Boundary-Layer Transition Prediction Through Loose Coupling of OVERFLOW and LASTRAC

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Outline

- Motivation & Objectives
- Solvers for CFD and Stability Analysis
- Workflow
- Intermittency Distribution Function
- Test Cases and Results
  - 2D: Flate plate, NLF(1)-0416
  - 3D: 6:1 prolate spheroid, NASA Juncture flow (new expt.)
- Summary & Future Work

Motivation

- Push for greener and safer aerospace technologies
  - Accurate prediction of laminar-turbulent boundary layer transition is important
  - NLF wing design, crewed reentry vehicle design
  - Current state-of-the-art methods not sufficient
    - RANS-based models (easy to use, efficient, inaccurate/lacks physics)
    - Stability-based methods (physics-based, expensive, significant user-expertise)
- **CFD Vision 2030**
  - Build CFD tool chain with automated prediction of boundary layer transition

Objectives

Develop framework to enable automated CFD-integrated physics-based modeling of the transition process

- **Focus of this work**: OVERFLOW (CFD) + LASTRAC (Stability analysis)
- Minimal burden on the user & capability to handle complex geometries robustly
- Concurrent work involving FUN3D + LASTRAC (Hildebrand et al., AIAA Paper 2022-1952)

CFD Solver & Stability Analysis Solver

CFD: OVERFLOW 2.3b[1]

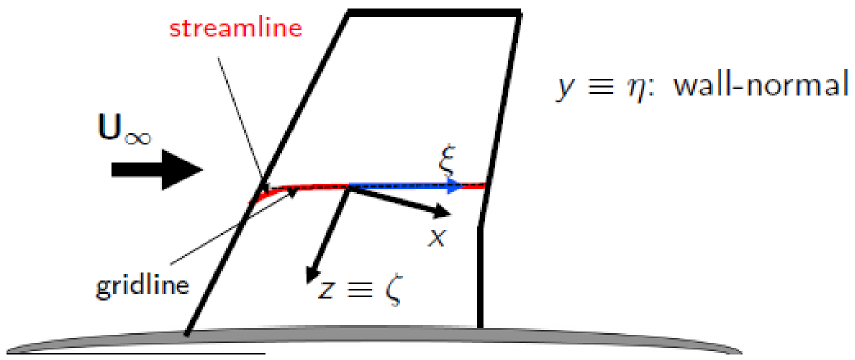
- Implicit structured overset grid Navier-Stokes solver
- Variety of choices for spatio-temporal discretization
- RANS-based transition models: Langtry-Menter (LM), Amplification Factor Transport (AFT), Medida-Baeder
- **Computations with imposed transition (specified laminar region) using SA/SST turbulence models**

Stability Analysis: LASTRAC 3.d Solver[2]

- Linear stability theory (LST), Parabolized stability equations (PSE)
- **Works with both structured and unstructured grids (via PyLASTRAC tool suite[3])**

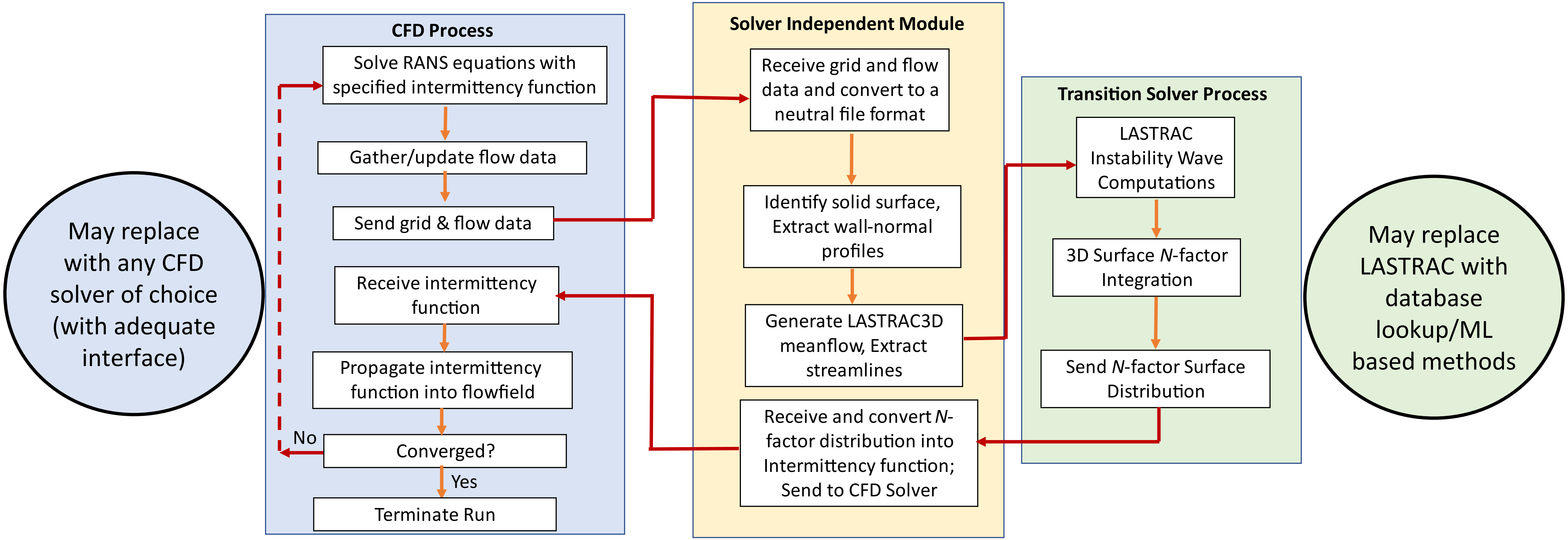
Mean flow for stability analysis

- **Computed with OVERFLOW: SA + imposed transition**



1. Nichols, R. H, and Buning, P. G., "User's Manual for OVERFLOW 2.3, Version 2.3," NASA Langley Research Center, Hampton, VA, Oct 2019.
2. Chang, C.-L., "LASTRAC 3d: Transition Prediction in 3D Boundary Layers," AIAA Paper 2004-2452, 2004.
3. Chang, C.-L., "Development of Physics-Based Transition Models for Unstructured-Mesh CFD Codes using Deep Learning Models," AIAA Paper 2021-2828, 2021.

