

Integrated Boundary-Layer Transition Prediction



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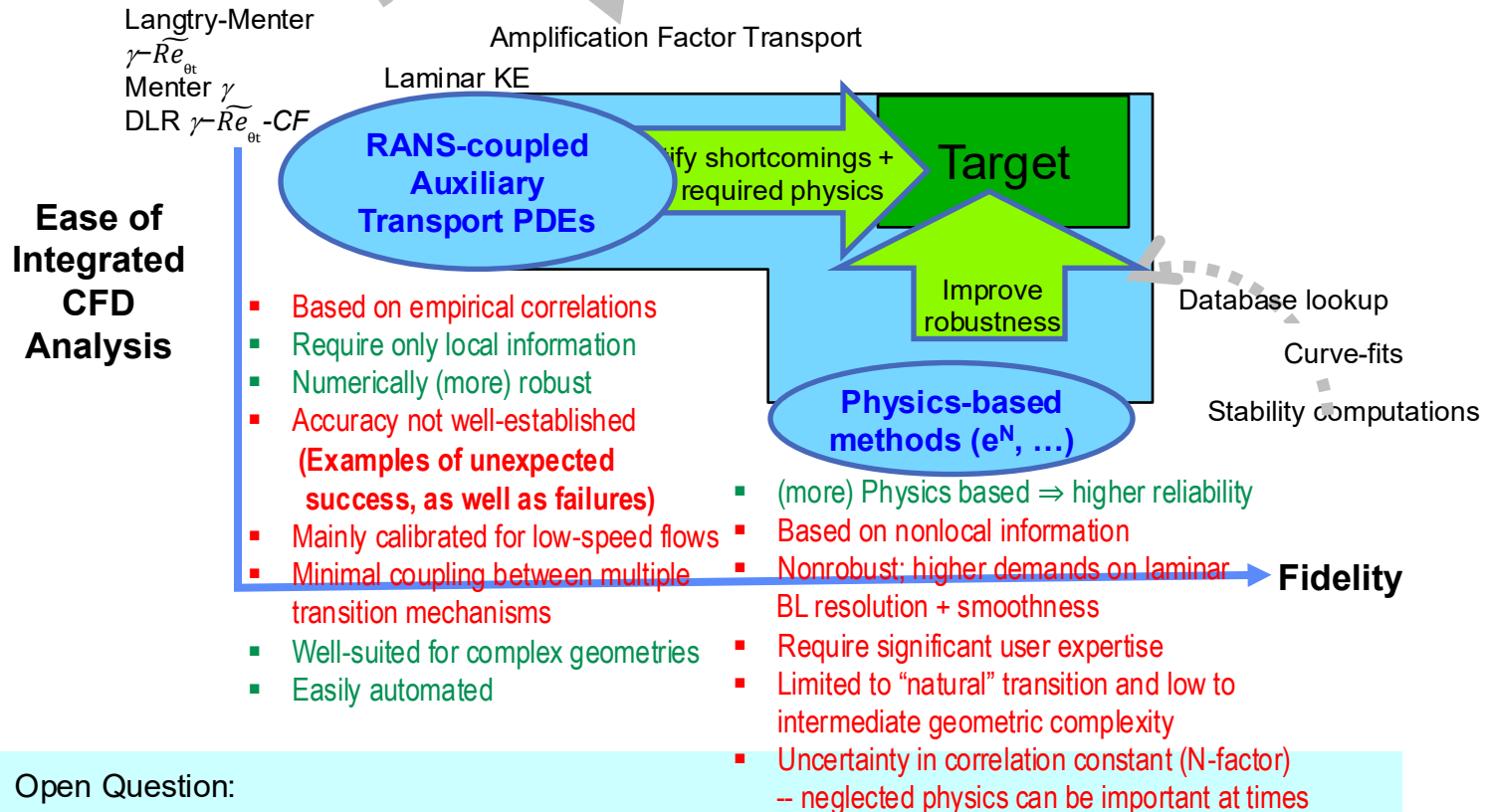
Technical Challenge

Develop and validate **fully automatic** transition prediction capability for CFD, incorporating **necessary physics**, with **quantified uncertainty**.

Transition modeling vs. turbulence modeling:

- Transition is sensitive to disturbance environment
- Multiple competing paths to transition
- Unlike turbulence, transition cannot be treated via statistical framework alone

Transition Modeling: How



Open Question:

What is the best way to blend the two approaches to develop physics-based transition prediction capability that overcomes the shortcomings of PDE-based approach?



Outline

– Introduction

- Dual strategy for CFD-integrated transition modeling in NASA's OVERFLOW and FUN3D codes

– Case studies

- Stability-based transition prediction

– Swept wing configurations (Juncture Flow Model, CRM-NLF)

Mixed mode transition
 N_{tr} calibration for
different facilities and
flow regimes

– High-lift configuration (30P30N, CRM-HL)

Multiple surface patches with
different transition mechanisms

1st mode,
1st mode+crossflow

– Supersonic cones (0-deg AoA, nonzero AoA)

– Hypersonic BLs

2nd mode transition, modeling N_{tr} and
intermittency region

– Surrogate models (deep learning)

Robust predictions
w/o transition expertise

- Transport-equations-based transition prediction
- Integrated transition modeling to NLF design optimization

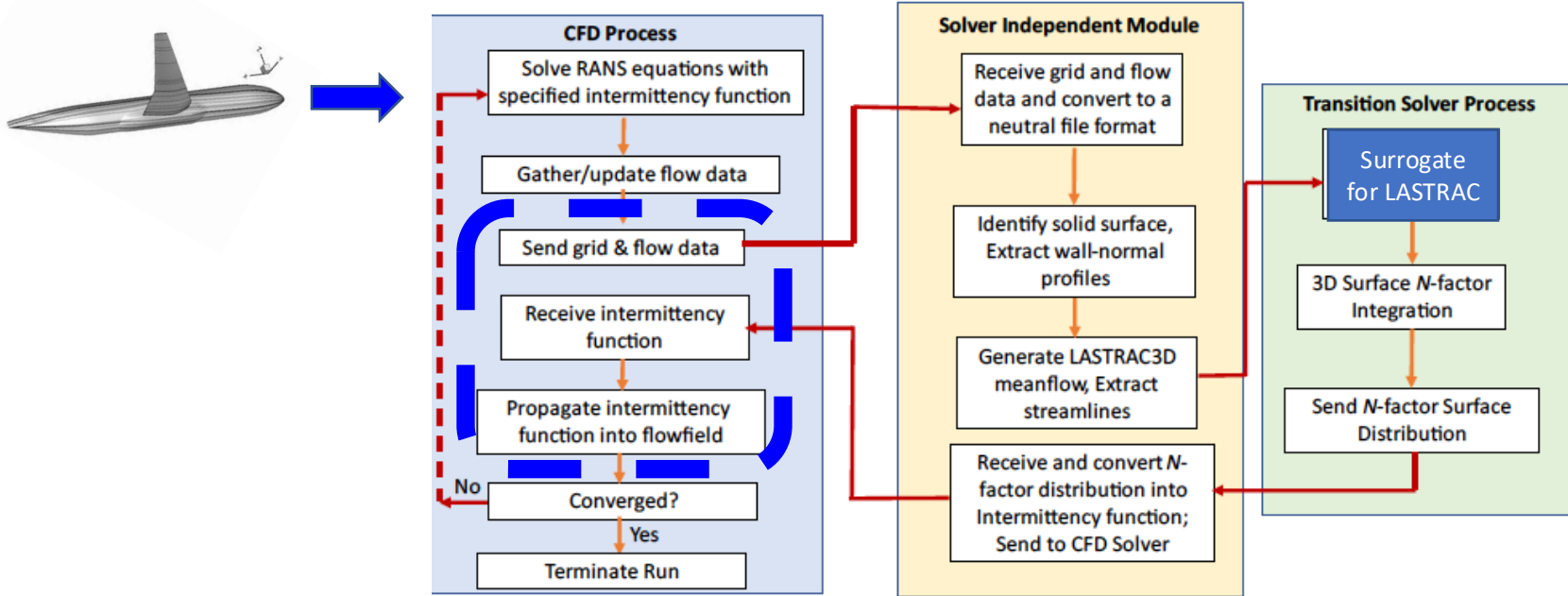
– Summary

LASTRAC-CFD → ML Surrogate-CFD Coupling



LASTRAC-FUN3D: Hildebrand et al. (2025)

