Approximate Boundary Layer Methods for a 3D Panel Code for Helicopter Simulations

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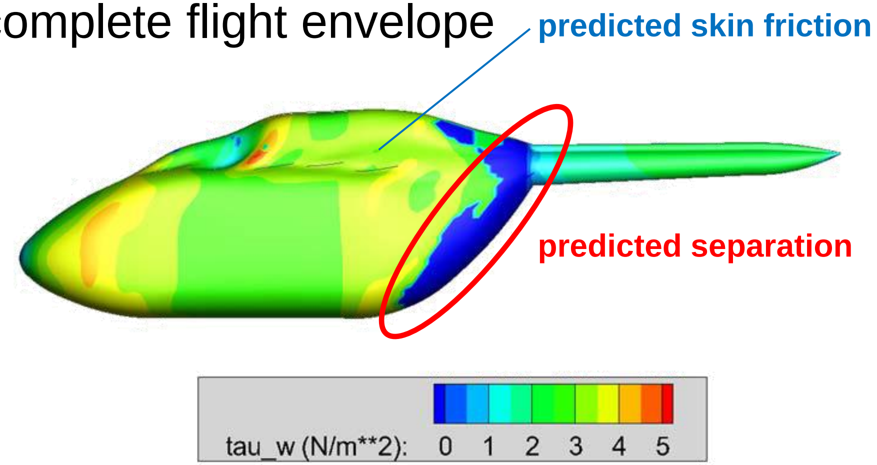
Motivation

Aim: Extend DLR's Unsteady Panel Method (UPM)

- Prediction of **separation** onset for detection of critical flight states
- Approximate calculation of **viscous friction drag**
- Applicable to full helicopter simulations, complete flight envelope



Requirements for analysis methods:

- Simple (implementation + application)
- Fast
- Robust

Selected approach:

- Lifting surfaces: stripwise integral boundary layer (BL) analysis
- Non-lifting bodies: simplified analysis based on local flow properties
- Attached flow only, no coupled viscous-inviscid interaction

Overview

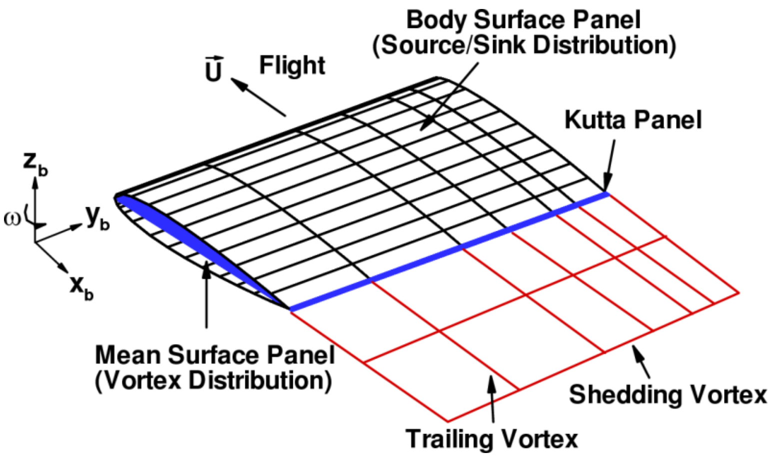
0. Motivation
1. Computational Method
    - Unsteady Panel Method
    - Approximate Boundary Layer Analysis
2. Results
    - Airfoils
    - Wings
    - Hovering Rotor
    - Fuselages
3. Conclusion and Outlook

Computational Method

DLR Unsteady 3D Panel and Free-Wake Method (UPM)

Legacy code originally intended for BVI-dominated aeroacoustics applications, currently being modernized and enhanced for interactional aerodynamics of complete helicopters

- Lifting surfaces:
  - Constant strength sink/source panels (displacement)
  - Vortex ladder (bound vortices)
  - Full-span free-wake made of constant strength vortex rings, different viscous vortex core models, optional wake aging (linear or Squire), temporal integration: 2nd order Adams-Bashforth
- Non-lifting bodies:
  - constant strength sink/source panels (displacement) only
- Optional tip vortex rollup model
- Recent application: Main rotor / empennage interaction [2]



UPM lifting surface model

Computational Method

Approximate Boundary Layer Methods – Lifting Surfaces

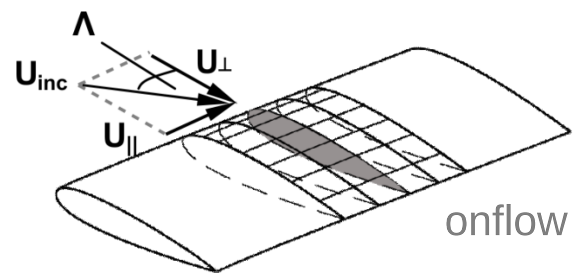
Stripwise analysis along wing/blade segments using integral BL methods & empirical transition prediction

