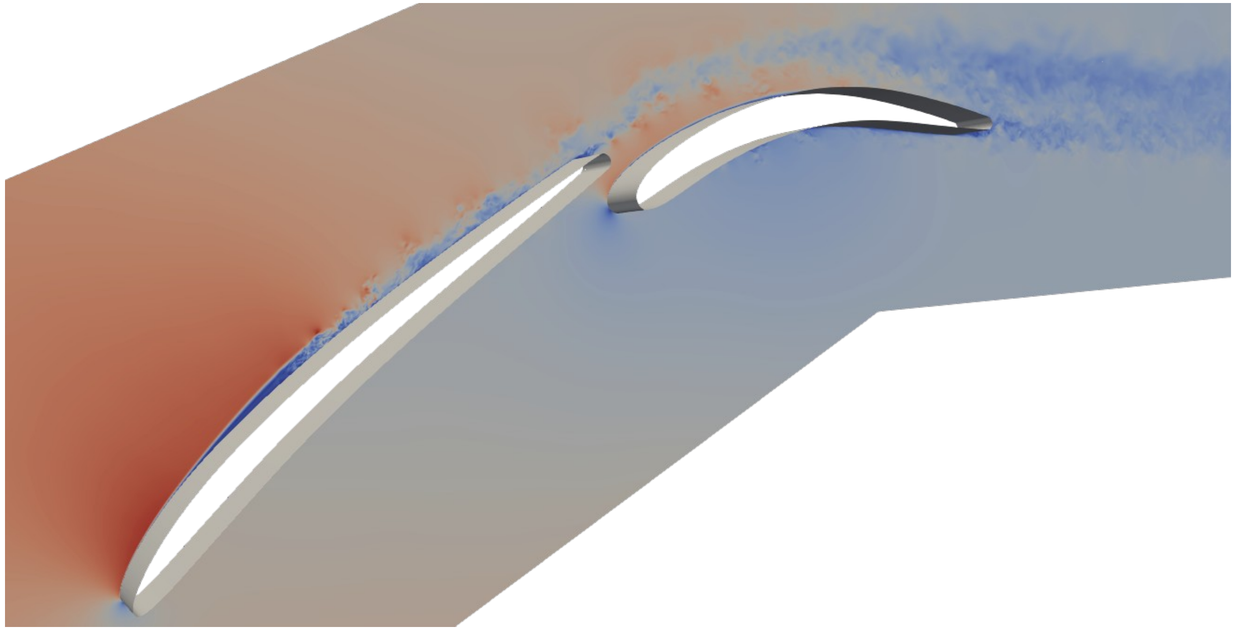
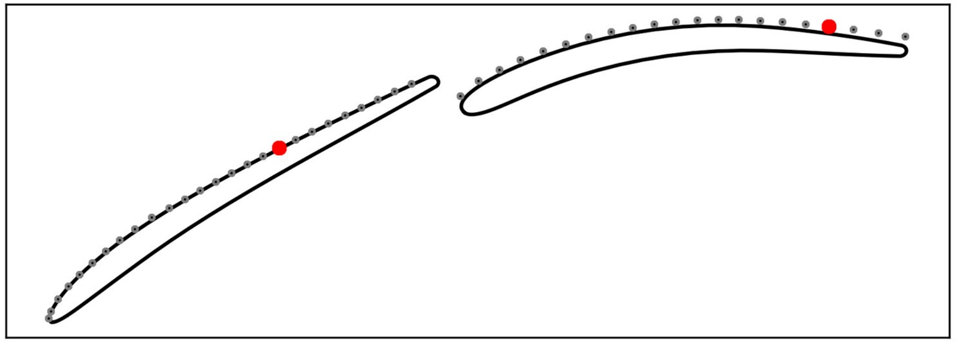
- **Objectives**
  - **Tandem blade cascade: preliminary study**
    - Focus on aerodynamic point
    - Moderate Reynolds number
  - **Insight into flow phenomena**
  - **Assess ability of standard CFD tools to predict flow & performance**

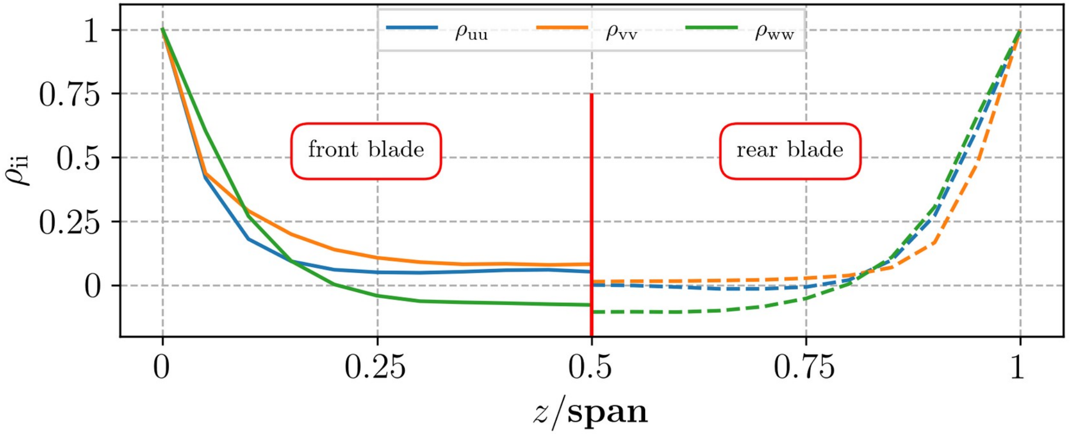
- **Two numerical approaches**
  - **High-fidelity CFD: wall-resolved (implicit) LES**
    - Code: Argo (in-house)
    - High-order Discontinuous Galerkin method
  - **Standard CFD: RANS**
    - Code: SU2 (open source)
    - Standard Finite Volume method
    - RANS turbulence model: k-ω SST
    - Additional transition model: γ-Re_θ (Menter-Langtry)



- **Operating point**
  - $Re_c = 300{,}000$
  - $Ma_{inlet} = 0.6$
- **Boundary conditions**
  - Inlet: total conditions
  - Outlet: static pressure
  - Pitch, span: periodicity







- **Domain extent in span**
  - **12% $C_{ax,FB}$ ~ 1/11 pitch**
  - **Correlation coefficients OK**

$$\rho_{ii}(z, \mathbf{x}, t) = \frac{\overline{u_i(\mathbf{x}, t)\, u_i(\mathbf{x} + z, t)}}{\overline{u_i(\mathbf{x}, t)\, u_i(\mathbf{x}, t)}}$$