LASTRAC-OVERFLOW: Venkatachari et al., Paredes et al. (journal submissions in preparation)



- Modular framework to maximize portability across multiple flow solvers and fidelity levels for instability modeling
- However, direct stability computations lack robustness, requiring accurate boundary layer profiles that demand high levels of grid resolution, and call for significant user expertise
 - Machine-learning based surrogate models for stability computations have also been developed

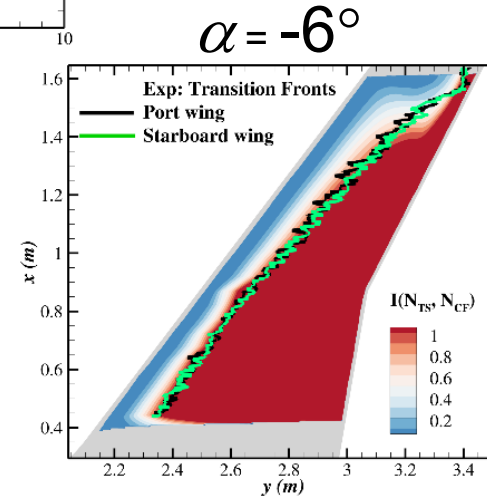
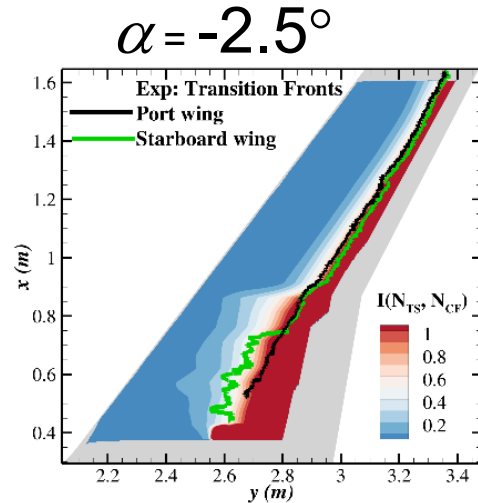
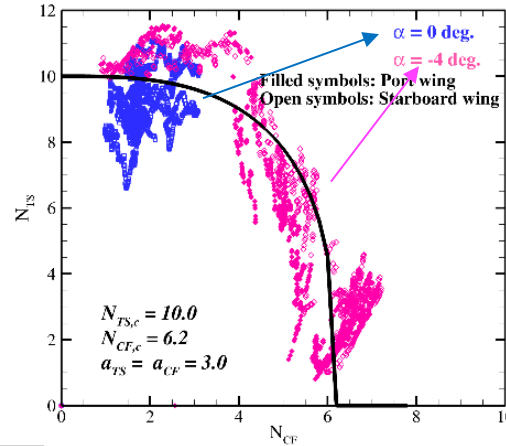


NASA Juncture Flow Model: Transition Predictions

Dual N-factor calibration

$$I(N_{TS}, N_{CF}) \equiv \left(\frac{N_{TS}}{N_{TS,c}} \right)^{a_{TS}} + \left(\frac{N_{CF}}{N_{CF,c}} \right)^{a_{CF}} = 1$$

$$N_{TS,c} = 10, N_{CF,c} = 6.2$$
$$a_{TS} = a_{CF} = 3$$





Swept-Wing Configurations: NASA CRM-NLF

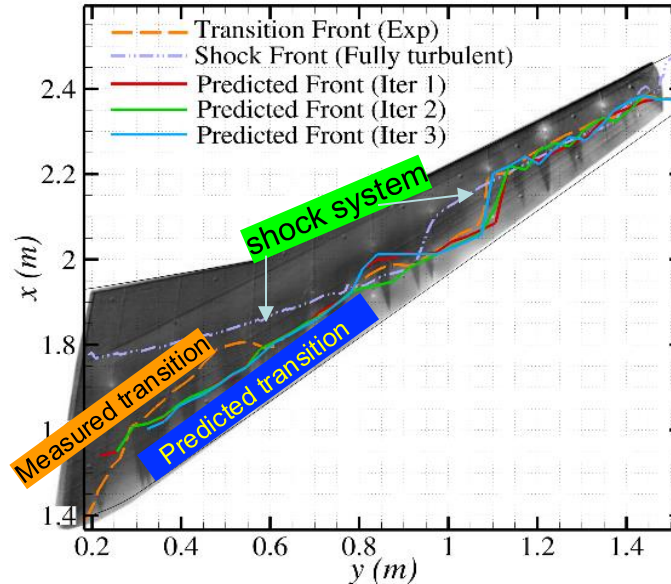
NASA National Transonic Facility Experiment (Lynde et al. 2019)

$$M = 0.856, Re_{MAC} = 15 \times 10^6$$

$$N_{TS,c} = 6, N_{CF,c} = 6$$

$$a_{TS} = a_{CF} = 3 \text{ (same as Juncture Flow Model)}$$

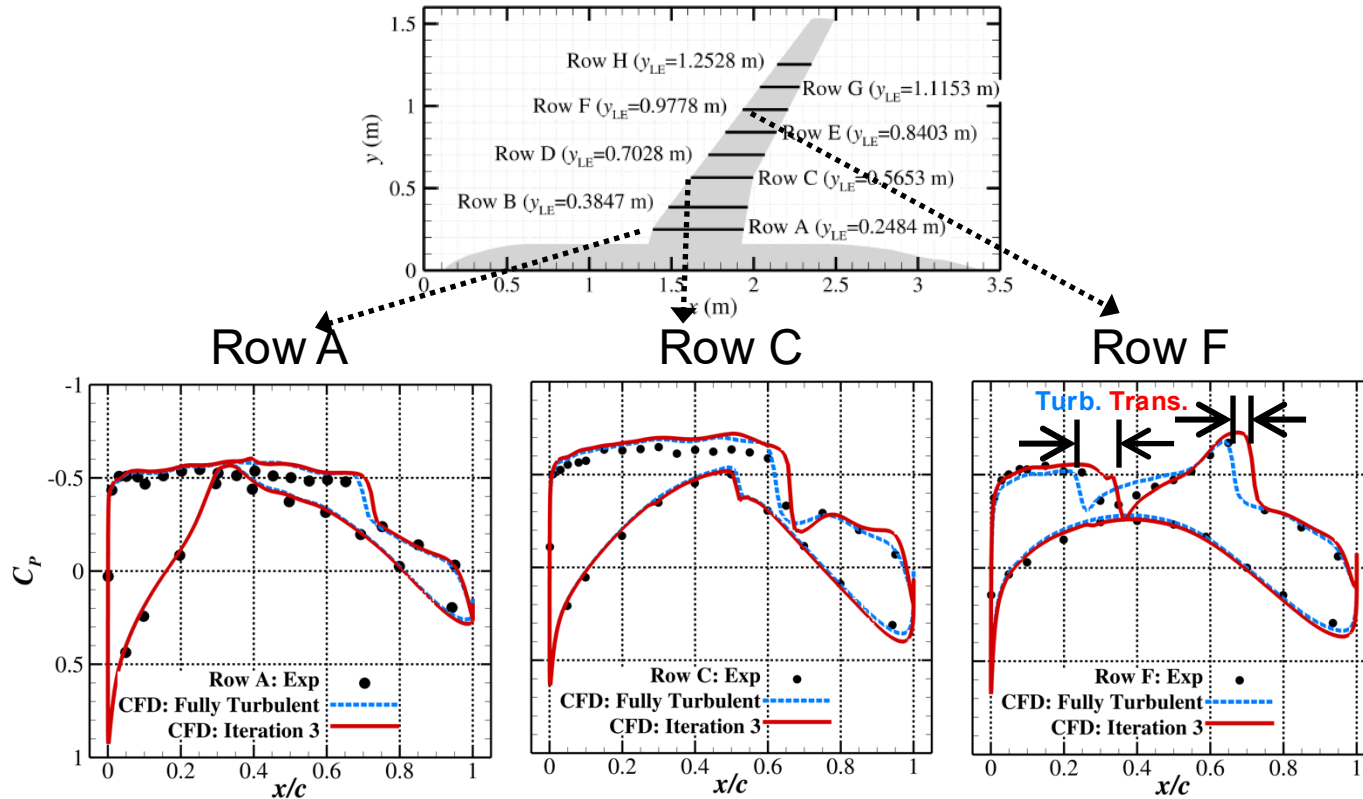
$$\alpha = 1.45^\circ$$





Swept-Wing Configurations: NASA CRM-NLF

$$M = 0.856, Re_{MAC} = 15 \times 10^6$$

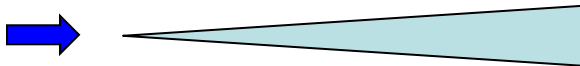
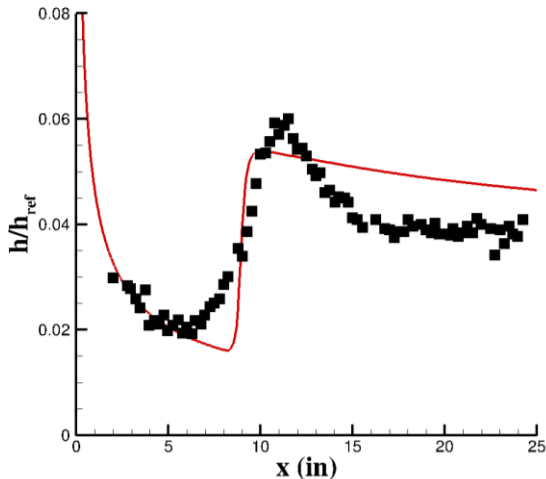