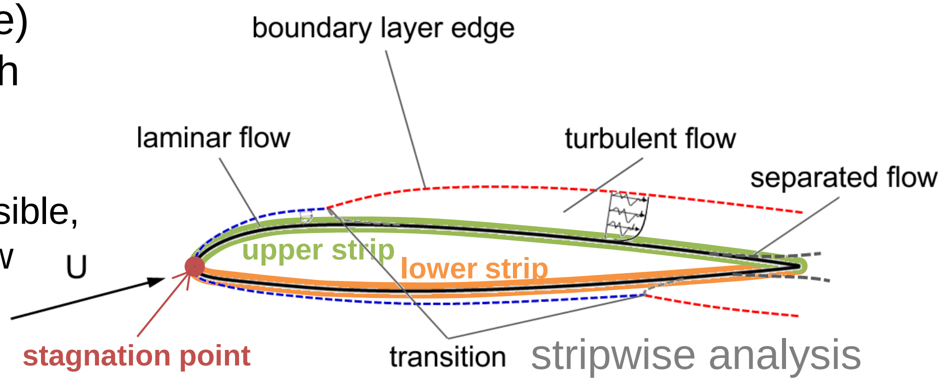
- **Laminar analysis**, available methods:
  1. Schlichting
  2. Eppler
  3. Thwaites/Curle

  assuming incompressible, planar, steady BL flow
- **Transition prediction** (9 methods available) or forced transition at given rel. chord length
- **Turbulent analysis**, available methods:
  1. Truckenbrodt
  2. Eppler
  3. Nash/Hicks

  assuming incompressible, planar, steady BL flow
- Analysis ends at **separation point**

wing/blade segment





Inputs:
- onflow conditions
- streamline arc length *s*
- inviscid velocity distr. $U_e(s)$

Stripwise Boundary Layer Analysis

Outputs:
- local BL properties (H_{12}, H_{32}, $\delta_{1/2/3}$, …)
- local skin friction coeff. c_f
- integral sectional and total friction forces
- transition and separation locations

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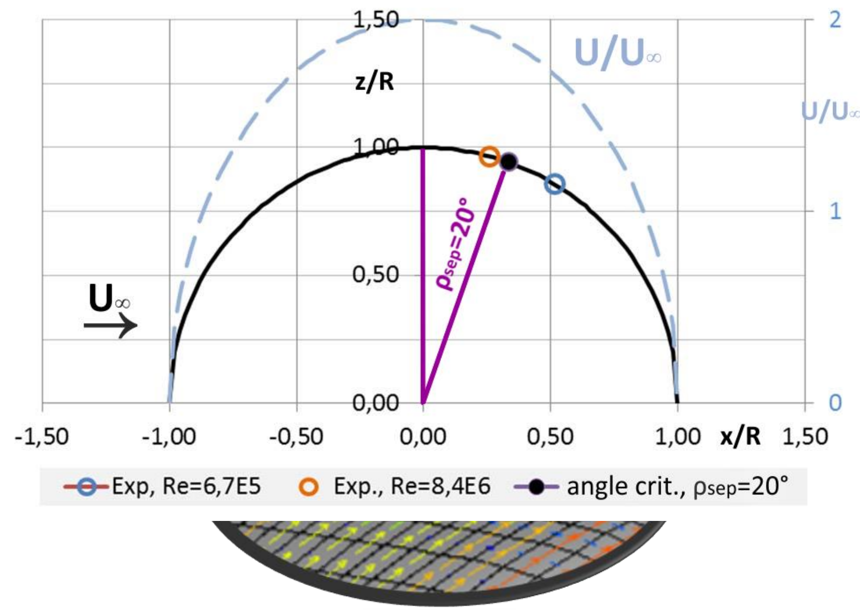
Computational Method

Approximate Boundary Layer Method – Non-Lifting Bodies

Simplified boundary layer analysis based on turbulent flat plate analogy & pre-design methods (flow separation)

1. Calculation of flux variable for each edge
2. Stagnation point detection
3. Arc length calculation ("advancing front")
4. Evaluation of local Re_s and c_f using turb. flat plate friction law by Schlichting:
   $c_{f,loc} = [2 \cdot \log_{10}(Re_s) - 0.65]^{-2.3}, Re_s < 10^9$
5. Flow separation using angle criterion



Inputs:
- onflow conditions
- inviscid velocity distr. $U_e(s)$

Simplified Boundary Layer Analysis

Outputs:
- local skin friction coeff. c_f
- integral total friction forces
- flow separation region

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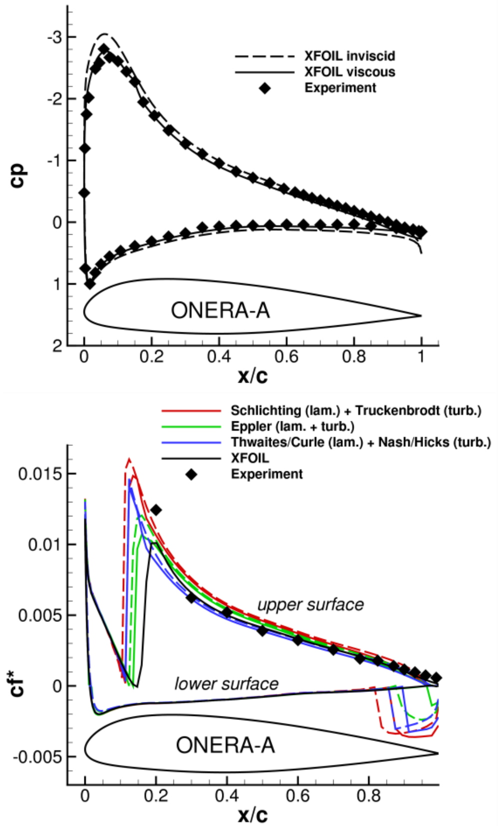
Results