Workflow



Uses: C++/Fortran90, Python and bash scripts

Intermittency Distribution Function

- RANS-based CFD solvers
  - Laminar region specified ⇒ turning off turbulence production terms or zeroing eddy viscosity
    - Binary nature of point transition causes abrupt jumps
    - Not physical, convergence difficulties

- Narasimha[1] : Smooth continuous intermittency function
  - Realistic modeling of the transition zone
  - Robust convergence process

$$\gamma = \begin{cases} 0\,, & x < x_{tr,beg} \\ 1 - \exp(-0.412\,\xi^2)\,, & x \geq x_{tr,beg};\ \ \xi = \dfrac{(x - x_{tr,beg})}{\underbrace{\lambda}} \end{cases}$$

λ = length of the transition region
Unknown!

- Simple choice
  - $\lambda = x_{tr,end} - x_{tr,beg};\quad x_{tr,beg} = 0.8N_{crit}$ and $x_{tr,end} = 1.1N_{crit}\ or\ 1.2N_{crit}$
  - N_{crit} for TS instability can be obtained from LST/PSE results along with Mack's correlation

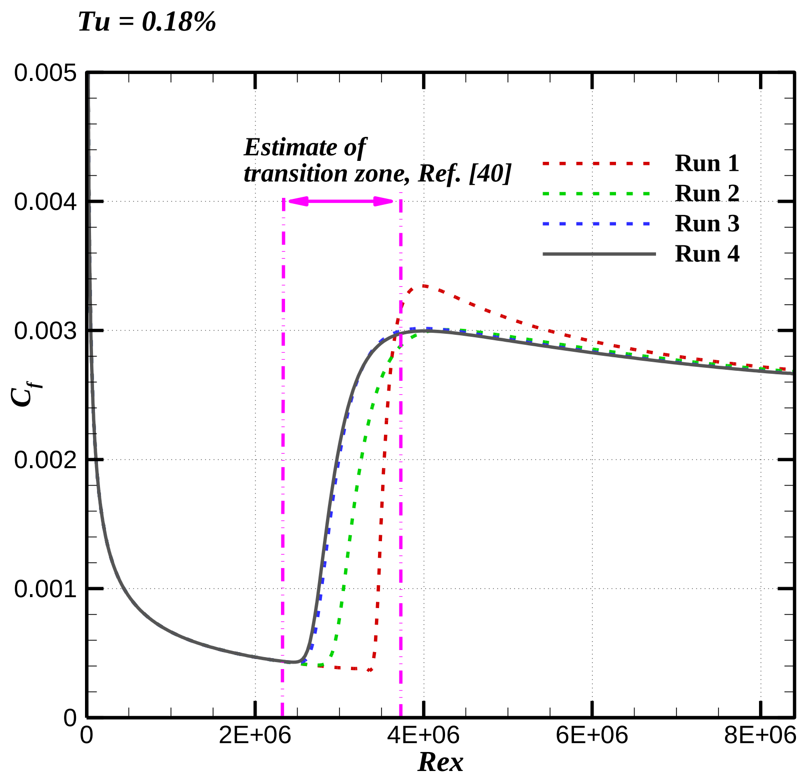
1. Narasimha, R., "The Laminar-Turbulent Transition Zone in the Boundary Layer," *Progress In Aerospace Sciences.*, Vol. 22, 1985, pp. 29–80

Test Cases and Results

Flat Plate

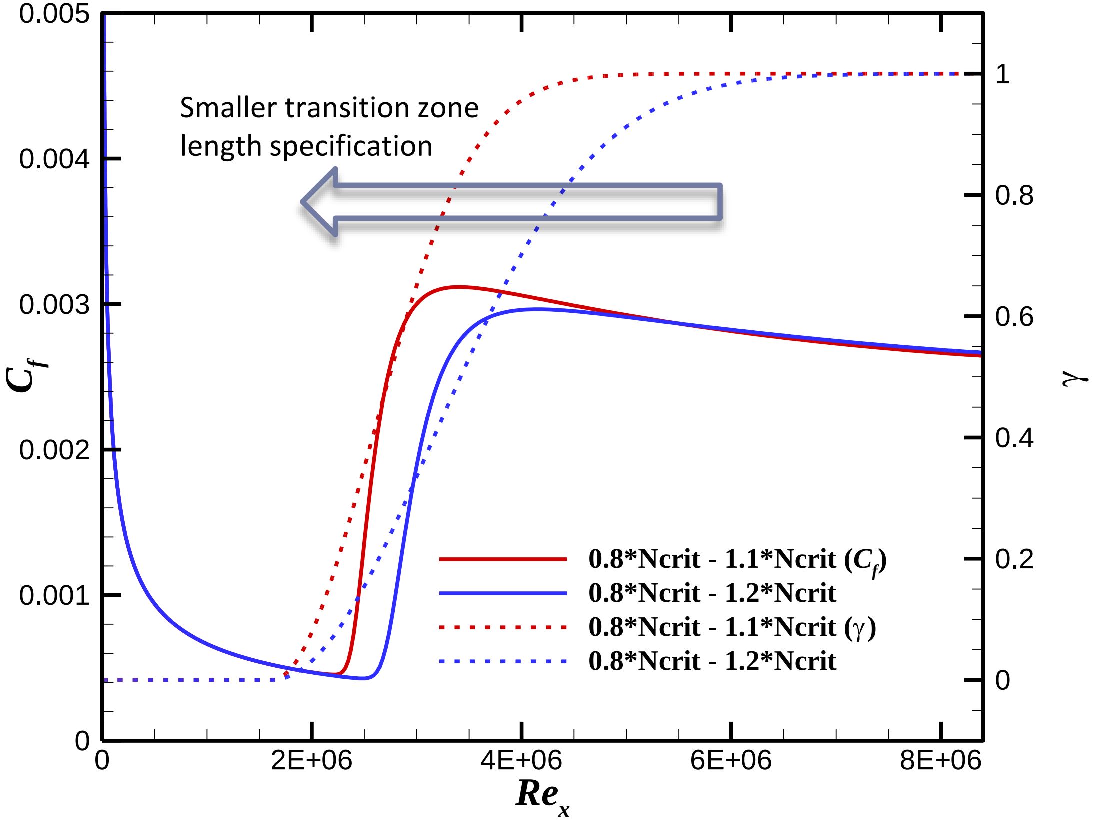
- Domain: 2.5 m (additional 0.15m upstream of leading edge) x 0.3 m
- Baseline mesh (Medium resolution): 721 x 385 ($y^+ < 0.5$ based on transition location; 100 points in boundary layer)