- Better agreement between measurements and turbulent C_p

OVERFLOW-LASTRAC Analysis for High-Speed Flows

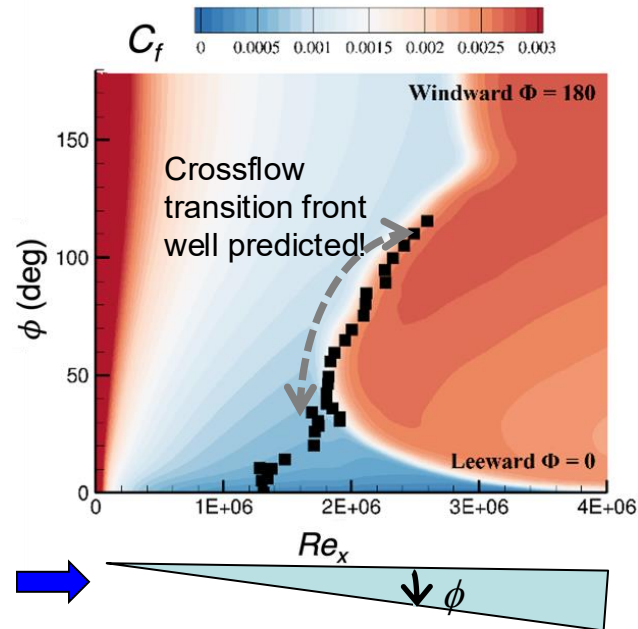
Second-mode transition

$M = 6$, 7-deg cone at $\alpha = 0^\circ$
Exp: Horvath et al. (2003)



1st mode + crossflow

$M = 2$, 7-deg cone at $\alpha = 2^\circ$
Exp: Tokugawa et al. (2015)



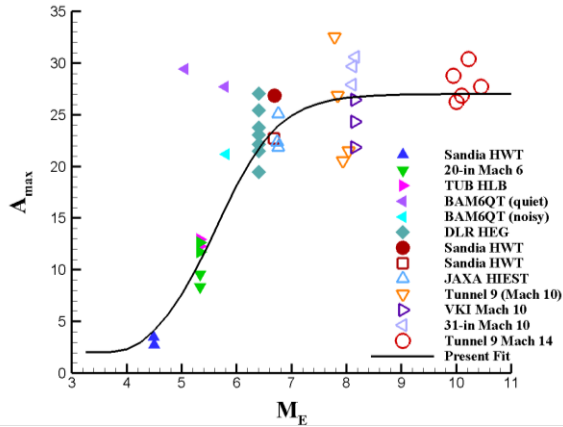
- Reasonable predictions possible if N_{tr} can be prescribed
 - Mack's correlation is not applicable to high-speed flows!
 - $\Rightarrow$ An element of post-diction in these results!



Correlation for Transition N-factor in High-Speed Flows

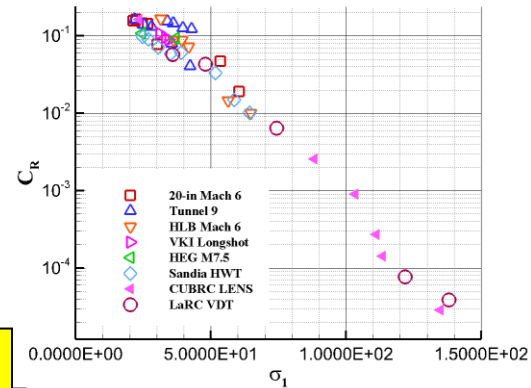
— Analogous to Mack's correlation for $N_{tr}(Tu)$

Critical Amplitude

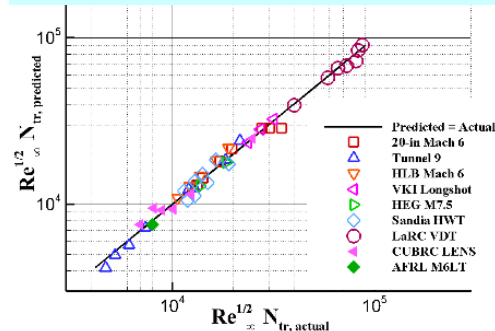


/

Receptivity Coefficient



Transition N-factor (N_{tr})



Correlation inputs:

- Freestream disturbance intensity
- Mach number
- Slenderness Reynolds number
- Test section size

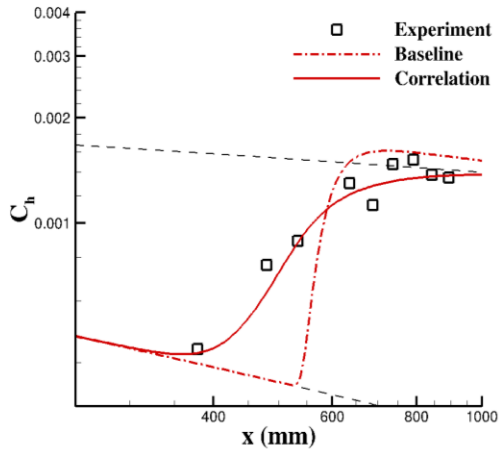


Intermittency Modeling for High-Speed Flows

Transition zone tends to be longer for high-speed configurations
⇒ Intermittency modeling important for predictions of total heat load as well as peak heating

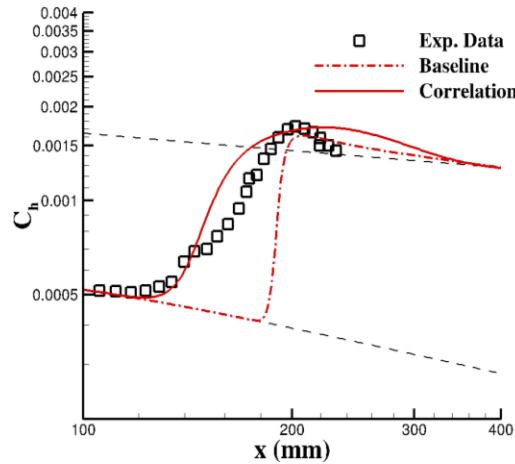
$M = 6.1$ Flat Plate (Mee 1996)