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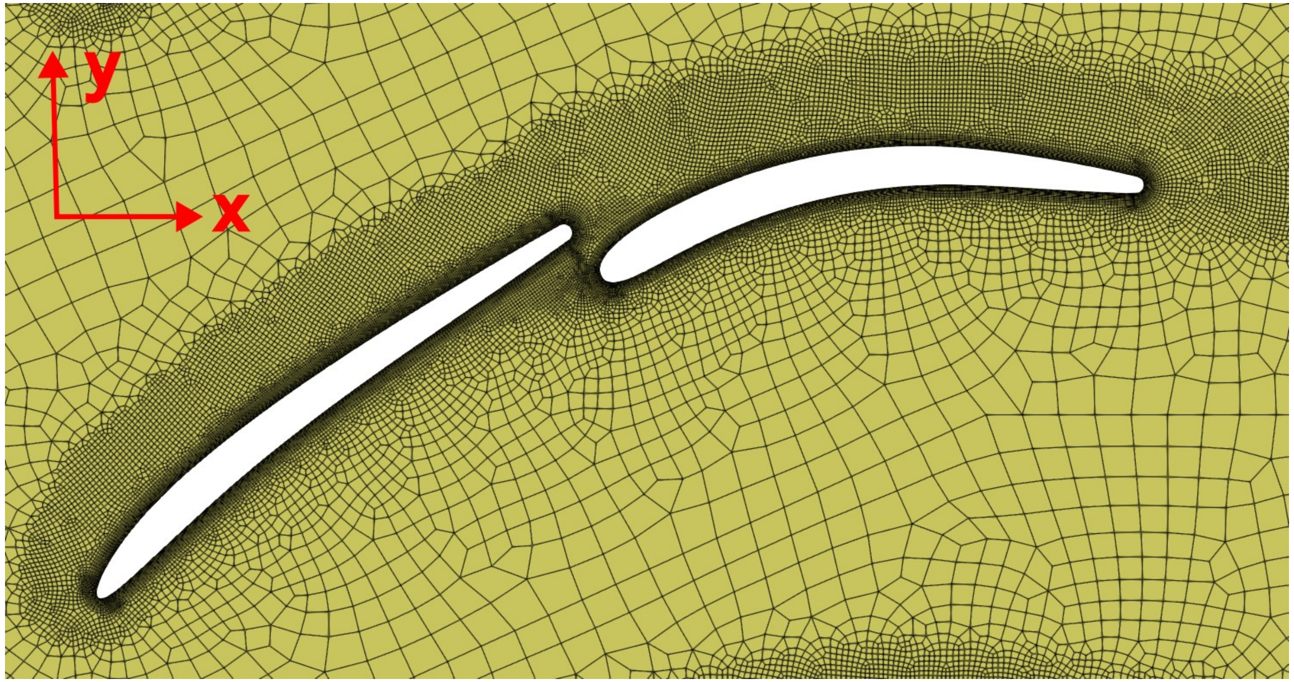
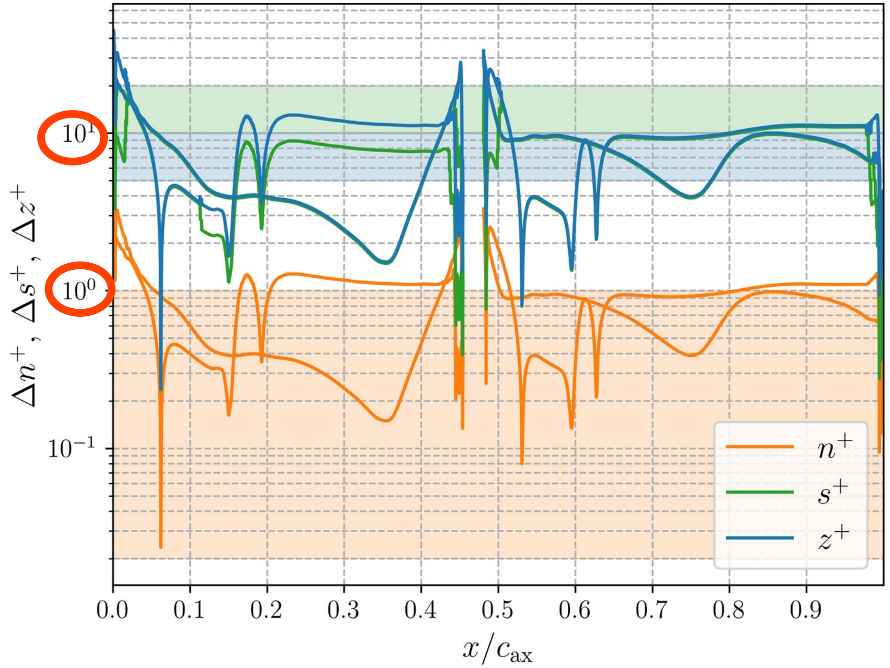
Simulation Methodology
Discretization for LES





- **Spatial discretization**
  - **Hybrid hex-dominant mesh: 440k cells**
  - **DG P3 (4th-order accurate)**
  - **Total: ~ 30M DoF/eq.**
  - **Near-DNS resolution**
- **Time discretization**
  - **BDF2 (2nd-order accurate)**
  - **Time step: 10^{-7} s (below unit convective CFL)**
  - **Duration: 22 CTU (C_{ax}-based)**

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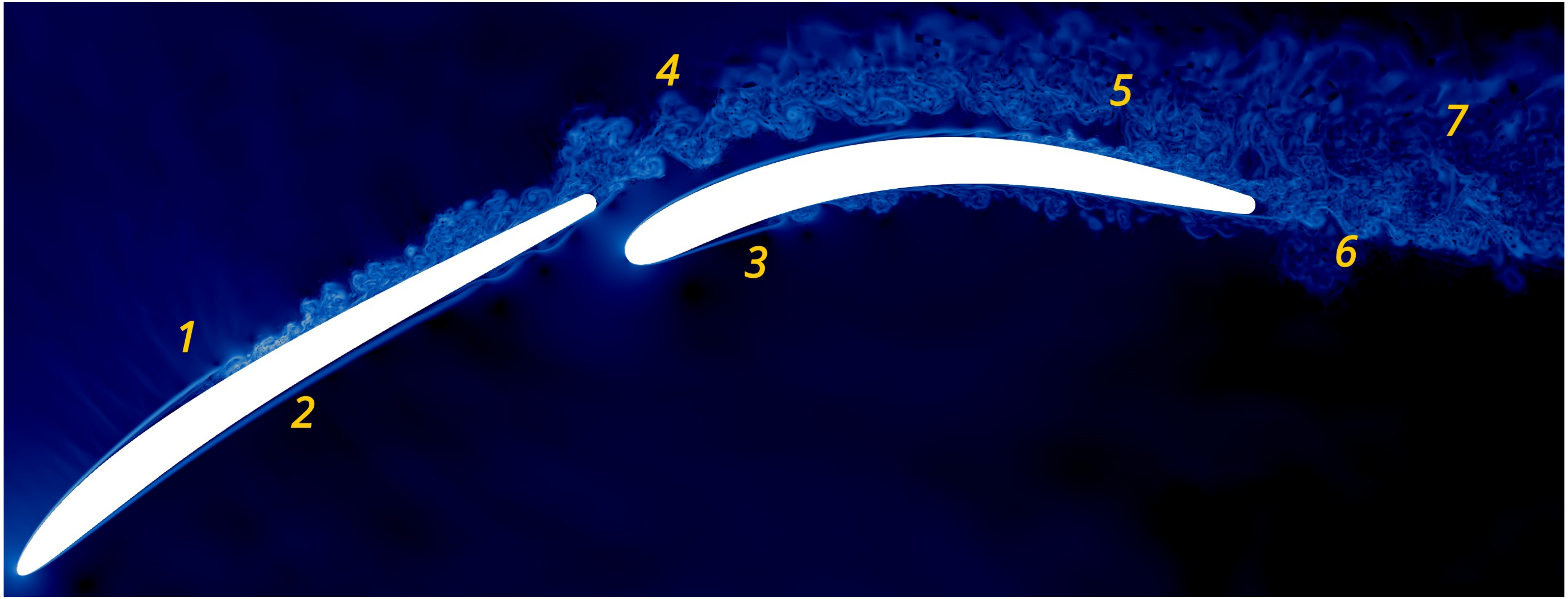