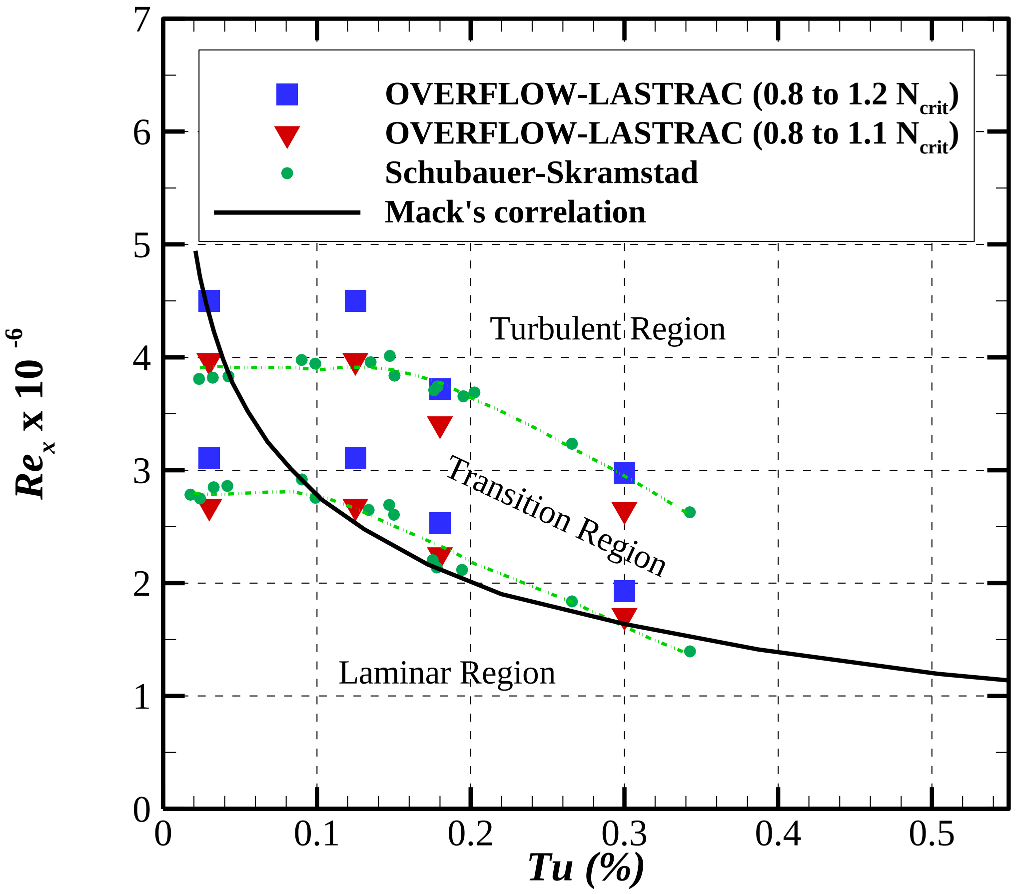
Case	Tu at the leading edge (%)	Freestream Velocity (m/s)	Density (kg/m^3)	Freestream Temperature (K)
Schubauer and Skramstad [40];	0.03, 0.125, 0.18, 0.3	50.1	1.2	288.17
ERCOFTAC T3A-	0.875	19.8	1.2	288.17



Schubauer, G. B., and Skramstadt, H. K., “Laminar Boundary Layer Oscillations and Stability of Laminar Flow,” *J. Aero. Sci.*, Vol. 14, No. 2, 1947, pp. 69–78