$Re = 4.9 \times 10^6/m$

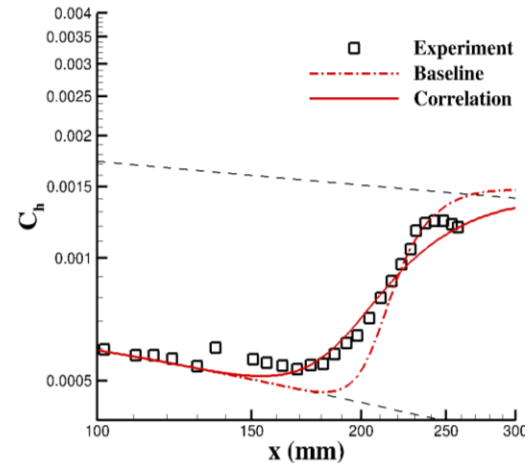


VKI 7° half-angle cone, $M = 6$

$Re = 22.8 \times 10^6/m$



$Re = 18.0 \times 10^6/m$





Surrogate Models Based on Deep Learning

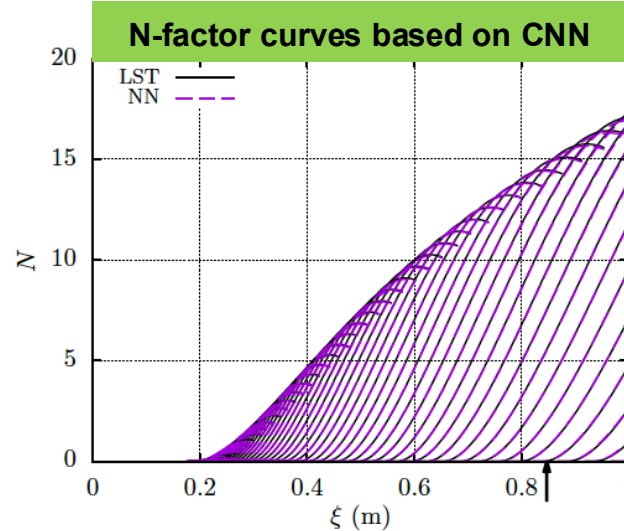
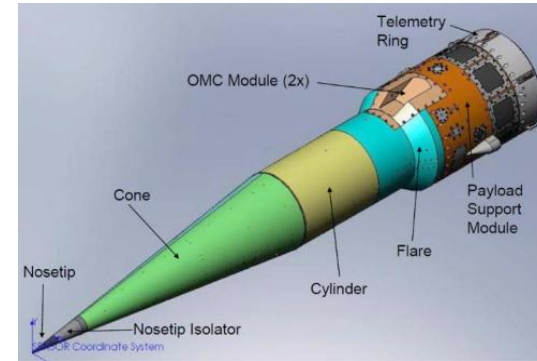
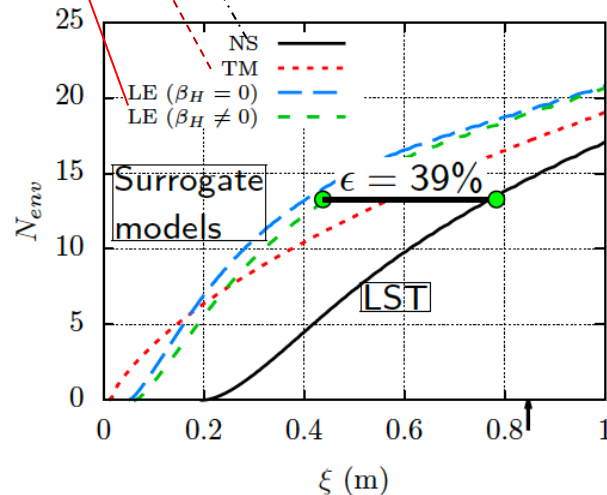
HIFiRE-1 Flight Experiment: Ascent Phase ($t = 21.5$ sec)

N-factor envelopes:

NS: Navier-Stokes (NS)

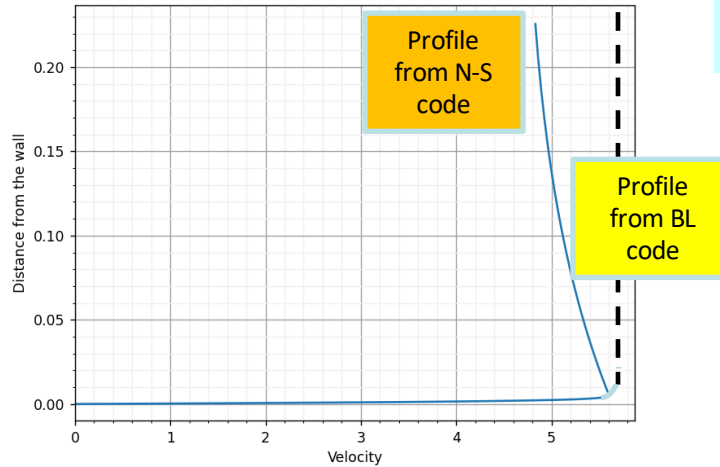
TM: locally self-similar profiles based on Taylor-Maccoll post-shock conditions

LE: self-similar profiles based on local edge conditions (LE) with zero or nonzero Hartree pressure gradient parameter β_H

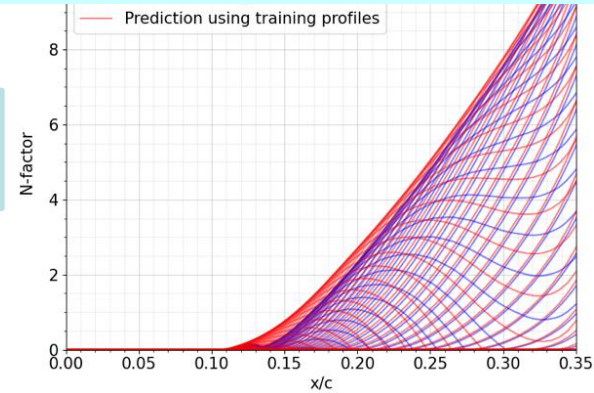




ML Model Integration with PyLASTRAC: NN-based Prediction of Growth Rate of T-S Instabilities



NLF-0416 Airfoil, 0-degree AoA, $Re_c = 9 \times 10^6$



- **Main challenge:** Training and application of ML model requires BL edge determination, estimates of δ^* , θ and H
- **Training database: N-factor computations for 35K+ airfoil/ Re_c /AoA combinations**
- Developed a novel way to map N-S profiles into BL-like profiles based on physical interpretation of integral thicknesses
 - Transformed non-dimensional velocity profiles asymptotically approach unity in freestream
 - Use BL profiles with CNN or POD coefficients for BL profiles as input features: best accuracy with fewest parameters
- **Seamless integration within PyLASTRAC**



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– Case studies

- Stability-based transition prediction
- Transport-equations-based transition prediction
 - Pazy Wing (3D separation bubbles)
 - **Juncture Flow Model**
 - **Compressibility effects at transonic speeds** (inject stability trends to improve accuracy!)
 - **CRM-HL High-Lift Configuration**
 - Transition models for hypersonic BLs
 - **Transition model V & V, grid-adaptive CFD with transition models**
 - **Effect of local perturbations (step excrescences)**
 - Shielding functions to prevent side-effects of FSTI-sustaining terms

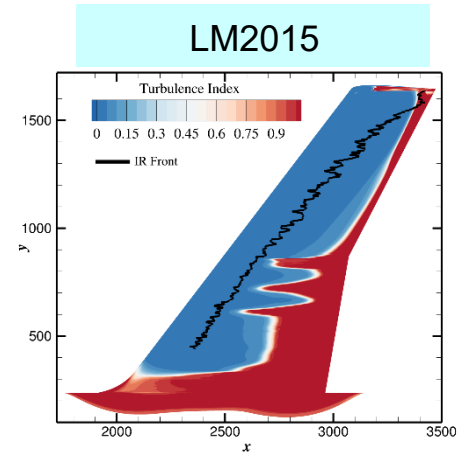
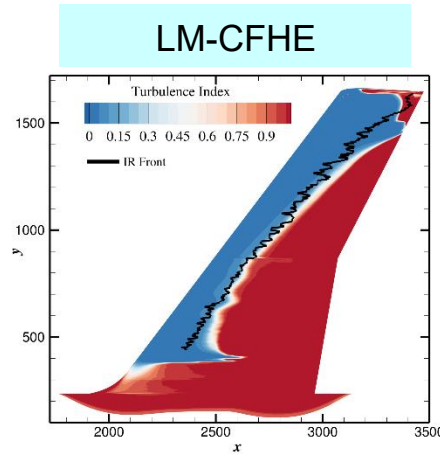
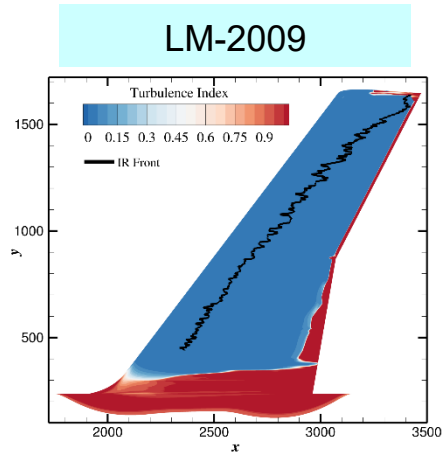
– Summary



NASA Juncture Flow Model

Crossflow Transition via Different Transition Models

$$Re_c = 2.4 \times 10^6, \alpha = -6^\circ$$



- Crossflow dominates transition
- LM-CFHE model provides satisfactory predictions!