1, 2, 3 – Laminar separation bubbles and transition
4, 6 – Front and rear blade wakes
5 – Wake – boundary layer interaction
7 – Front blade wake bifurcation

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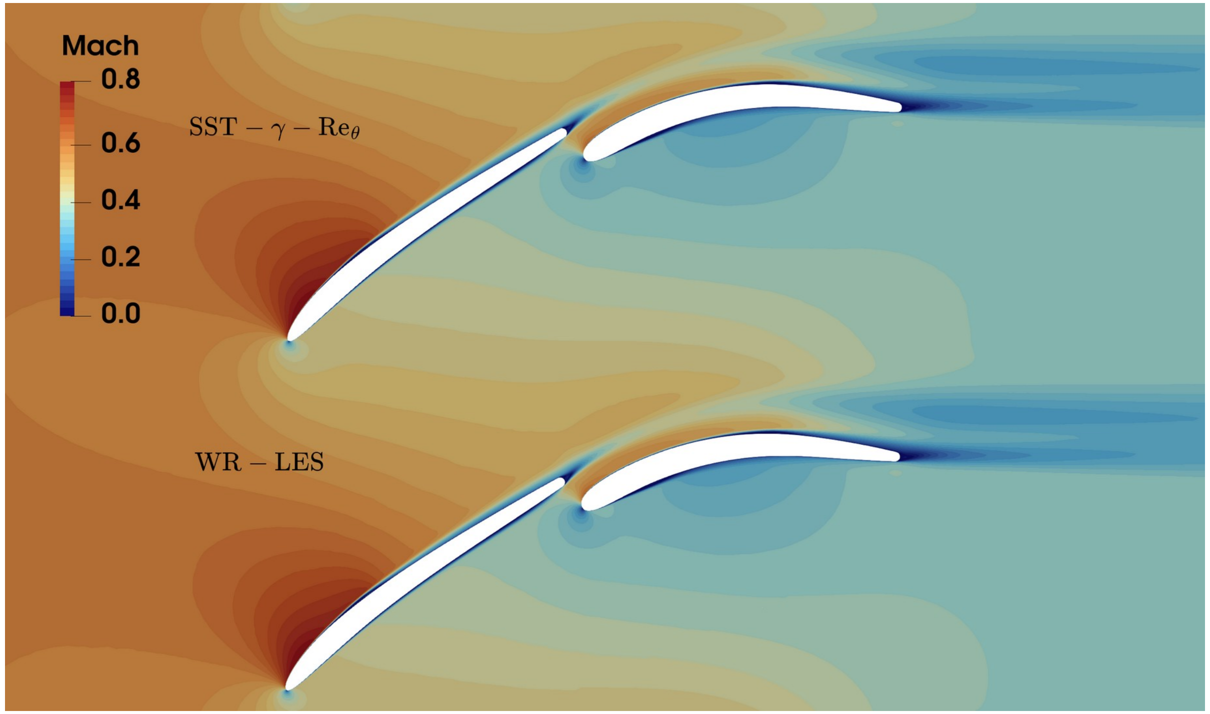