Airfoils: Skin Friction – UPM vs. XFOIL and Experiment

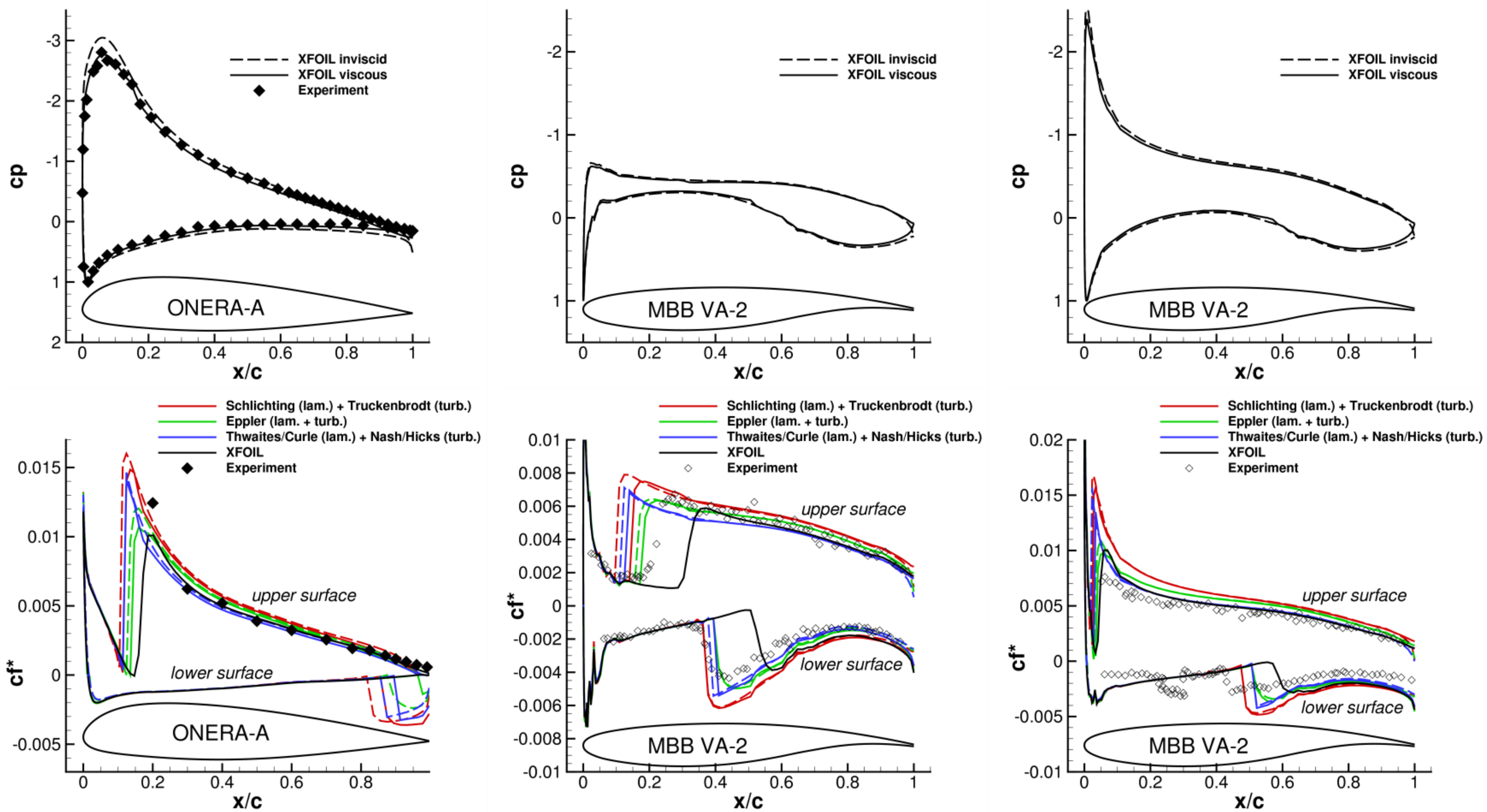


α = 8°

- Isolated test of implemented integral BL methods
- Using XFOIL results (arc length, velocity distribution) as inputs
  - Inviscid solution
  - Viscous solution (includes boundary layer displacement effects)
- Very good agreement of all methods in laminar region
- Transition / separation is delayed when taking BL displacement into account
- Implemented methods return conservative estimate when compared to XFOIL results (esp. Truckenbrodt method overpredicts skin friction)

Results

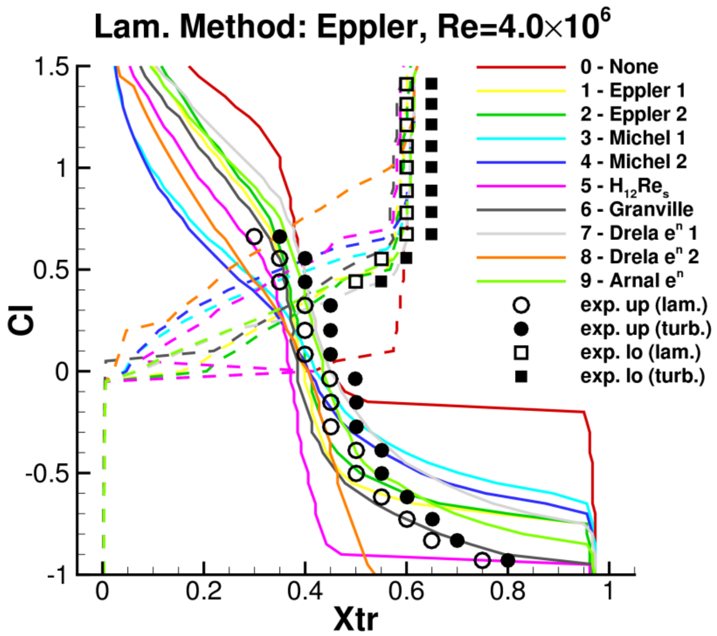
Airfoils: Skin Friction – UPM vs. XFOIL and Experiment