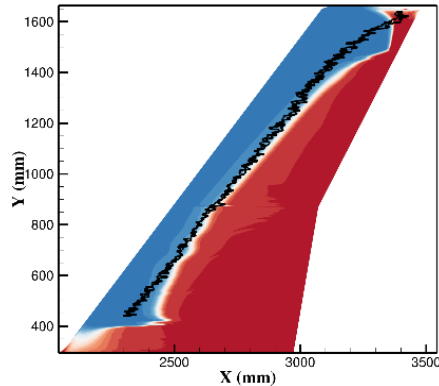
- Roughness sensitized model fails to capture measured transition front
- Additional spurious features!

Juncture Flow Model

$$Re_c = 2.4 \times 10^6, \alpha = -7.5^\circ$$

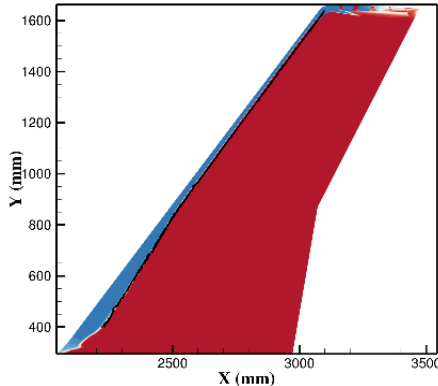
LM-CFHE Model

Upper Surface



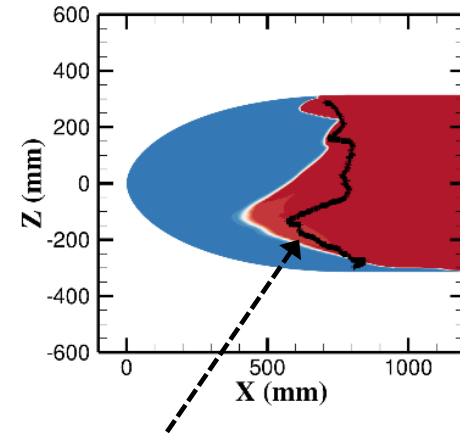
- Crossflow-dominated transition

Lower Surface



- TS-dominated transition

Fuselage Nose



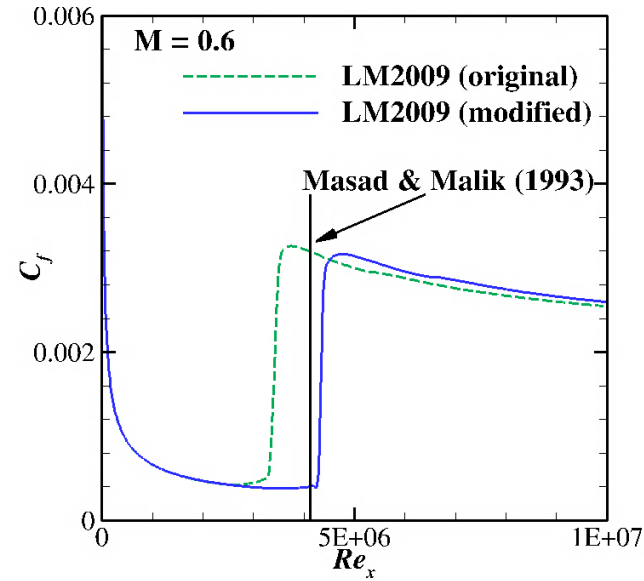
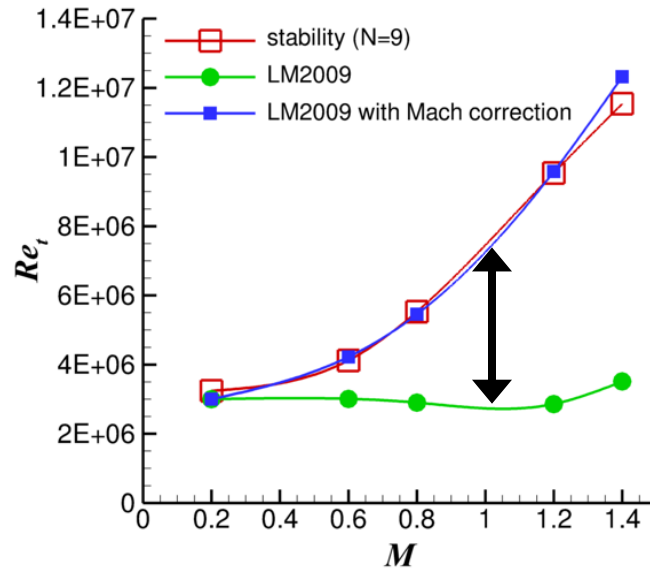
- Shape of fuselage transition front well predicted by LM-CFHE

- LM-CFHE model provides satisfactory predictions on wing and fuselage, but does not account for surface roughness effects



Compressibility Effects: Flat Plate

Correction Based on Stability Database

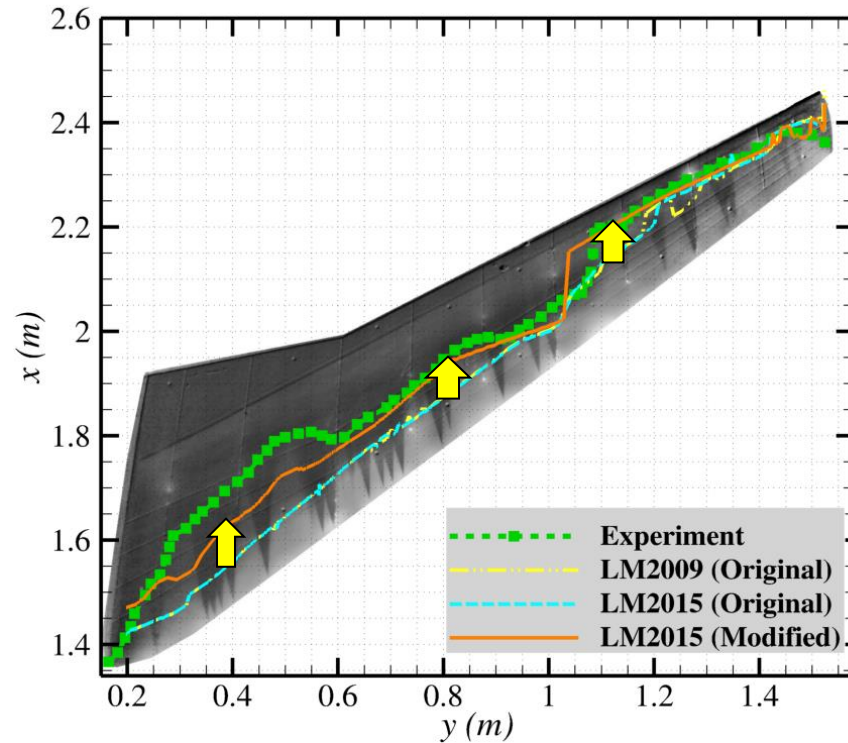


- Poor predictions by LM even at transonic speeds
- Mach number correction based on stability database captures delayed transition at $M=O(1)$!
- Similar correction for AFT model



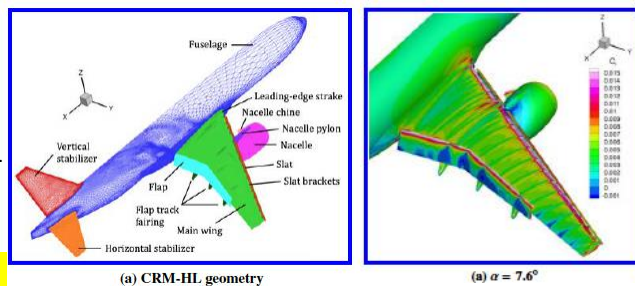
Compressibility Effects: CRM-NLF Swept Wing

$$Re_c = 15.0 \times 10^6, \alpha = 1.45^\circ, Tu = 0.15\%$$

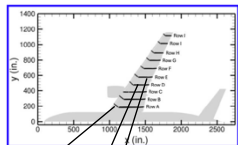


High-Lift Common Research Model (CRM-HL)