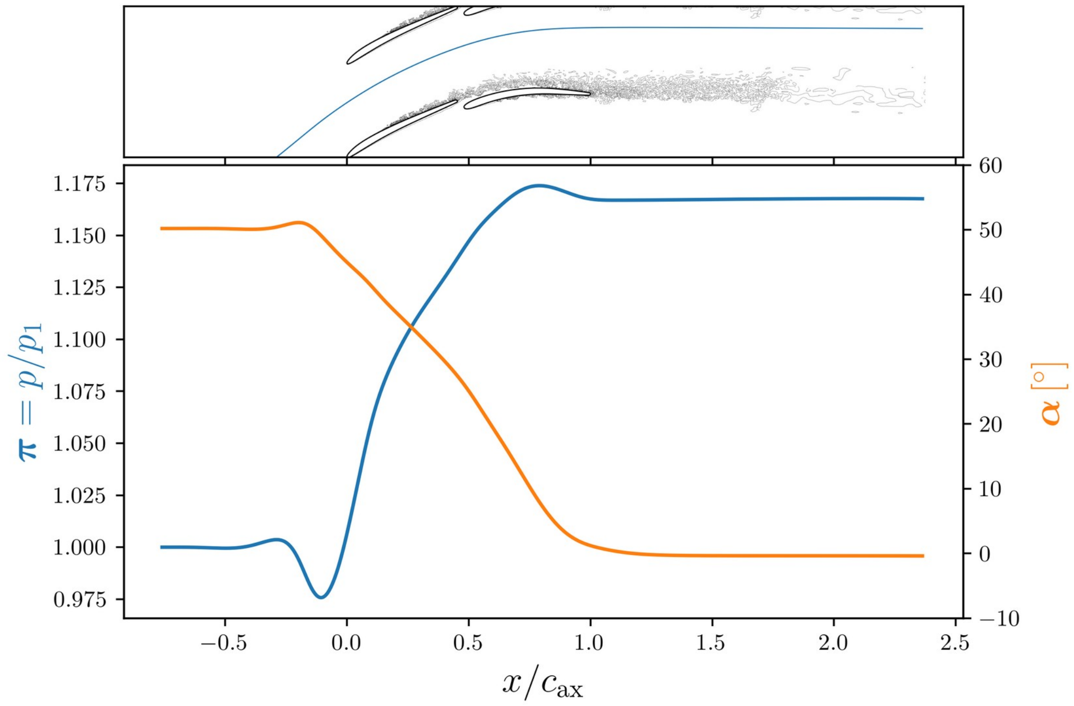

- **Average flow solution: virtually identical between RANS and LES**

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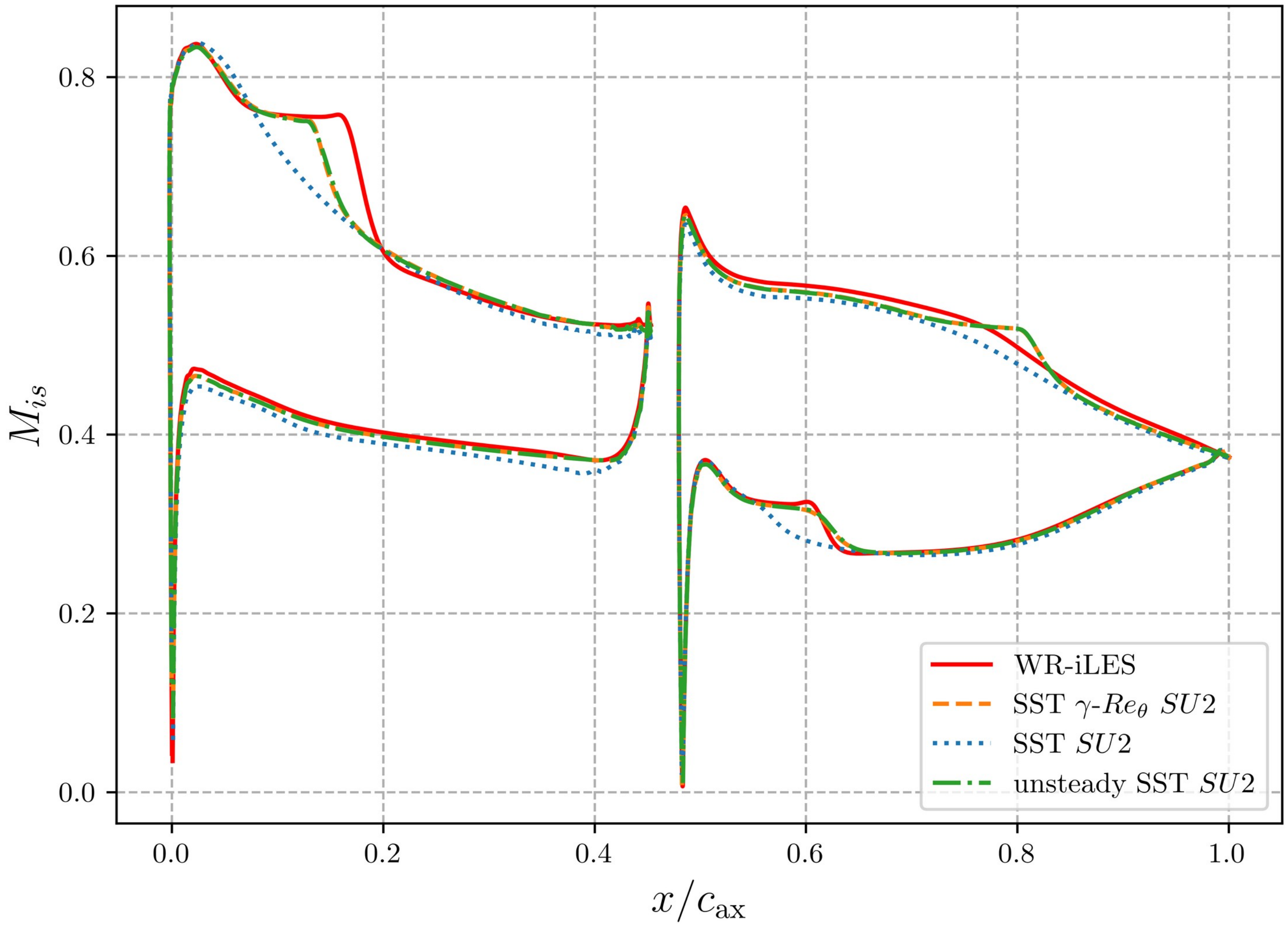