Flat Plate

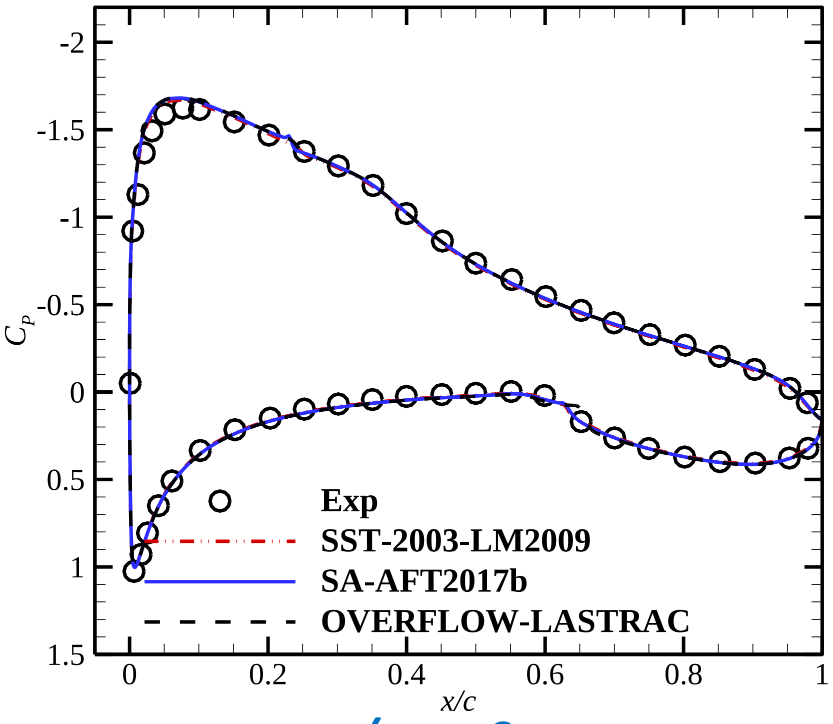




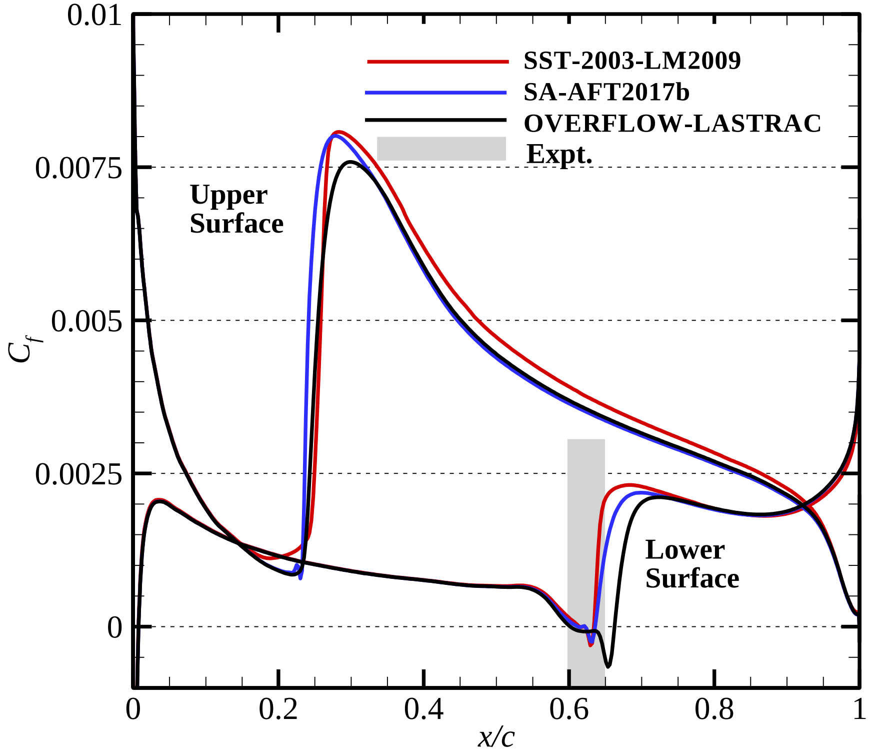
- Sensitivity to transition zone length specification
- Shifting $x_{tr,beg}$ instead of $x_{tr,end}$ needs to be assessed
- See paper for T3A- results and related discussion

NLF(1)-0416 Airfoil

- $M_\infty = 0.1, \mathrm{Re}_c = 4 \times 10^6, c = 1\,m, \alpha = 5°$
- Tu = 0.15 % (N_{crit} = 7.2); $x_{tr,beg} = 0.8N_{crit}; x_{tr,end} = 1.1N_{crit}$
- Extrafine C-grid from AIAA TMPW committee (1025 x 193 points)



x/c vs. C_p



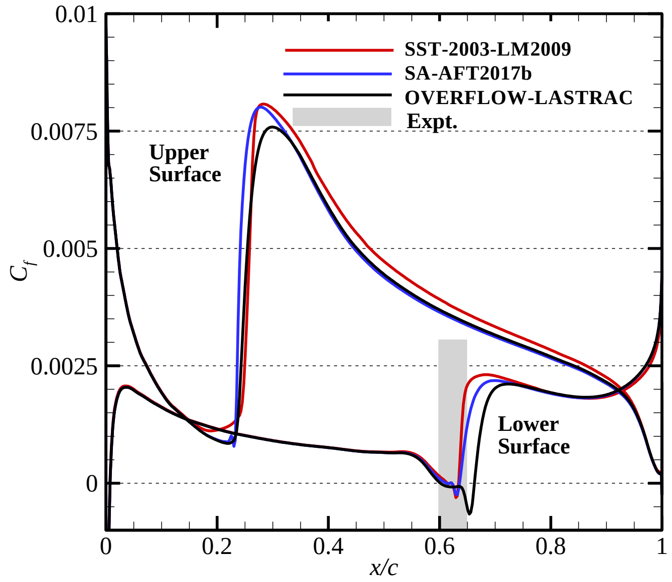
x/c vs C_f

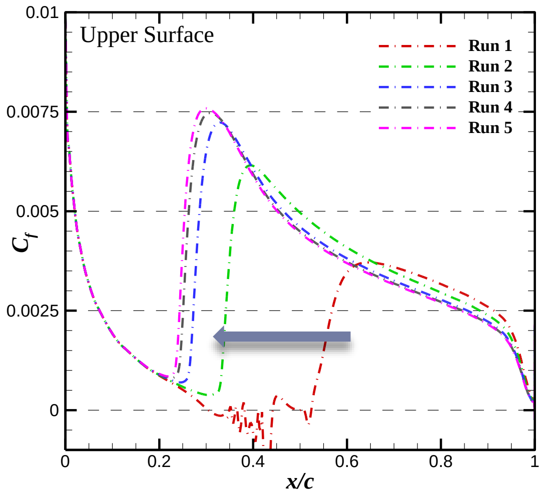
➢ TS instability on the upper surface

➢ Separation bubble induced transition on the lower surface

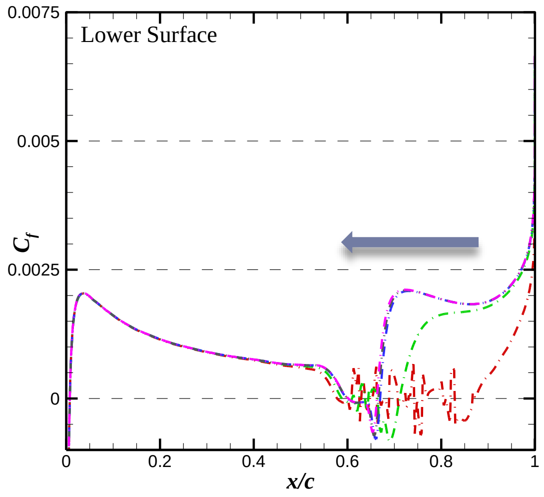
NLF(1)-0416 Airfoil

- Robustness of converged results to initial location of specified transition
- Automated process is able to recover when initial transition location is specified significantly upstream
- Reattachment of bubble downstream of that seen in Expt.
  - Influence of intermittency distribution
- See paper for results at $\alpha = 0°$ and $\mathrm{Re}_c = 4 \times 10^6$ & 9×10^6 (TS instability)