- Motivation:** Coupling between transition and flow separation can alter high-lift performance -- slat transition suspected to influence high-lift performance, especially C_{Lmax} behavior, of CRM-HL model.
- LM-CFHE model applied to characterize CRM-HL configuration 2.4 for $\alpha = 7.6^\circ$
- Significant laminar regions on slat suction surface at $\alpha = 7.6^\circ$. Inboard transition due to chine vortex?**



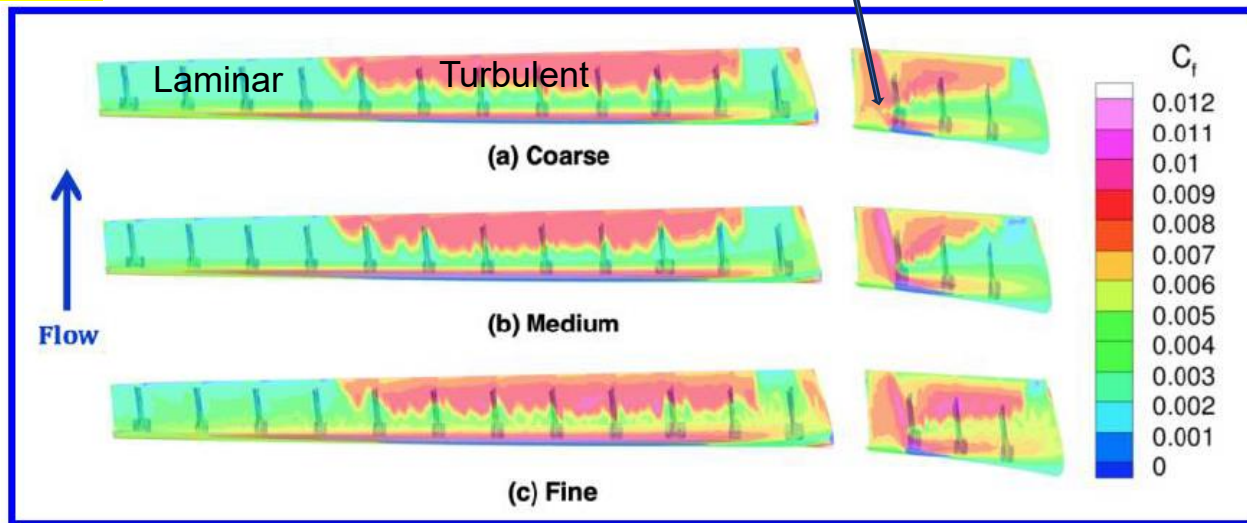
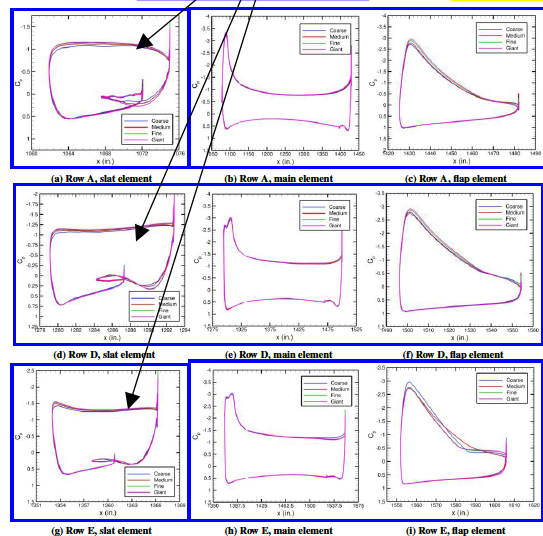
C_p :



$\alpha = 7.6^\circ$

Skin Friction:

Impingement of chine vortex appears to cause transition on inboard slat?

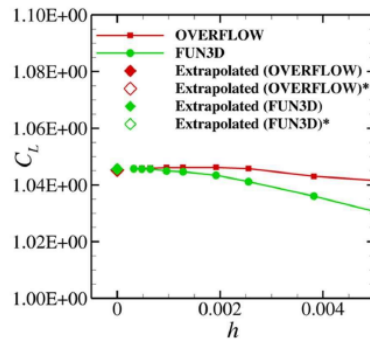


Transition Model Verification

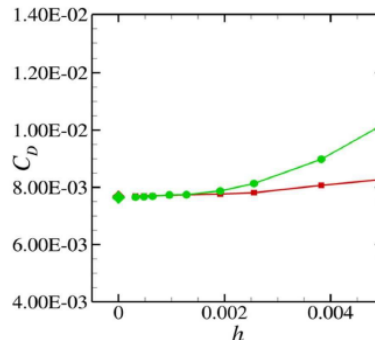
AIAA and NATO AVT – 313 Transition Modeling Workshops

- Significant scatter in contributed results using same transition model and same computational grids
- **Model verification pre-requisite for model validation!**

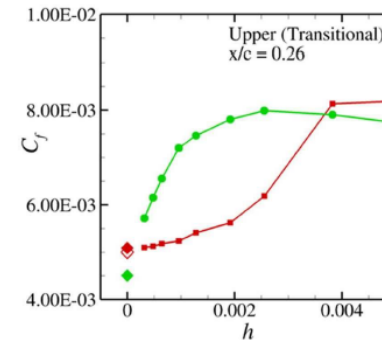
NLF(1)–0416 airfoil at $\alpha = 5^\circ$ ($M = 0.1$, $Re_c = 4 \times 10^6$, $Tu = 0.15\%$) Convergence of Global and Local Flow Metrics



(a) Lift coefficient C_L



(b) Drag coefficient C_D



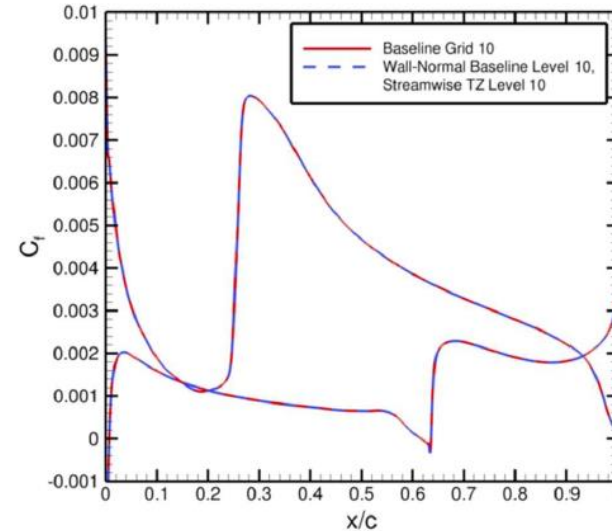
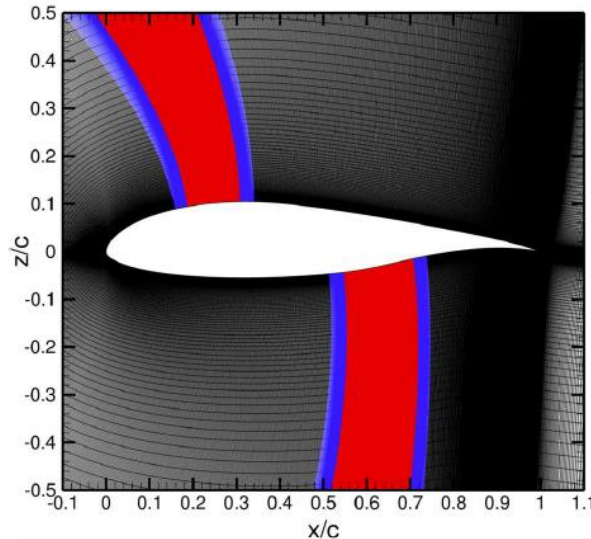
(c) Skin-friction coefficient at a selected chordwise location ($x/c = 0.26$) on the upper surface.