α = 8° α = 0° α = 4°

Results

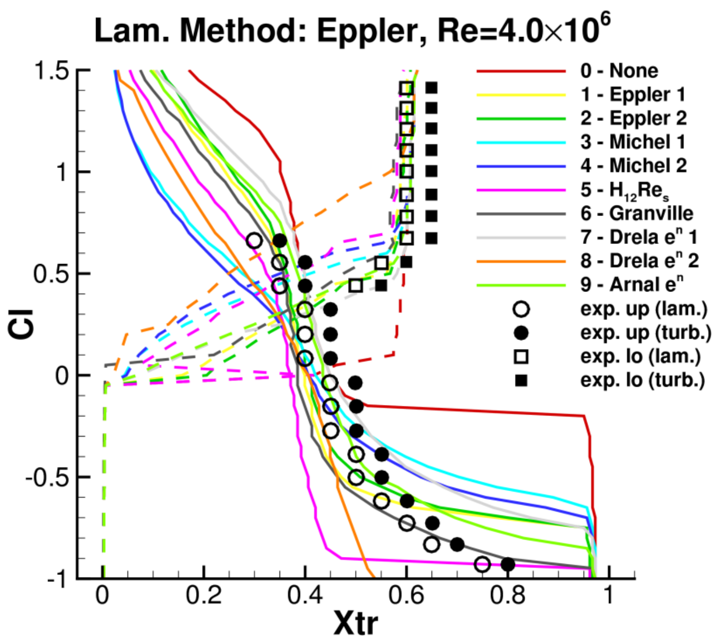
Airfoils: NLF(1)-0416 Transition Criteria & Polar

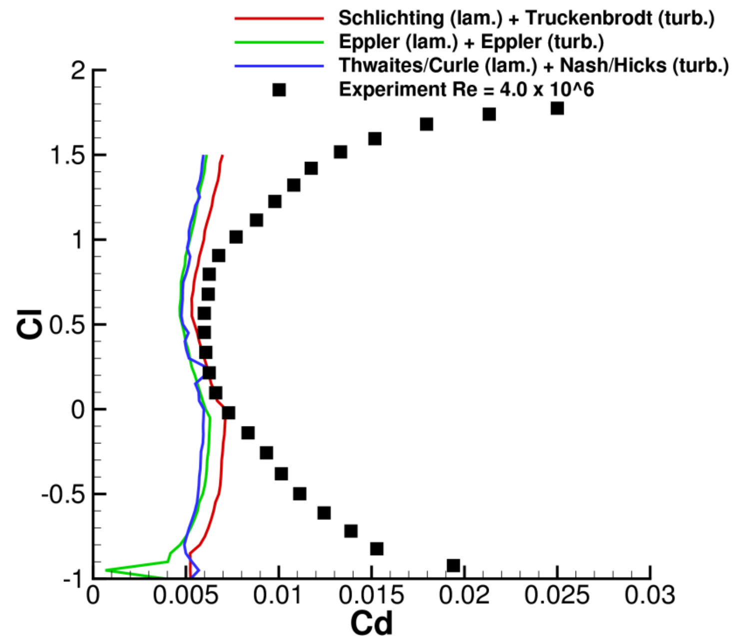


- 9 empirical transition criteria implemented (transition due to Tolmien-Schlichting instabilities only)
- Comparison of computed transition locations by all methods (n_{crit}=9) with experiment
- e^n envelope based method by Arnal selected as default

Results

Airfoils: NLF(1)-0416 Transition Criteria & Polar

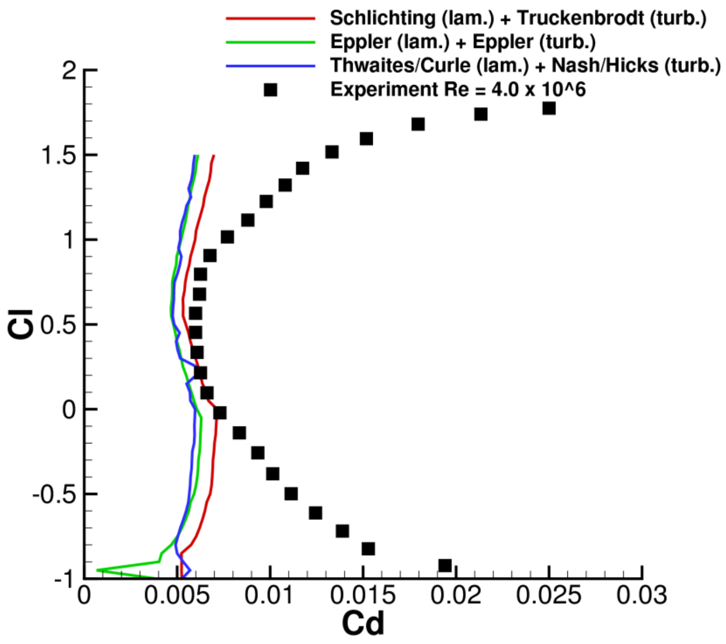




Results

Airfoils: NLF(1)-0416 Transition Criteria & Polar

- Polar using the different integral methods, transition method Arnal n_{crit}=9
- Fully attached flow:
  good agreement with experiment
- Separated flow:
  Effects due to BL displacement (form drag) not captured