Results

Isentropic Mach distribution and transition phenomena



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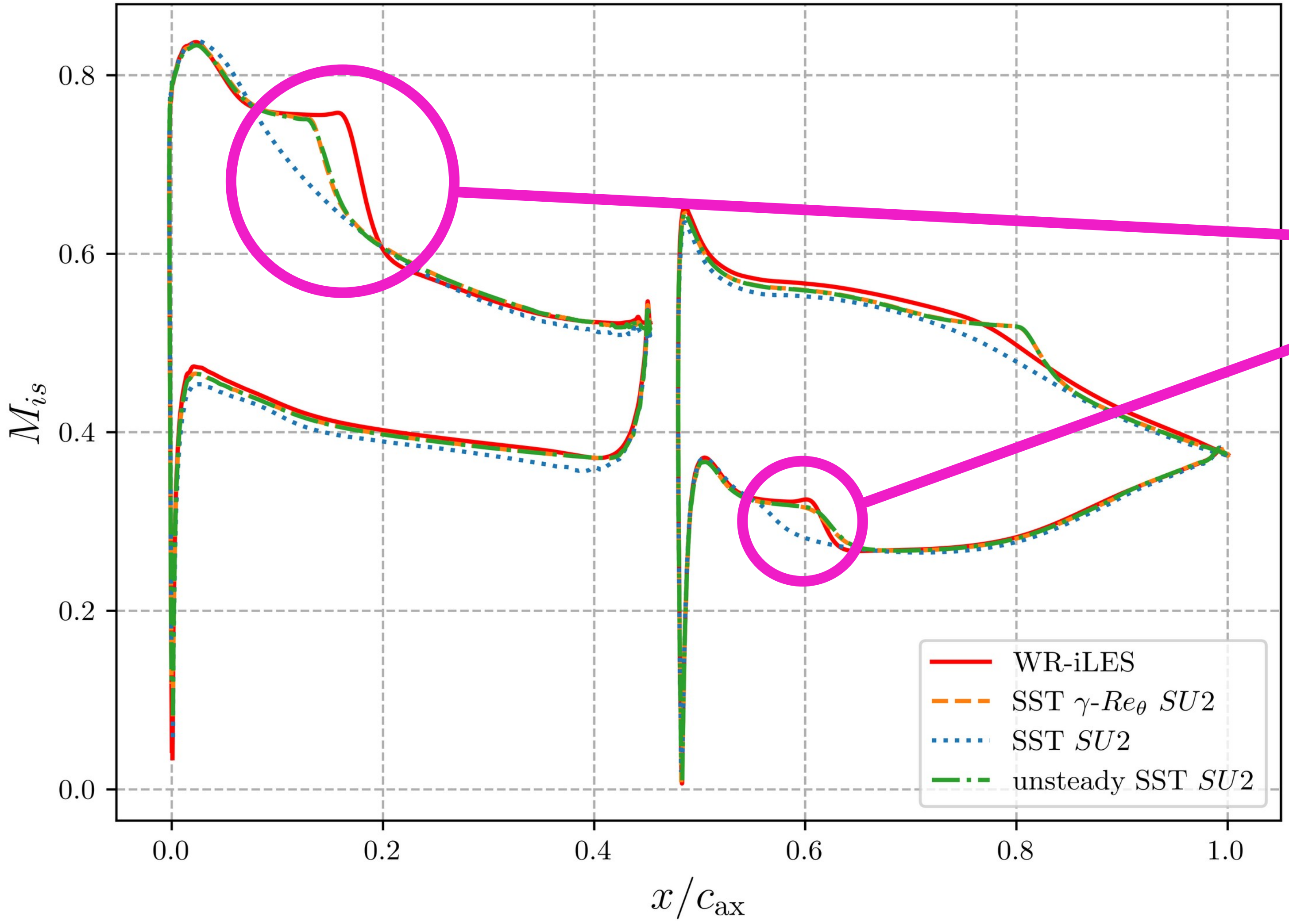
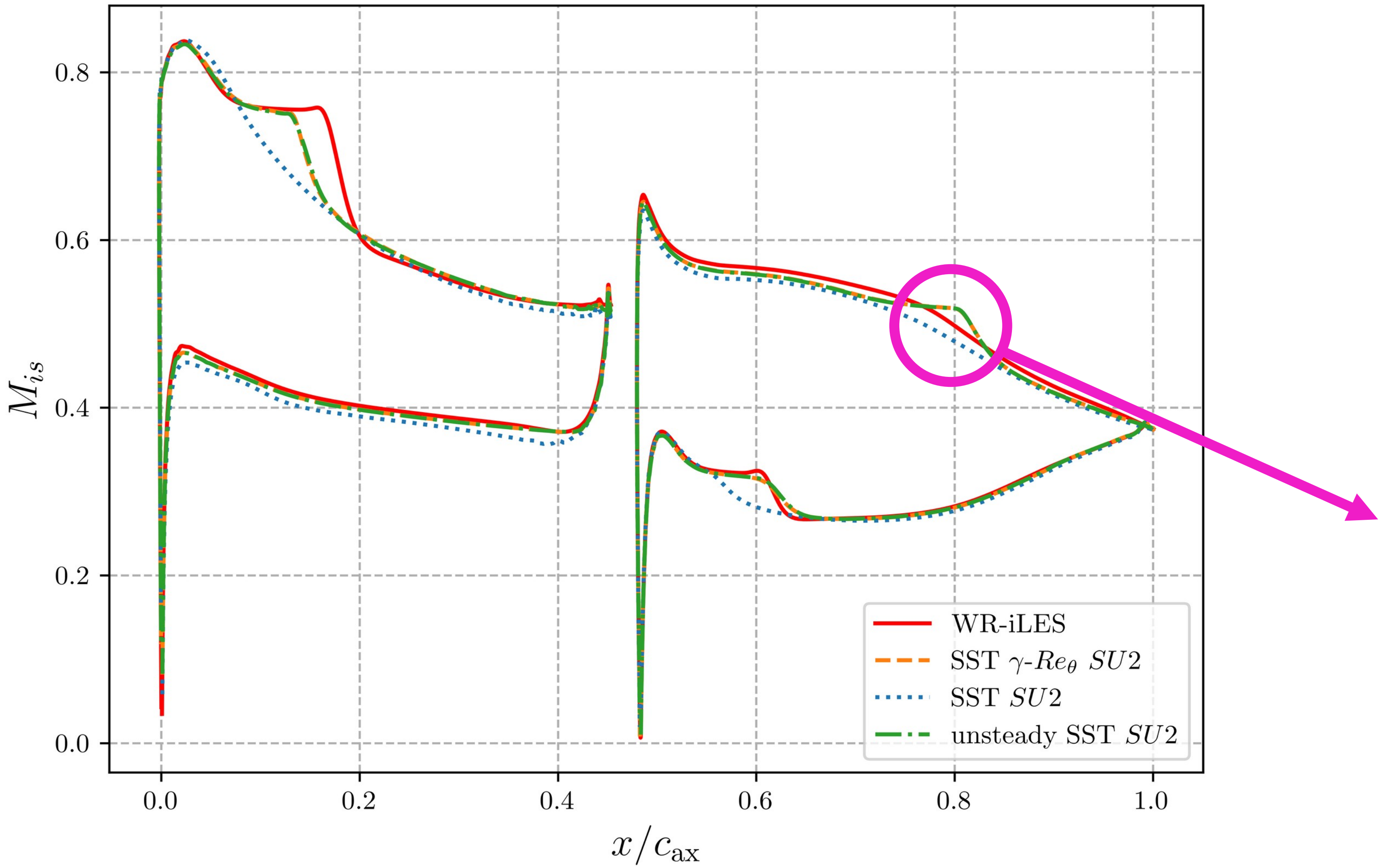