Verification data
released
via NASA TMR

- **Grid size required to achieve converged results are very large**
→ Model verification for 3D cases may require solution-adaptive gridding
- **Similar results for hypersonic configurations with high-speed models**

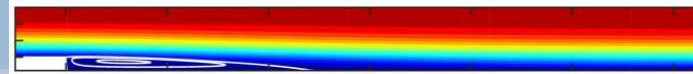
Transition Model Verification: Zonal Streamwise Grid Refinement

NLF(1)-0416 airfoil at $\alpha = 5^\circ$ ($M = 0.1$, $Re_c = 4 \times 10^6$, $Tu = 0.15\%$)



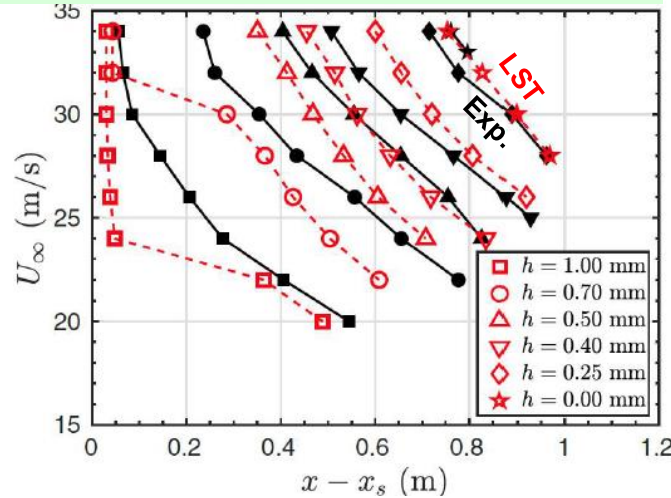
- Zonal streamwise grid refinement surrounding transition zone
→ 2.7x reduction in grid points relative to uniform grid refinement
- Other strategies being examined: “*refine*” library in FUN3D solver, adjoint-based adaptation, OVERFLOW adaptation for overset grids

Effect of Backward Facing Step on Transition: Stability-Based Prediction

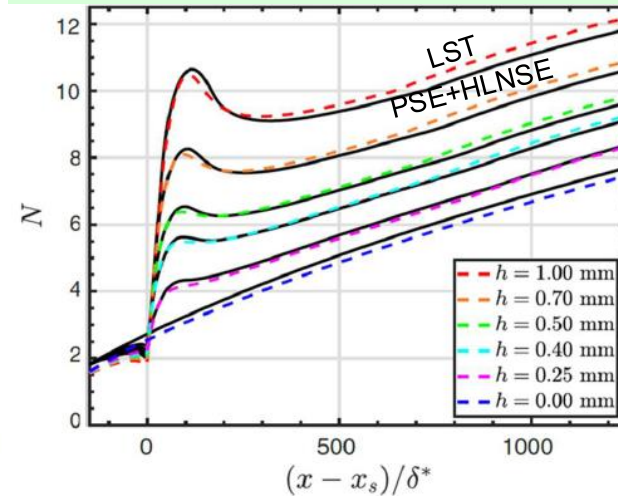


Low-Speed Flat-Plate Experiment (Wang and Gaster 2005)

Transition location for several step heights and flow speeds: **LST** vs. **Experiment**



N-factor envelopes for several step heights at $U_\infty = 34$ m/s: LST (dashed) vs. PSE/HLNSE

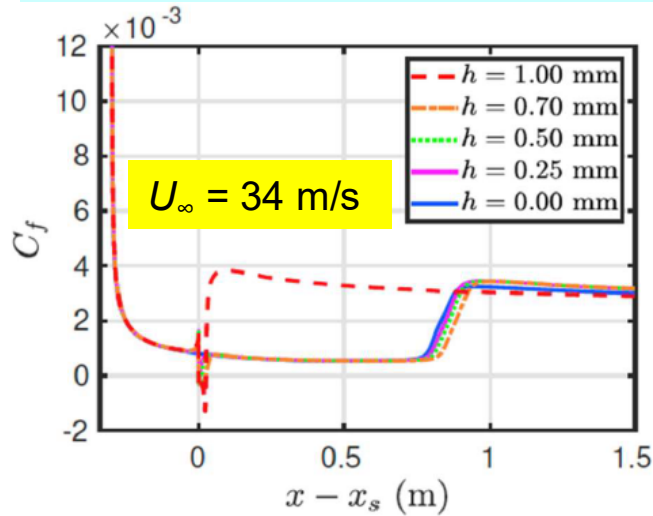


LST-based predictions capture the database trends until transition moves very close to step

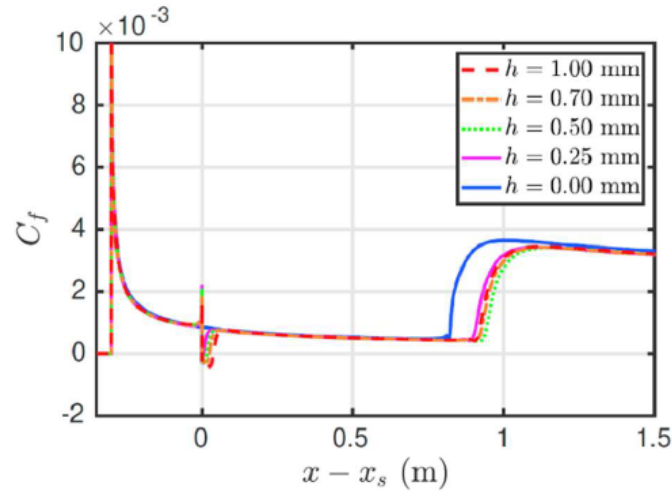


Effect of Backward Facing Step on Transition: Transport-Based Transition Models

Low-Speed Flat-Plate Experiment (Wang and Gaster 2005)



(a) LM2009 Model



(b) AFT2019b Model

- Transport-based models fail to account for step excrescence effects
 - Inability to account for history effects?



Summary

- Dual strategy for transition modeling is crucial for improved prediction reliability and uncertainty quantification in practical applications
- Robustness of stability-based prediction significantly increased, but the need to specify transition N-factor remains a key limitation
- Physical richness of diverse transition mechanisms and intrinsic empiricism in transport equation models necessitates continued improvements in this model class.
- Both approaches encounter challenges with complex transition scenarios involving multiple dominant instability mechanisms
 - **Future progress will require significant expansion of validation datasets!**



Extra Charts

Integrated Boundary-Layer Transition Prediction



$C_{L,max}$ Prediction

Rotorcraft
Performance

Planetary
Explorers

Wind
Turbines

Ultra-
efficient
Subsonic
Transports

Turbomachinery

UAM

- Transition modeling an important component of CFD for flow regimes including the edge of flight envelope
 - Impact on C_L , C_D , C_m , heat transfer, separation characteristics, noise, propulsion efficiency, maneuverability, and ground-flight scalability....
- Need efficient & validated CFD tools to enable:
 - Design of X-planes/transformational commercial vehicles
 - Aircraft certification by analysis (CbA)
- CbA requires CFD across full flight envelope
- Modeling transition in eddy resolving CFD computations → 10x – 100x reduction in grid count

Re-entry
vehicles

Hypersonic
Airbreathers

Innovation in
Commercial
High-Speed
Aircraft



Model Implementation: Current Snapshot

Model	Type	FUN3D	OVERFLOW	VULCAN
LASTRAC Integration (subsonic/transonic /non-overset grids, moderate complexity)	S-1-0	✓	✓	Initiated
LASTRAC Integration (supersonic/hypersonic /non-overset grids)	S-1-0		✓	Initiated
SST— $\gamma - Re_{\theta t}$	T-2-2	✓	✓	✓
SST— γ	T-2-1	✓	✓	
SST— $\gamma - Re_{\theta t}$ + compr. correction	T-2-2		✓	
SA-AFT2014, 2017a	T-1-1	✓	Under way	✓
SA-AFT2017b, 2019	T-1-2	✓	✓	✓
SA— $\gamma - Re_{\theta t}$	T-1-2		✓	
SA— γ	T-1-1		✓	
SST— $\gamma - Re_{\theta t}$ + Langtry crossflow	T-2-2	✓	✓	
SST— $\gamma - Re_{\theta t}$ + CFHE crossflow	T-2-2	✓	✓	
SST— γ (Hypersonic)	T-2-1		✓	
SST— $v_L - \gamma$ (Hypersonic)	T-2-2		✓	
SST — $\gamma - A_r$ (Roughness)	T-2-2	Planned	Initiated	
SST (Algebraic), SA (Algebraic)	T-2/1-0	Planned	Planned	

KEY

✓	Baseline capability
✓	RCA funded basic implementation + limited testing; further refinements ongoing/targeted
✓	Spinoff from RCA HTP funded AATT funded

KEY for model type: S/T-turb-trans

S	Stability paradigm
T	Transport-eq. based
turb	Order of turbulence model
trans	Order of transition model

Contributed to NATO-Group's assessment related to BOLT flight experiment

Robust Surrogate Models for Crossflow Transition Prediction on Swept Wings: Bridging Stability Theory and Practical CFD

APPROACH:

- Extend existing neural network-based surrogate models for Tollmien-Schlichting instability in 2D boundary layers to predict the linear amplification of crossflow instabilities in 3D boundary layers, eliminating the computational overhead and practical limitations of direct stability calculations.
- Increase generalizability by leverage a database of amplification characteristics for stationary crossflow modes in over 100,000 flows encompassing 26 airfoil shapes with multiple combinations of sweep angle, angle of attack, and Reynolds number.
- Multiple neural network architectures: (i) Multilayer Perceptron (MLP) based on proper orthogonal decomposition (POD) coefficients of velocity profiles and (ii) a convolutional neural network (CNN).