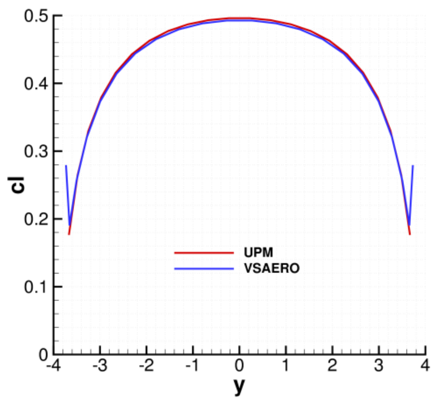


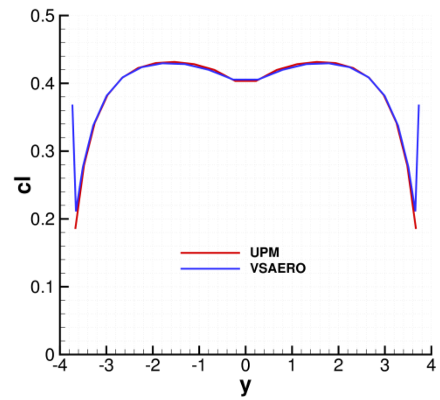
Results

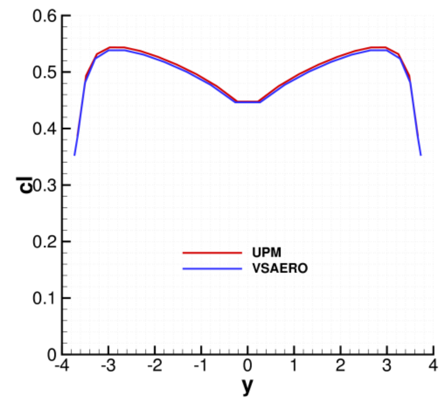
Wings: 3 planforms (planar, untwisted, NACA0012)

Comparison with VSAERO (state-of-the-art, commercial panel code, steady)

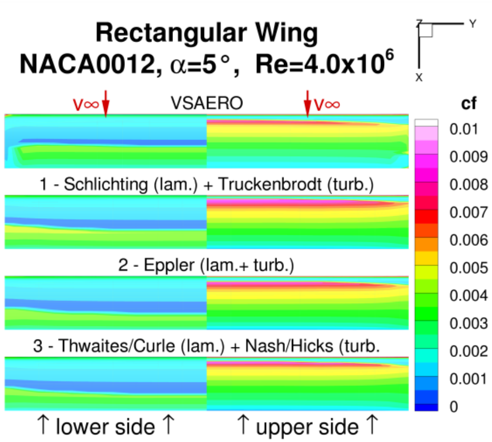
lift coefficient

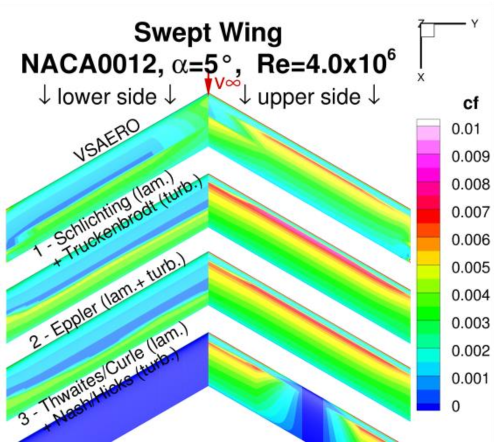


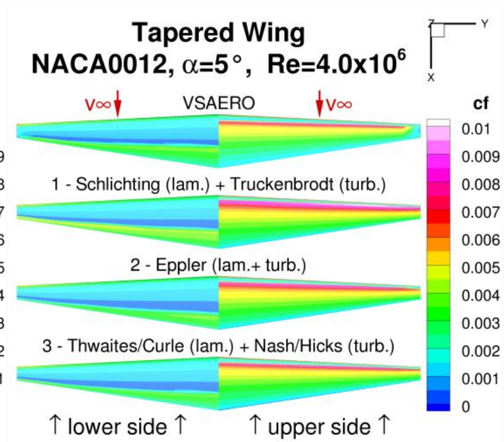




skin friction







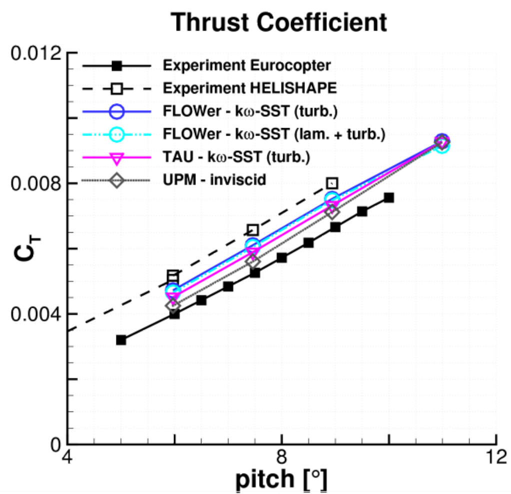
Results
Rotor 7A in Hover

Testcase properties	
Ma_{tip}	0.617
R	2.11 m
c	0.14 m
Θ_0	5.97°, 7.46°, 8.94°, 10.99°

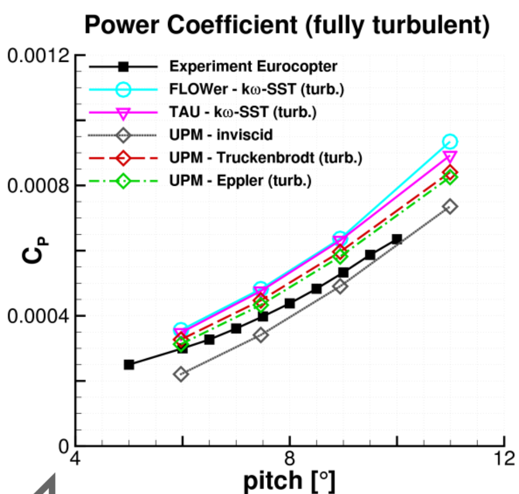
Computational settings	
# chordwise panels	98
# radial panels	17 (per blade)
# revolutions	8
time step	5°