Laminar separation bubbles (qualitatively) captured by SST + γ-Re_θ model

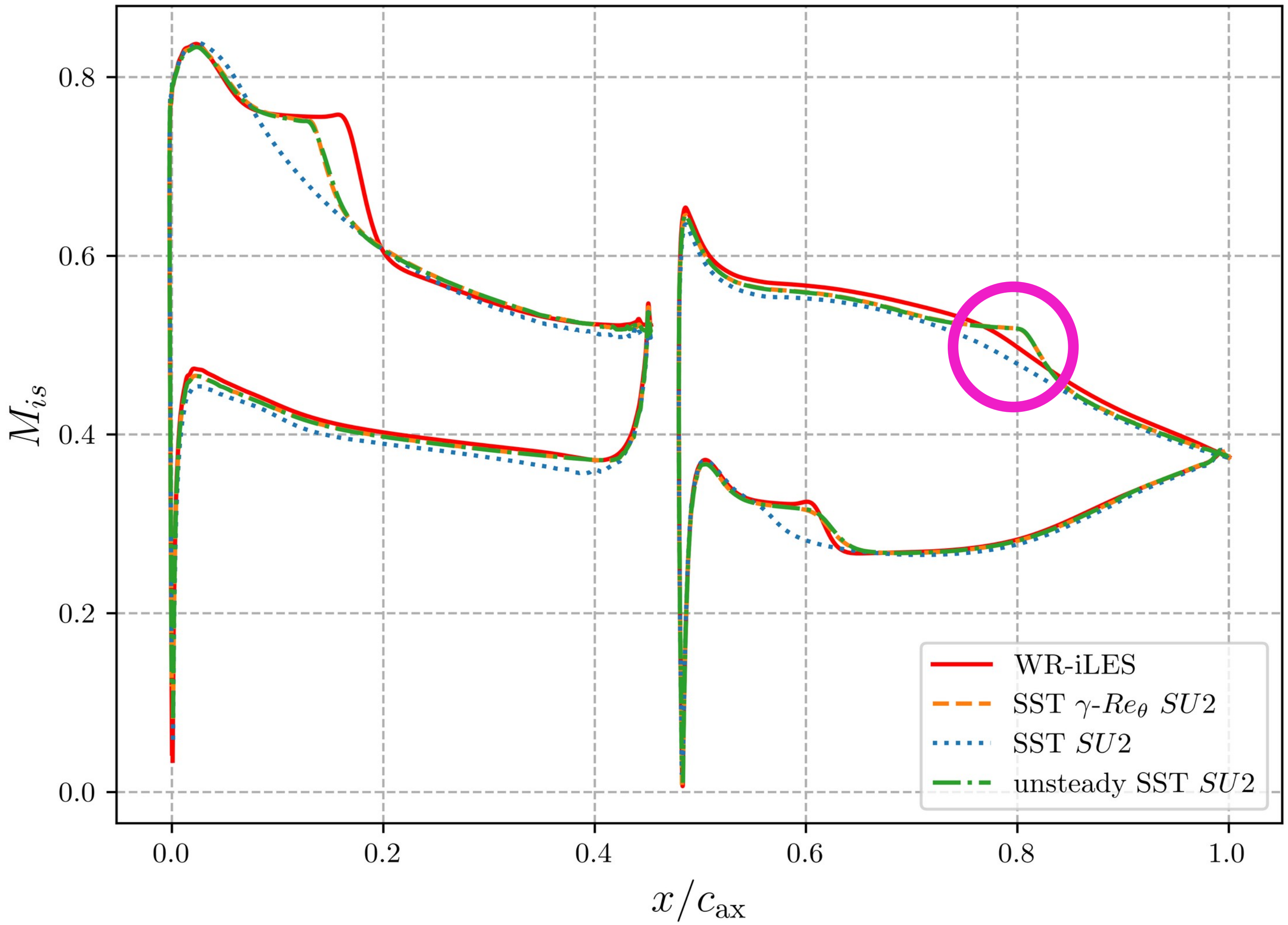


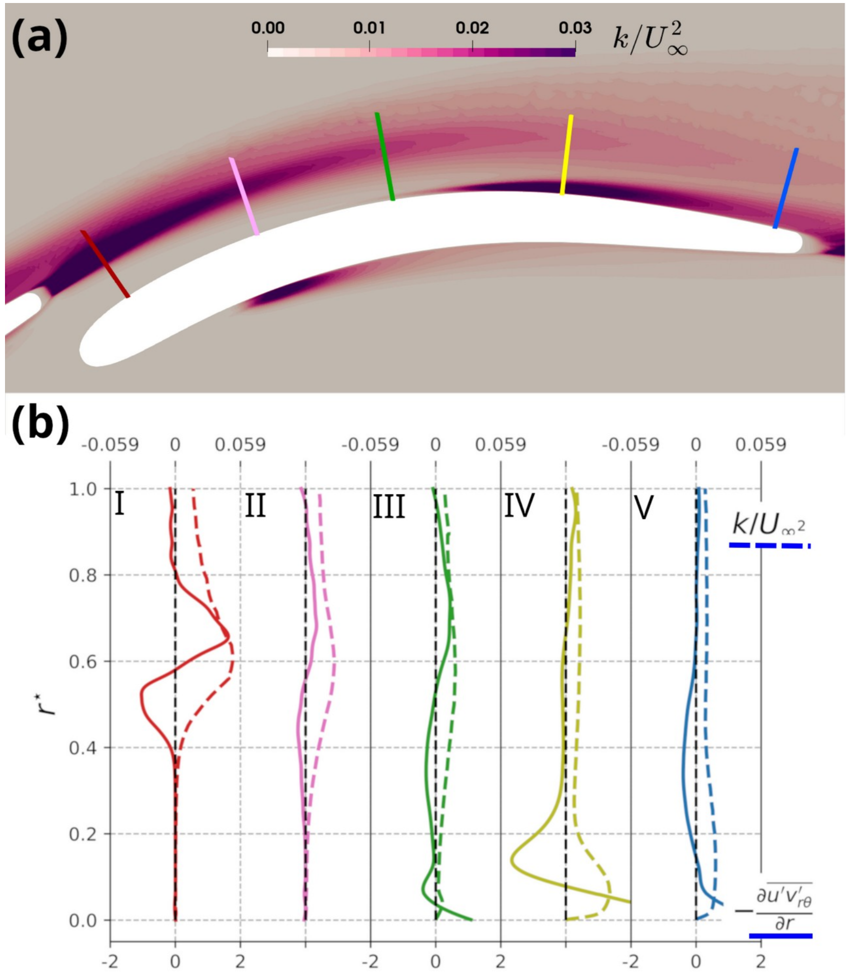
Laminar separation bubbles (qualitatively) captured by SST + γ-Re_θ model

Laminar separation bubble wrongly predicted by SST + γ-Re_θ model?

Results

Isentropic Mach distribution and transition phenomena





Transition governed by wake – BL interaction?

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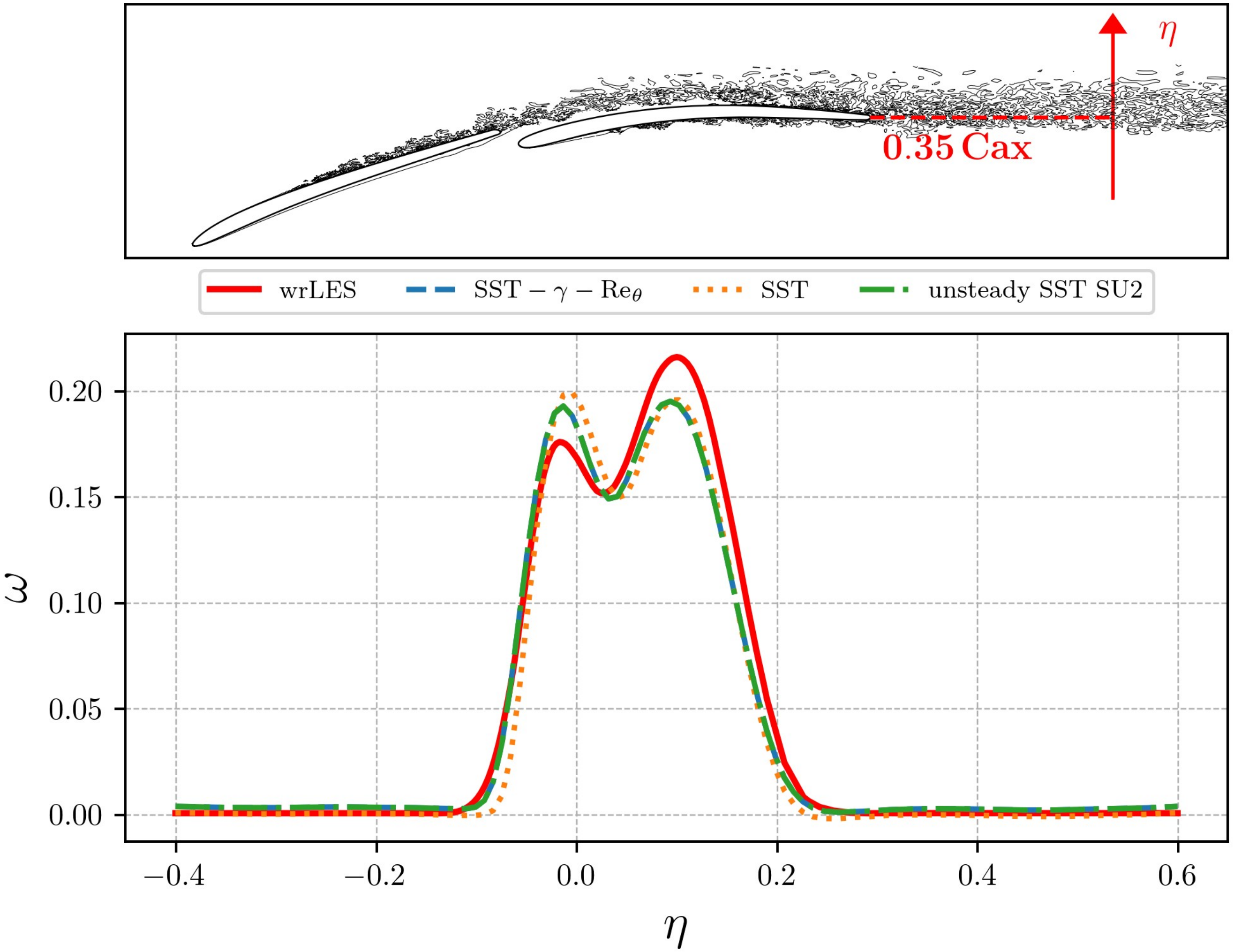


Non-symmetric loss profile not predicted by SST (with or without γ-Re_θ model)?

Boussinesq hypothesis:

$$-\rho\,\overline{u'_i u'_j} = 2\,\mu_t \left(\overline{S}_{ij} - \frac{1}{3}\frac{\partial U_k}{\partial x_k}\delta_{ij}\right) - \frac{2}{3}k\rho\delta_{ij} \qquad \overline{S}_{ij} = \frac{1}{2}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)$$

$$\overline{R}_{ij} = \rho\,\overline{u'_i u'_j} - \frac{2}{3}\rho\,k\delta_{ij}$$

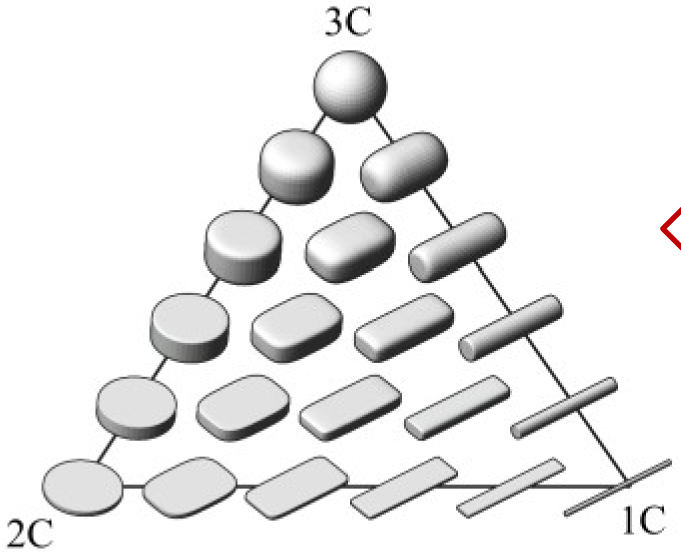
$$a_{ij} = \frac{\overline{R}_{ij}}{2k}$$