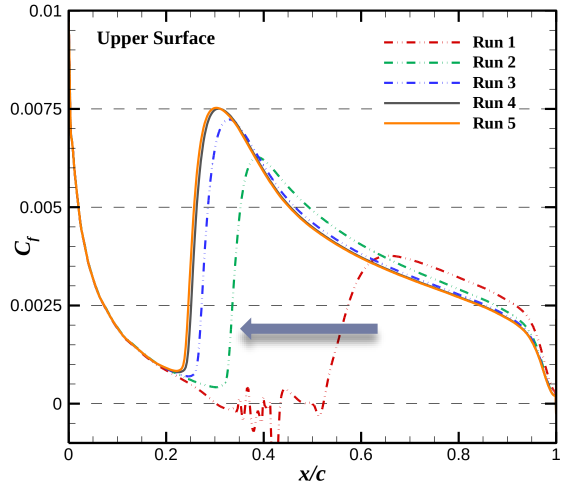




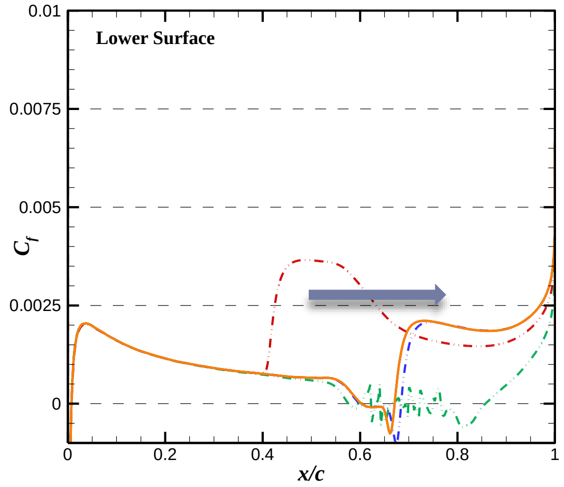
Initial tr location: downstream



Initial tr location: downstream



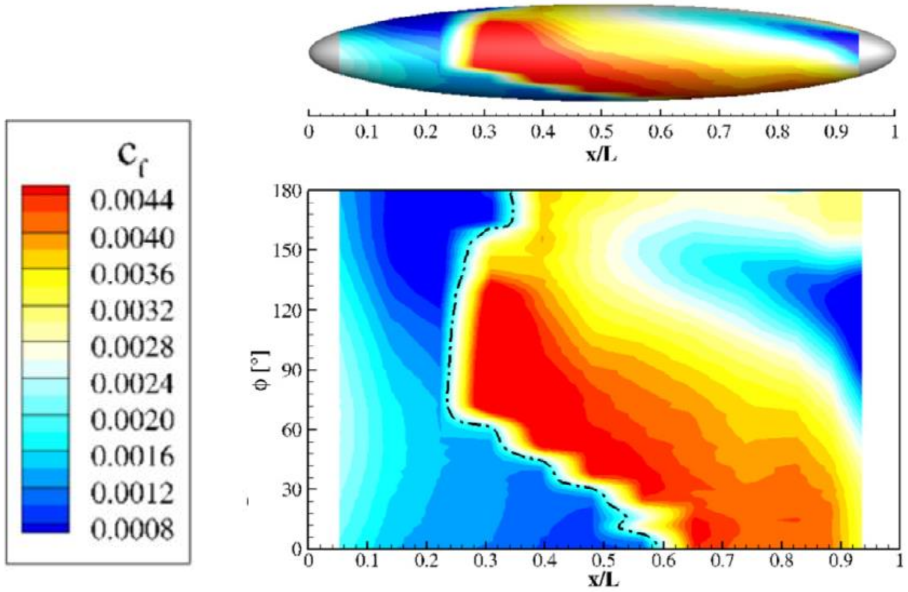
Initial tr location: downstream



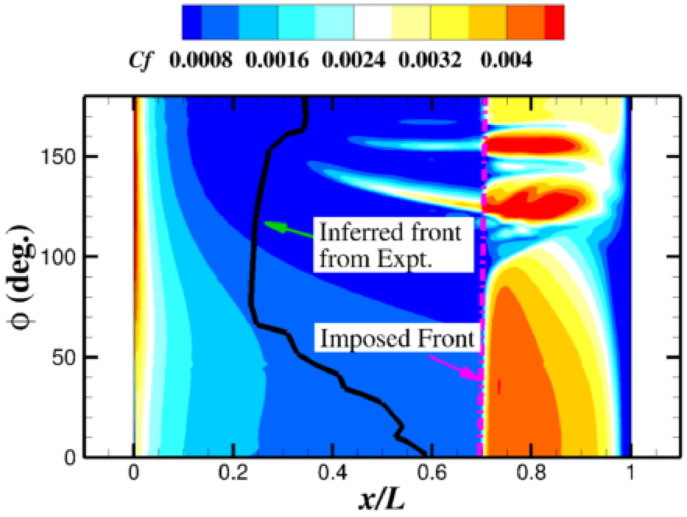
Initial tr location: upstream

6:1 Prolate Spheroid

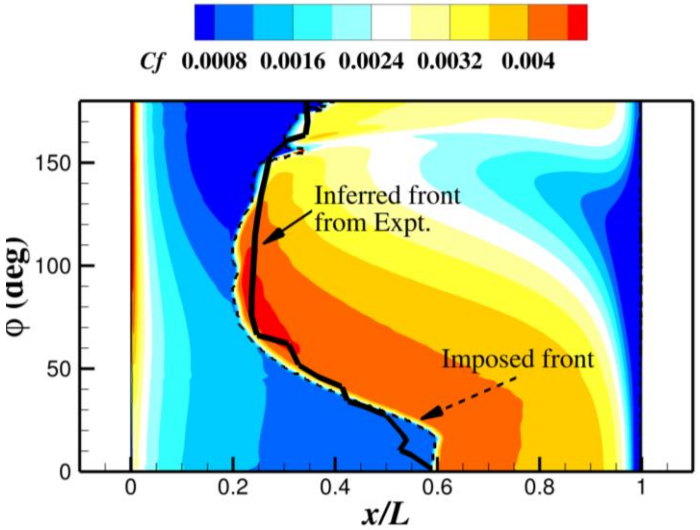
- $L = 2.4m;\ M_\infty = 0.136, \mathrm{Re}_L = 6.5 \times 10^6, \alpha = 10°$
- TS + CF instability
- Multiblock grid ($y^+ < 0.25$; 100 points in boundary layer) (see details in paper)
- **No use of intermittency distribution function in iterative process**



From Expt.