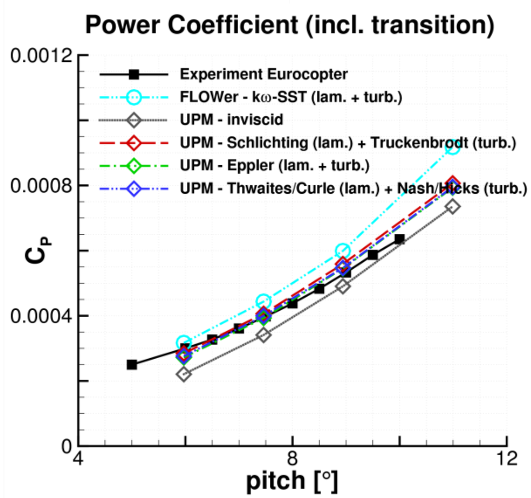
Results

Rotor 7A in Hover: Polar



- UPM predicts slightly lower thrust compared to CFD, similar slope
- Except largest collective angle: UPM can't capture lift decline due to separation onset

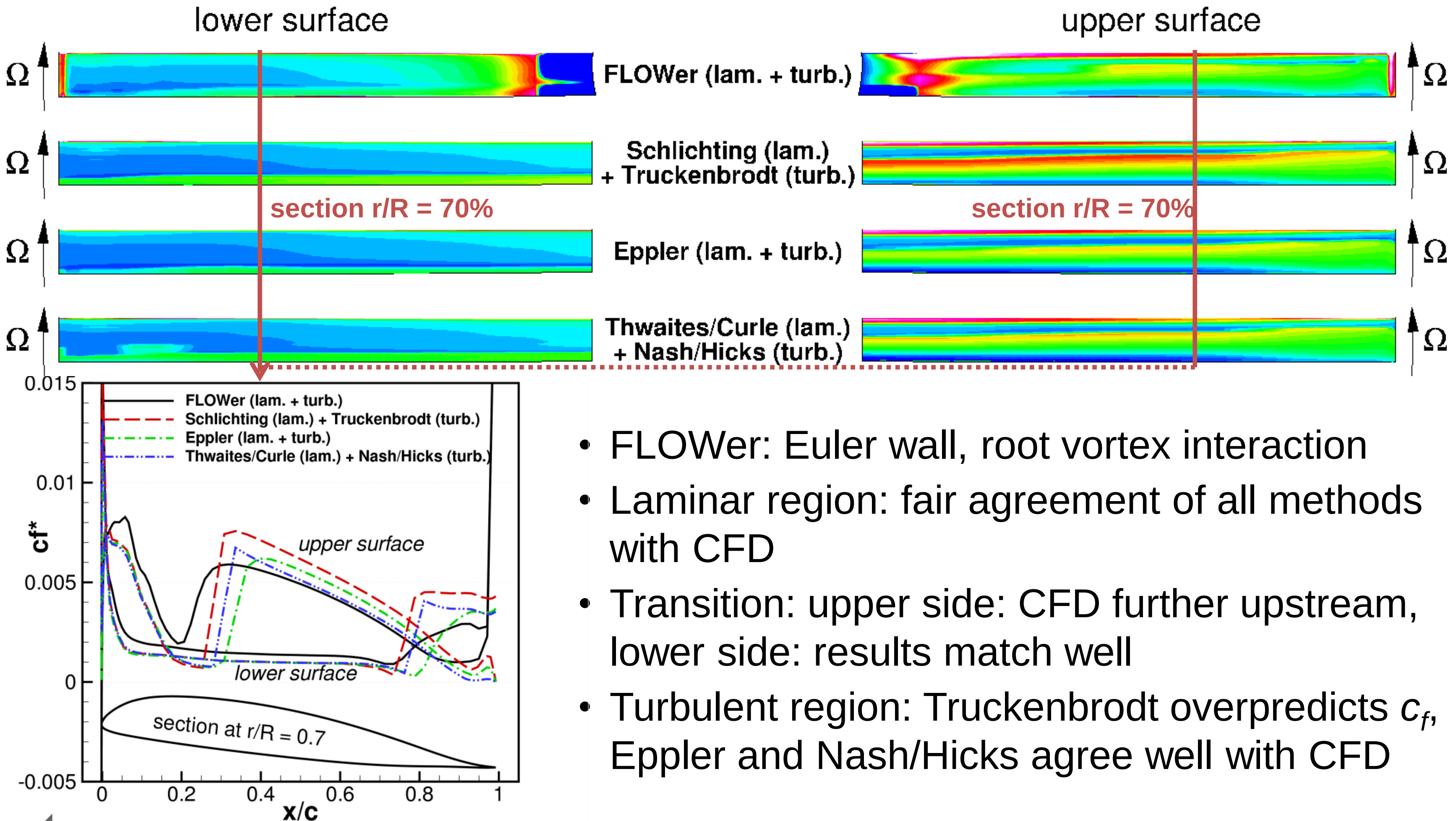




- UPM predicts slightly lower power compared to CFD
- Constant offset, except largest coll. angle: UPM can't capture form drag due to separation onset
- Differences due to different integral analysis methods are small