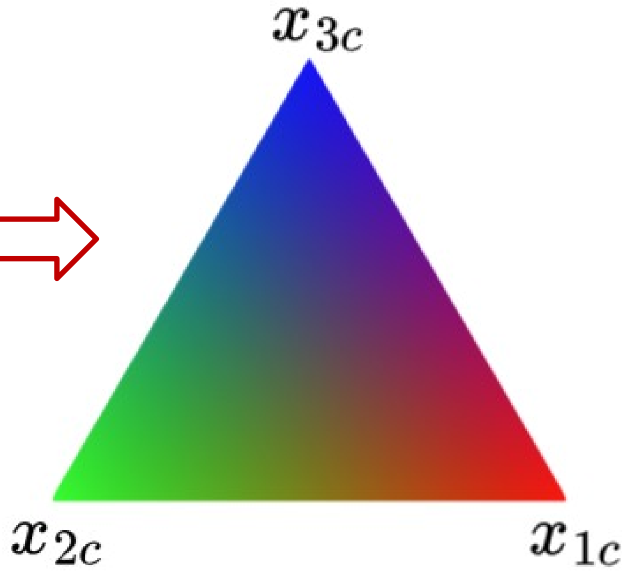
$$C_{1c} = \lambda_1 - \lambda_2$$
$$C_{2c} = 2(\lambda_2 - \lambda_3)$$
$$C_{3c} = 3\lambda_3 + 1$$

$$x_B = C_{1c}\,x_{1c} + C_{2c}x_{2c} + C_{3c}x_{3c}$$
$$y_B = C_{1c}y_{1c} + C_{2c}y_{2c} + C_{3c}y_{3c}$$

Baricentric representation of turbulence state between limiting states [Banerjee et al. 2007]

Mapping between turbulence state and RGB colour [Emory & Iaccarino 2014]





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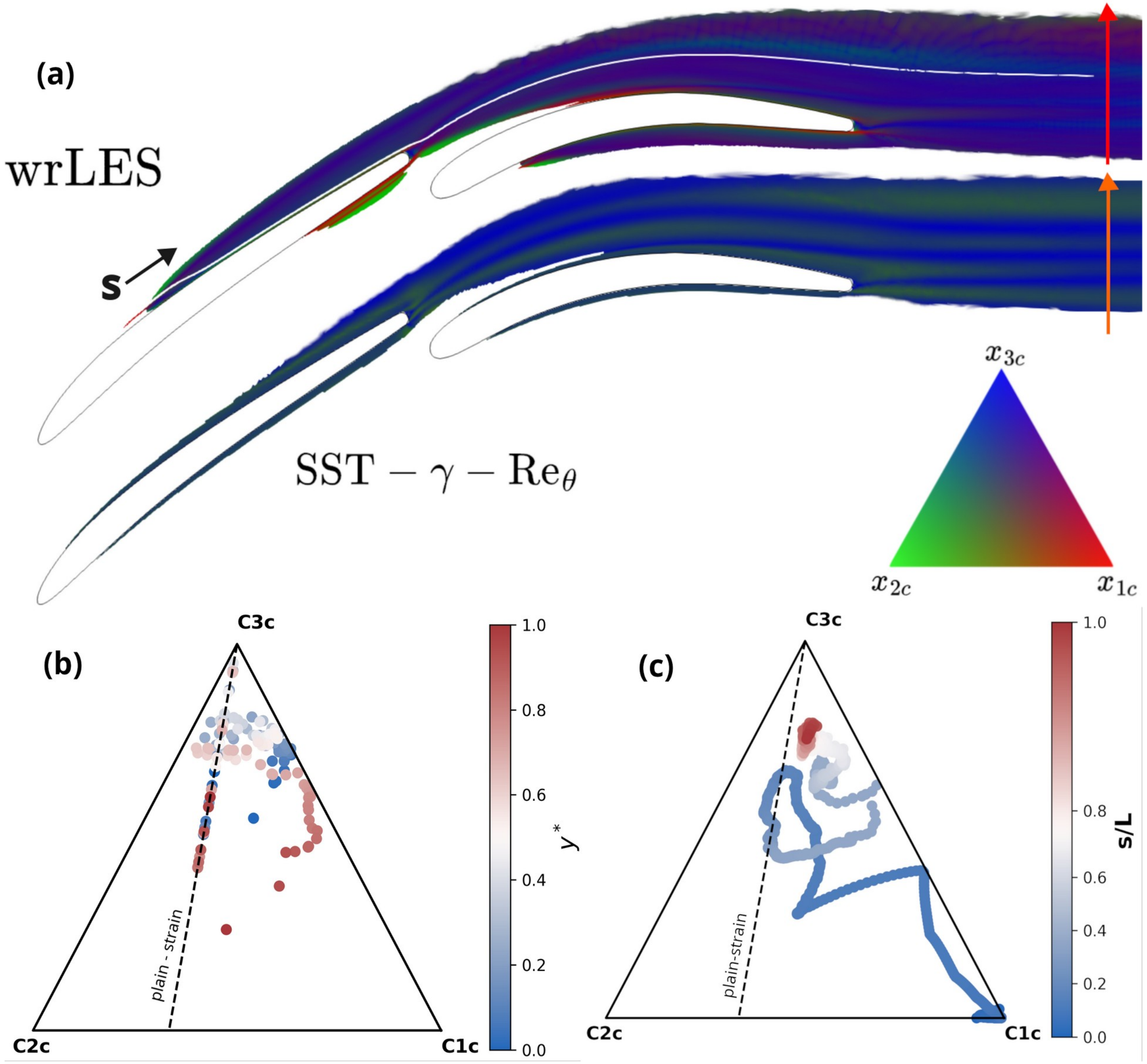
Results

Barycentric map for visualization of turbulence anisotropy

RANS: turbulence state close to isotropic or plane strain

LES: evolution from axisymmetric (close to blade) to isotropic state (in the wake)