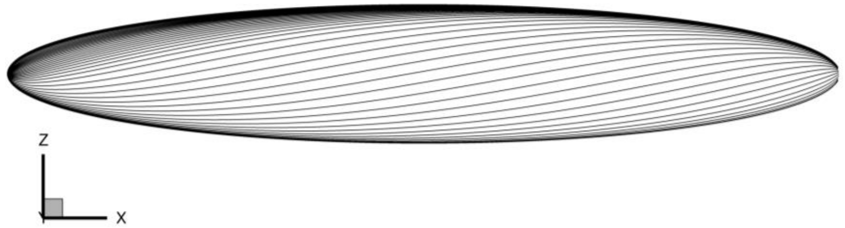


From CFD after first iteration of coupled solver



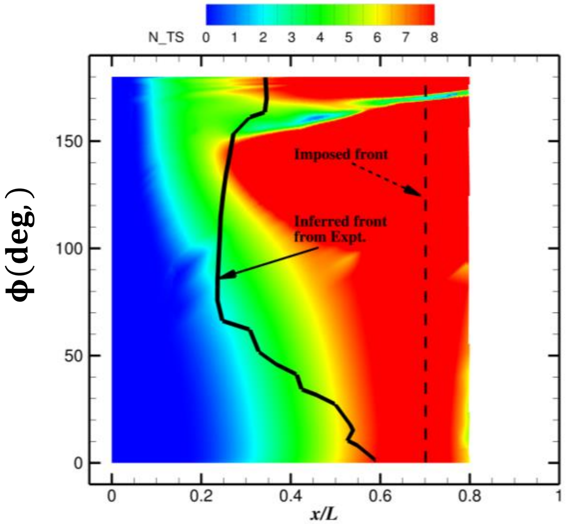
From CFD after two iterations of coupled solver

6:1 Prolate Spheroid

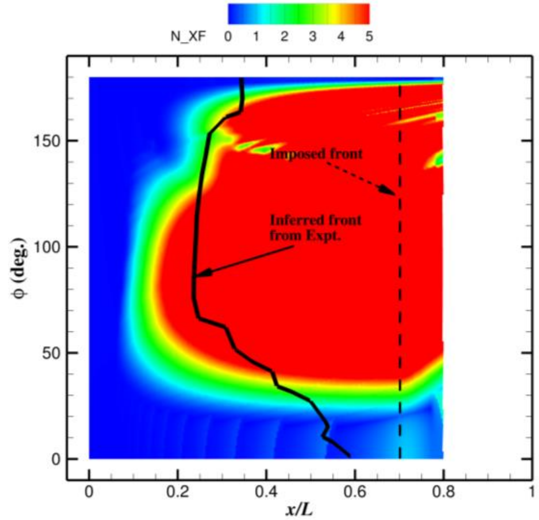


64 Streamlines used in PSE

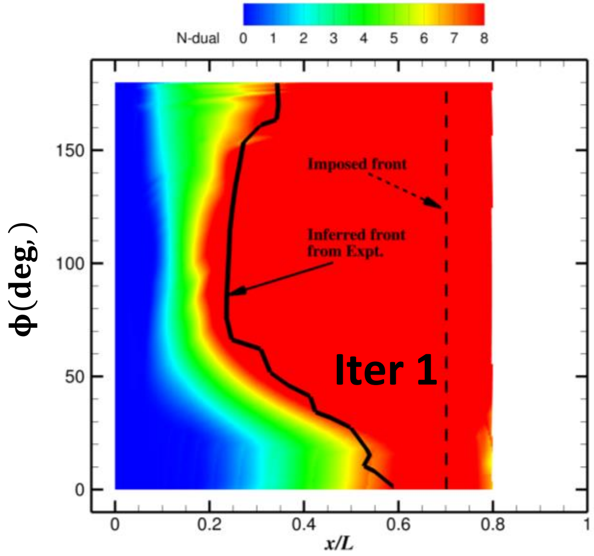
- $N_{dual} = NTS + NCF$
- Contour level = 8 coincides with expt.
- Need to investigate alternate forms of N_{dual}
- Complete convergence to be demonstrated