Results

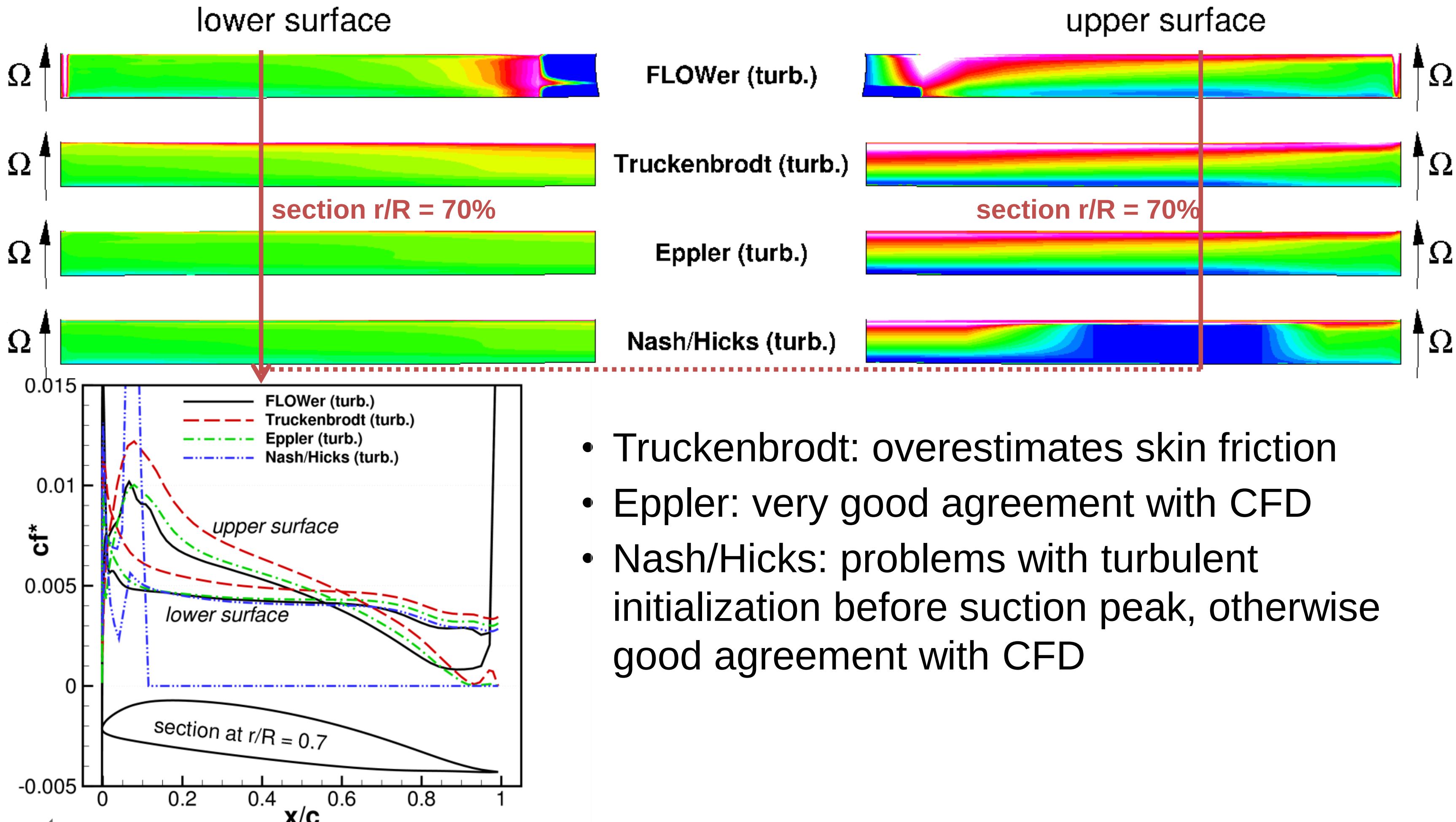
Rotor 7A in Hover: Skin Friction (lam./turb. trans. analysis)



- FLOWer: Euler wall, root vortex interaction
- Laminar region: fair agreement of all methods with CFD
- Transition: upper side: CFD further upstream, lower side: results match well
- Turbulent region: Truckenbrodt overpredicts c_f, Eppler and Nash/Hicks agree well with CFD

Results

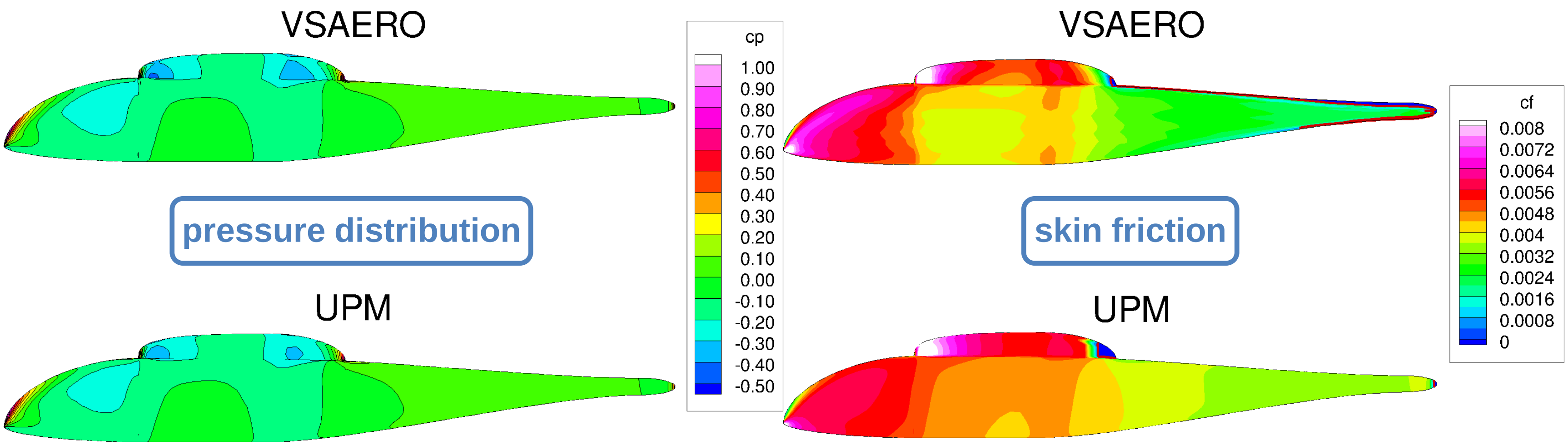
Rotor 7A in Hover: Skin Friction (fully turb. analysis)