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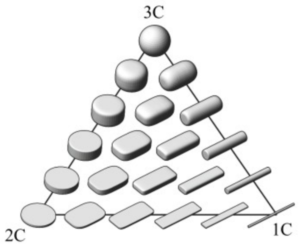
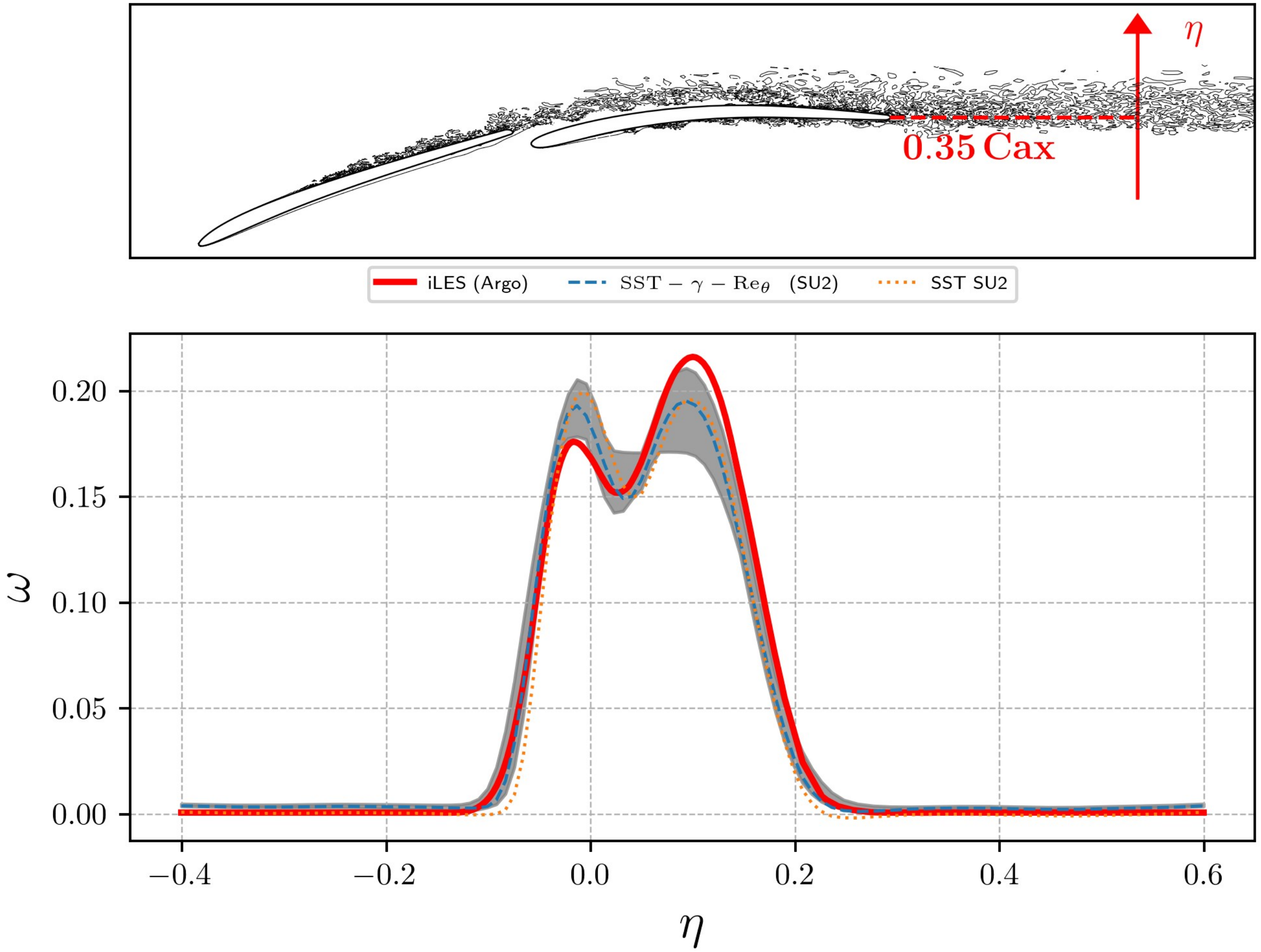
EQUiPS methodology [Iaccarino et al. 2017, Thompson et al. 2019], tool available in SU2:

$$R^{\star}_{ij} = 2k^{\star}\left(\frac{\delta_{ij}}{3} + v^{\star}_{ij}\Lambda^{\star}_{nl}v^{\star}_{lj}\right)$$

with perturbed states:

$$\mathbf{x}^{*} = \mathbf{x}_{1C}, \mathbf{x}_{2C}, \mathbf{x}_{3C}$$





LES not fully in band because of methodology limitations (homogeneous perturbation in whole domain, disregard other causes than anisotropic)

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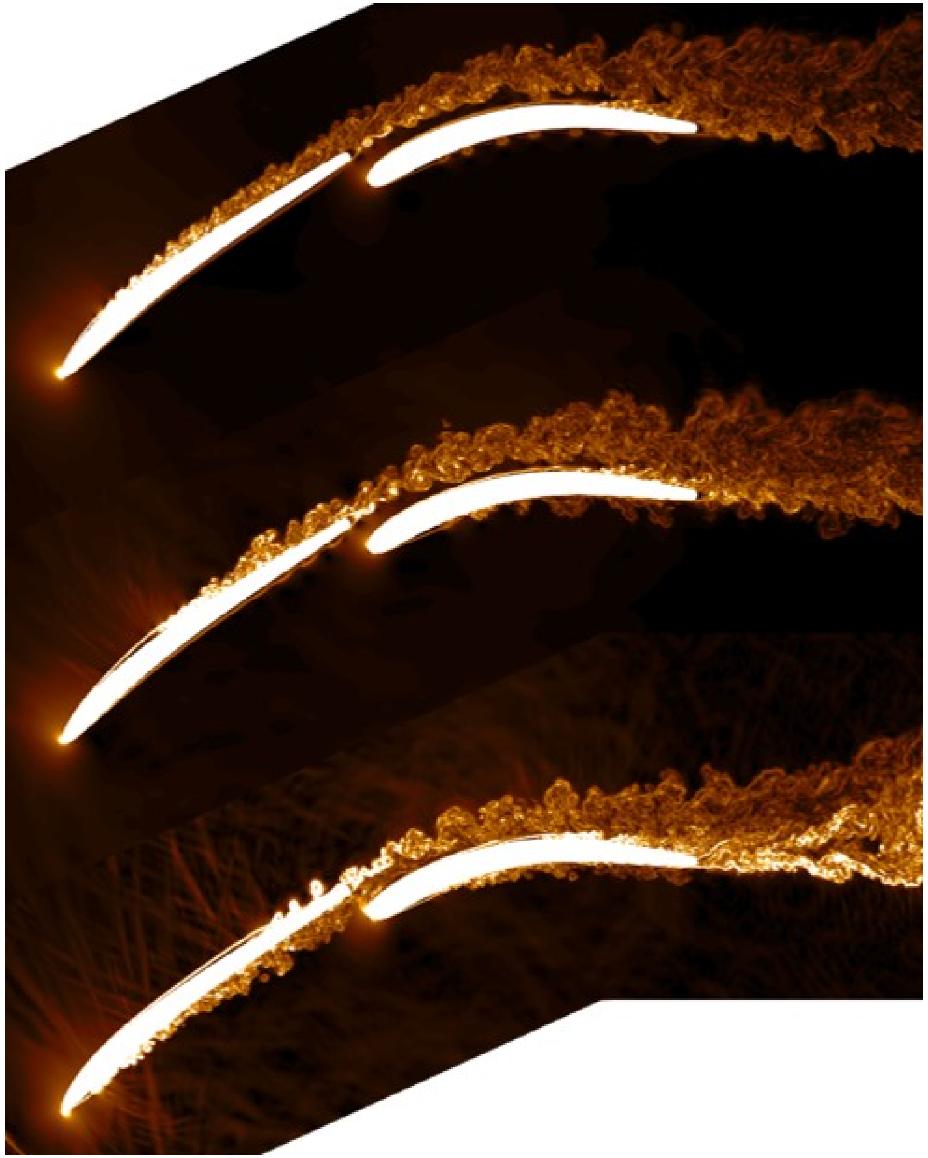
Conclusions and perspectives

- **Complex flow phenomena around tandem blades**

- **Structural RANS limitations affect the prediction of tandem blade flow and performance**
  - **Transition modeling**
  - **Boussinesq hypothesis and Reynolds stress anisoptropy**

- **Further investigations**
  - **Off-design points**
  - **Reynolds effects**
  - **Inlet turbulence**
  - **Comparison with experiments**



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