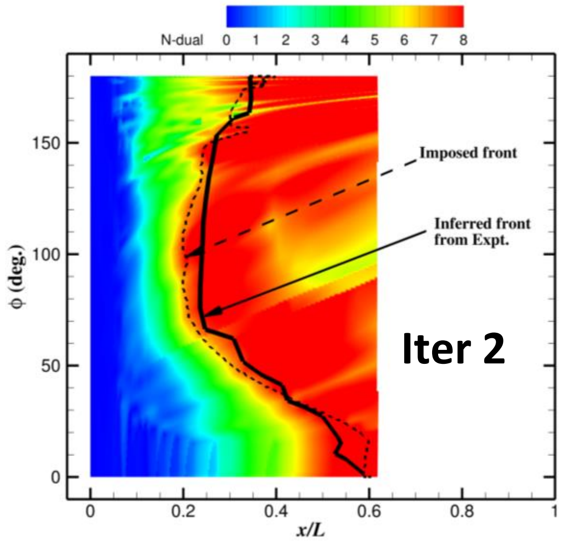
N_{TS} contour



N_{CF} contour

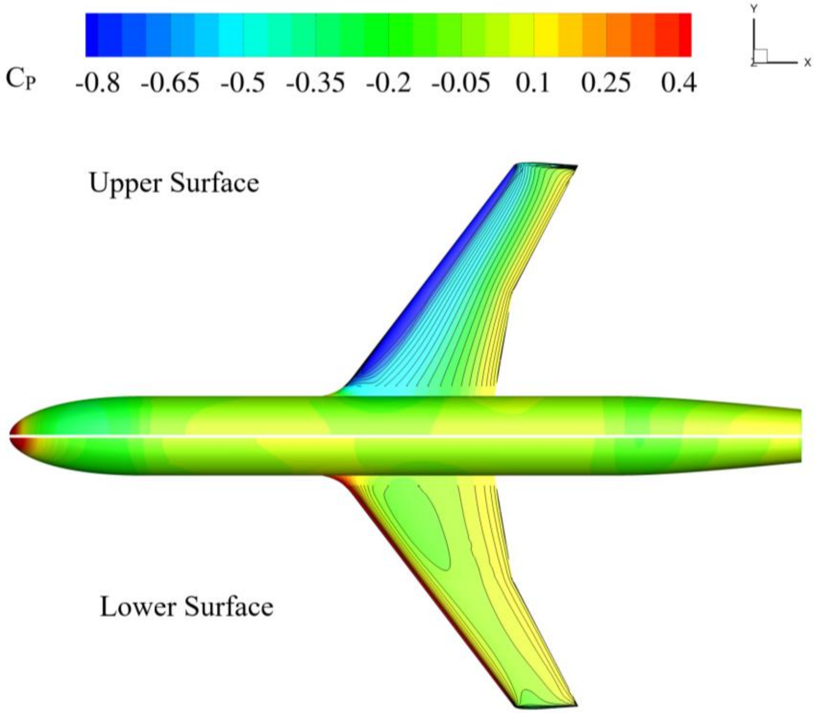


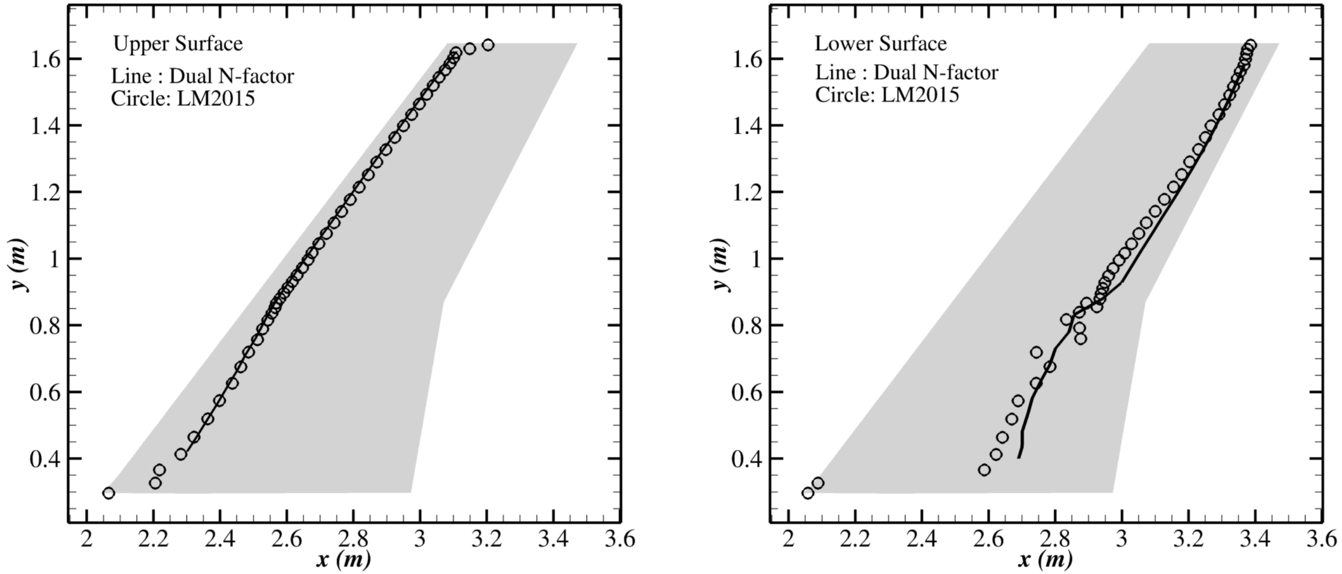
N_{dual} contour



NASA Juncture Flow (symmetric wing)

- Recently completed experiment at NASA Langley
- $M_\infty = 0.189, \mathrm{Re}_c = 2.4 \times 10^6, \alpha = 5°$
- **Only one iteration of coupled solver**
- TS on upper surface; TS + CF instability on lower surface





Comparison of transition front obtained with integrated solver and using LM model

Transition onset occurs when N_{dual} = 1.0 *(See Paredes et al. AIAA Paper 2021-1431)*

$$N_{dual} = \left(\frac{N_{TS}}{N_{TS,c}}\right)^{a_{TS}} + \left(\frac{N_{CF}}{N_{CF,c}}\right)^{a_{CF}}; \quad N_{TS,c} = N_{CF,c} = 8; \; a_{TS} = a_{CF} = 3$$

Summary

- **Demonstrated automated CFD-integrated transition prediction through coupling of OVERFLOW and LASTRAC**
  - Work in-progress; robustness and automation needs to be improved
- **Convergence of solution and match with experiments demonstrated for 2D cases** (TS + laminar separation bubble)
  - Flat Plate: allowed for calibration of intermittency distribution function
  - NLF(1)-0416: robustness of predicted solution to intial specification of transition location
- **Iterative convergence to be demonstrated for 3D cases** (TS + CF instability) - work in progress
  - Prolate spheroid, New NASA juncture flow: Needs alternate N_{dual} criterion and underrelaxation procedure

Future Work

- **Improve robustness of hands-off stability computation**
- **Time-to-solution performance comparison against RANS-based transition models**
- **Identifying more universal N_{dual} criterion for use with 3D geometries**
- Overset grid specific developments

Acknowledgments

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- LaRC K-Midrange Cluster resources

Thank You for Listening!

Back up Slides

Motivation

- Push for greener and safer aerospace technologies
  - Accurate prediction of laminar-turbulent boundary layer transition is important
  - NLF wing design, crewed reentry vehicle design

- **CFD Vision 2030**
  - Build CFD tool chain with automated prediction of boundary layer transition

Current state-of-the-art

- **DNS/WRLES** – Accurate, computationally expensive, exact specification of IC's & BC's

- **RANS-based Transition Models –** Computationally efficient, unstructured-mesh-compatible, ease of implementation, lacking in transition physics, limited applicability flow regime and accuracy
- **Stability-based Methods (LST, PSE)** – Widely used, physics-based & accurate, need for well-resolved boundary layers, not robust, portability into modern CFD codes can be challenging, domain expertise in hydrodynamic stability theory

Objectives

Big Picture:

Develop framework to enable automated CFD-integrated physics-based modeling of the transition process

- Leveraging upon unique capabilities amongst NASA CFD tools (automated mesh adaption, adjoint-based design etc.)