- Truckenbrodt: overestimates skin friction
- Eppler: very good agreement with CFD
- Nash/Hicks: problems with turbulent initialization before suction peak, otherwise good agreement with CFD

Results

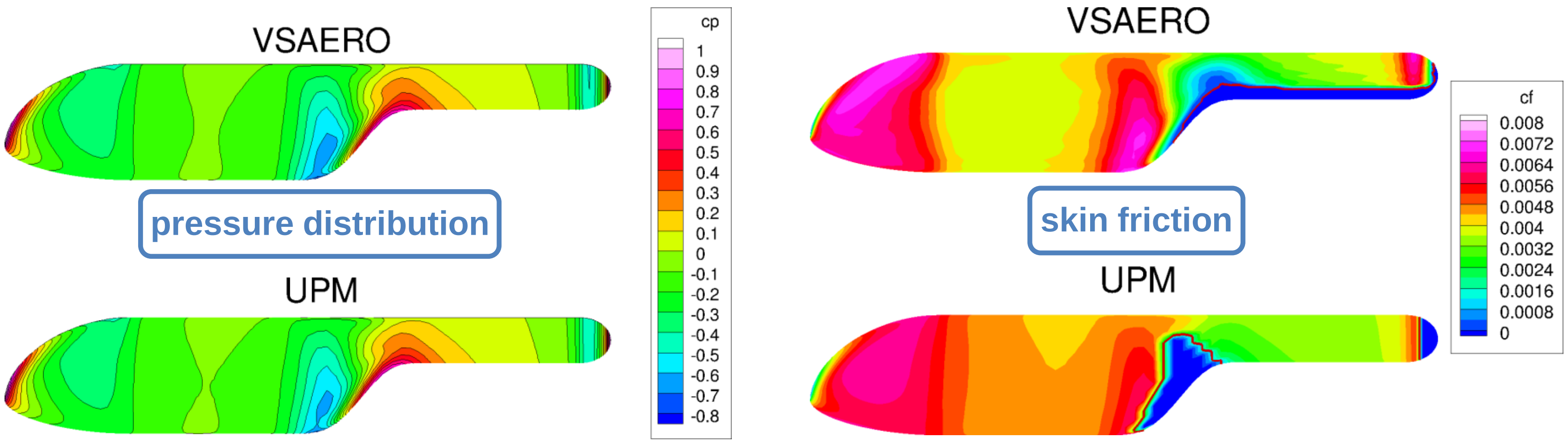
Fuselages: ROBIN @ Ma=0.1, Re=1.6x10^6, α=β=0°



- Inviscid pressure distribution: very good agreement
- Streamline arc length: works robustly even with multiple stagnation points
- Skin friction: simplified BL analysis tends to overestimate c_f
- Separation: angle criterion with $\varrho_{sep}=20°$ predicts earlier separation (conservative), separation state is not convected downstream

Results

Fuselages: ROBIN-mod7 @ Ma=0.1, Re=1.6x10^6, α=β=0°

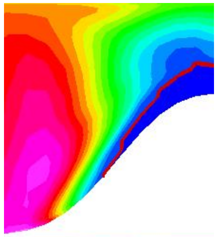


- Blunt aft body shape causes massive flow separation
- Conclusions from previous testcase results are confirmed

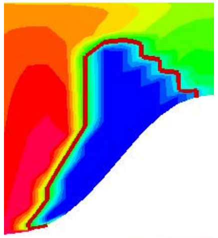
Results

Fuselages: ROBIN-mod7 – Flow Separation

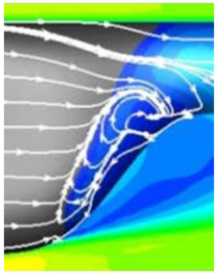
VSAERO:
c_f contours



UPM:
c_f contours



TAU (RANS)[1]:
contours: surface c_p
+ symm. plane *Ma*



Experiment[2]:
UV oil flow
visualization

- Separation line:
  - angle criterion agrees well with CFD and experimental results, VSAERO predicts separation further downstream

- Reattachment:
  - VSAERO: no
  - UPM: immediately, as soon as angle criterion doesn't trigger
  - CFD/Exp.: yes, further downstream

[1] Wentrup, M.: *An adjoint based optimization chain for complex helicopter fuselage parts using a free form deformation or CAD based parameterization method*. In: 41st European Rotorcraft Forum. 1-4 Sep. 2015, Munich, Germany (2015)

[2] Schaeffer, N., Allan, B., Lienard, C., Pape, A.L.: *Progress towards fuselage drag reduction via active flow control: A combined CFD and experimental effort*. In: 36th European Rotorcraft Forum. Paris, France (2010)

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Conclusion and Outlook

- Implemented fast and robust methods for approximate BL analysis of lifting and non-lifting surfaces.
  Considerable concessions in terms of modeling fidelity were made.
- Implemented methods were validated for several testcases: airfoils, wings, hovering rotor and fuselages
- Good results could be achieved (first estimate, conservative)
- Best practices / defaults for model parameters were developed

- Application to complete helicopter configurations, different points of the flight envelope
- Further enhancement of robustness and accuracy