This project:

Create an automated tool chain for CFD-integrated transition prediction with OVERFLOW and LASTRAC

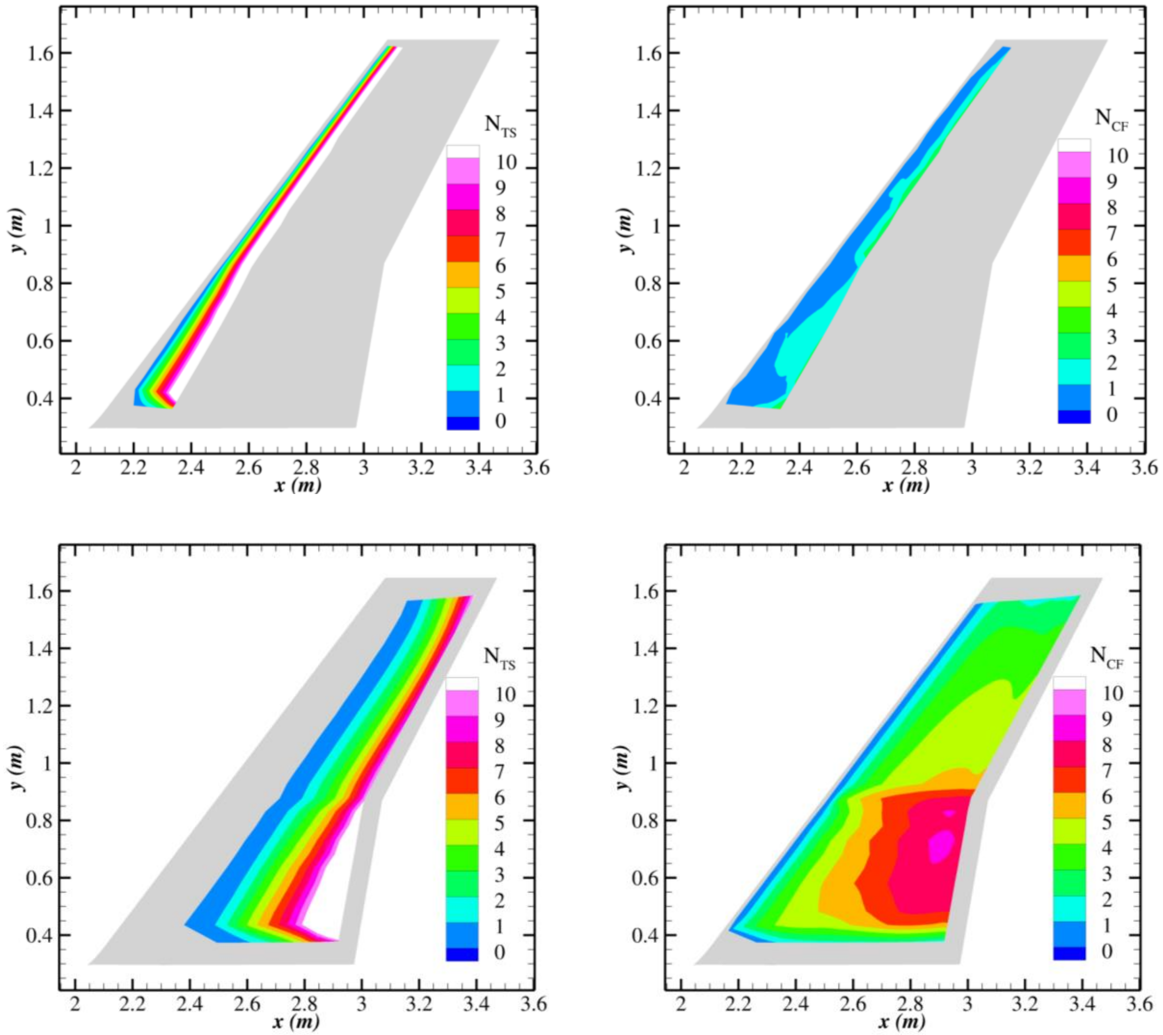
- Minimal burden on the user
- Sufficiently general to handle complex geometries robustly
- **Work in-progress**
- Concurrent work involving FUN3D is also underway (Hildebrand et al., AIAA Paper 2022-1952)

NASA Juncture Flow (symmetric wing)

N_{TS} contour N_{CF} contour

Upper Surface

Lower Surface



Long Summary

- Demonstrated automated CFD-integrated transition prediction through loose coupling of OVERFLOW and LASTRAC
  - Work in-progress; robustness and automation needs to be improved
- **Flat plate** : Tested under a range of Tu levels (TS instability)
  - Allowed for calibration of intermittency distribution function
  - Convergence of solution and match with experiments demonstrated
- **NLF(1)-0416 airfoil**: Low and High Re; TS + laminar separation bubble
  - Robustness of predicted solution to initial specification of transition location demonstrated
  - Alternate definitions for transition zone length definition needed for the case of separation bubbles
- **6:1 Prolate Spheroid**: AoA = 10 deg.; TS + CF instabilities
  - Predicted solution approaching convergence; more runs needed
  - Alternate N_{dual} criterion and ways to introduced underrelaxation currently under investigation
- **NASA Juncture Flow with symmetric wing:** AoA = 5 deg.; TS + CF instabilities
  - Preliminary pretest computation demonstrated; compares favorably with predictions from Langtry-Menter transition model
  - Iterative convergence needs to be demonstrated

Future work

- **Improve robustness of hands-off stability computation**
- **Identifying more universal and robust intermittency distribution functions and N_{dual} criterion for use with 3D geometries**
- **Time-to-solution performance comparison against RANS-based transition models**
  - Pending workflow optimization, established best practices
  - Mitigation of grid resolution requirements within boundary layer
- Transonic flow configurations
- Overset grid specific developments