RESULTS:

- Assessments demonstrated adequate accuracy in predicting crossflow instability growth over diverse test cases, with successful generalization to previously unseen swept airfoil configurations and cases with crossflow reversal.
- Interface to neural-network models is designed to enable seamless integration with current implementations of stability-based transition prediction in OVERFLOW and FUN3D flow solvers.

SIGNIFICANCE: ML surrogates maintain the physical fidelity of stability theory while offering robust, automated, and computationally efficient predictions for crossflow-induced transition in swept wing boundary layers. This work represents a significant step toward accelerating design cycles and optimizing laminar flow technology for future aircraft, advancing both green aviation initiatives and CFD Vision 2030 goals.

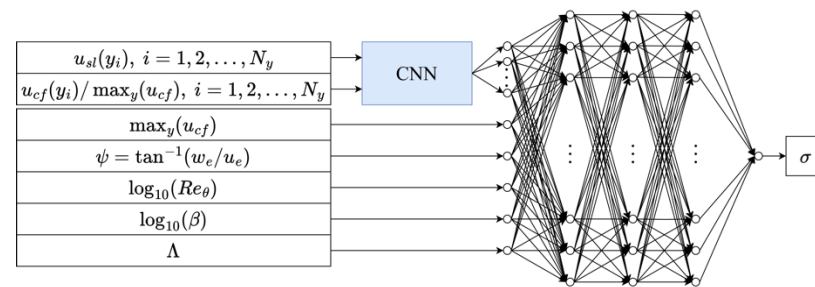


Fig. 1. Schematic of convolutional neural network (CNN)-based model architecture to predict local amplification rate σ of a stationary crossflow mode with spanwise wavenumber β .

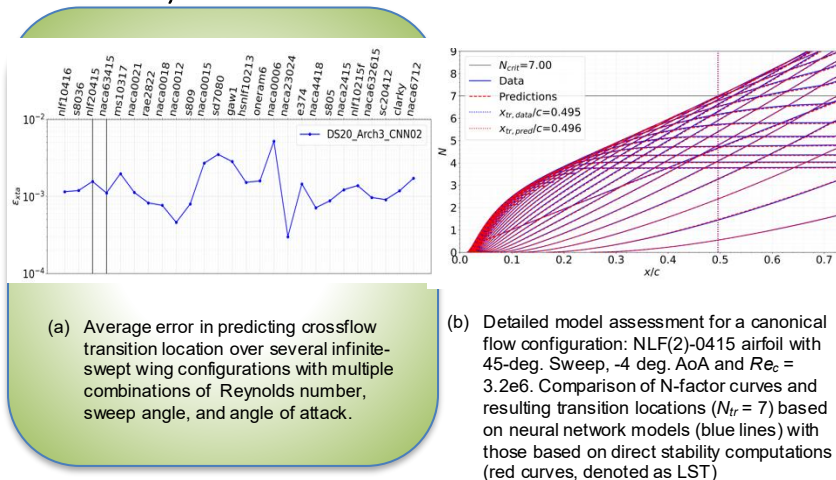
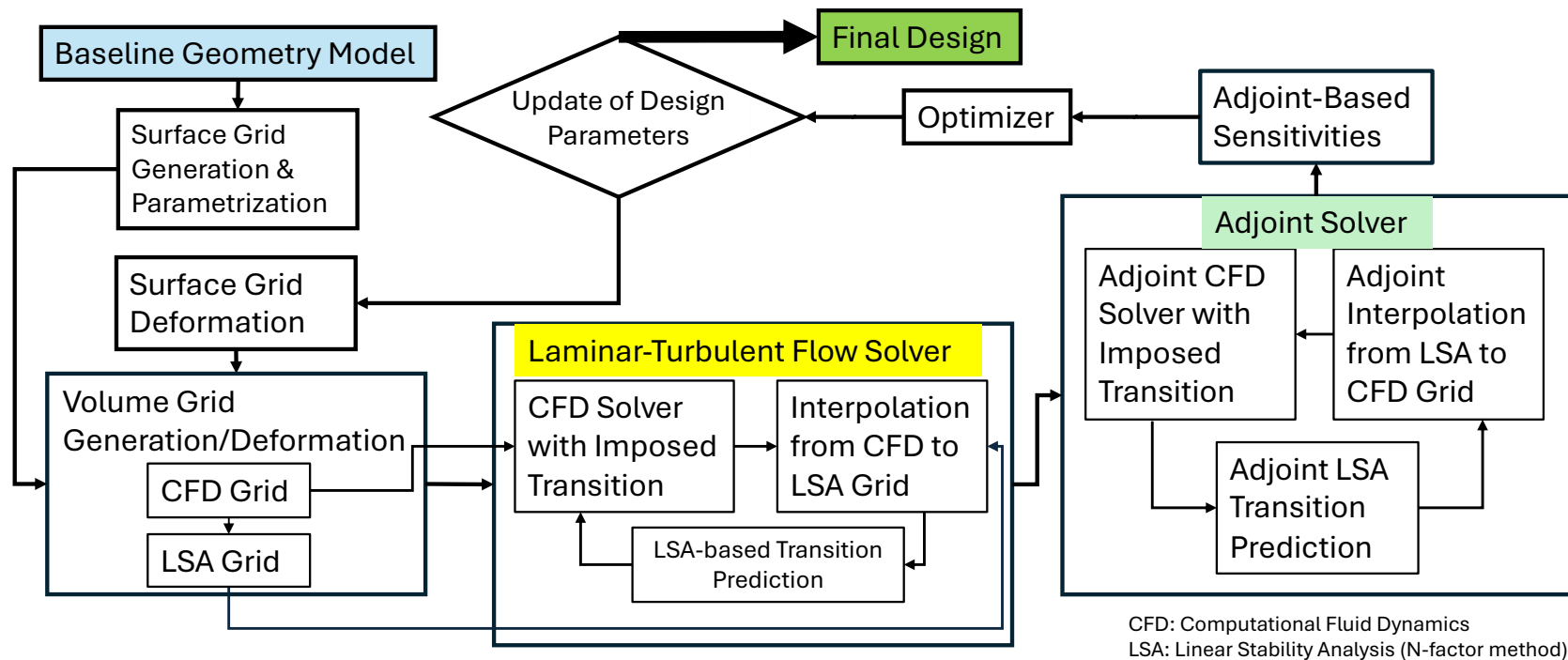


Fig. 2 Evaluation of neural network model

NLF Shape Optimization using Adjoint-Based Sensitivities: Unique NASA Capability



- Fully-Coupled Method: Sensitivities to transition location are accounted for within each design iteration

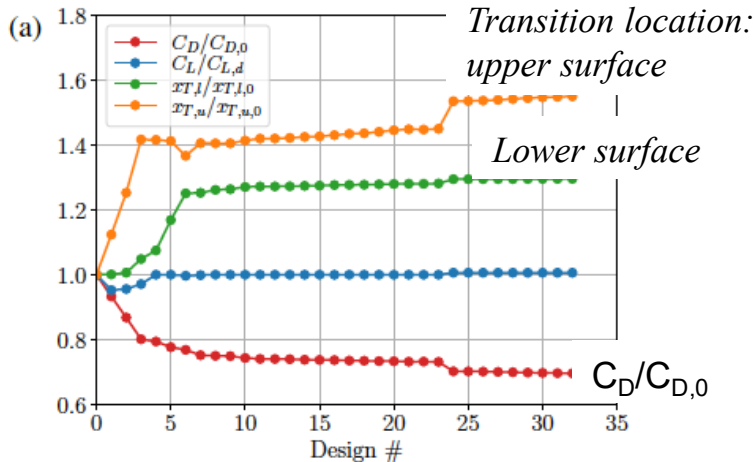


- Paper presented at Aviation 2024

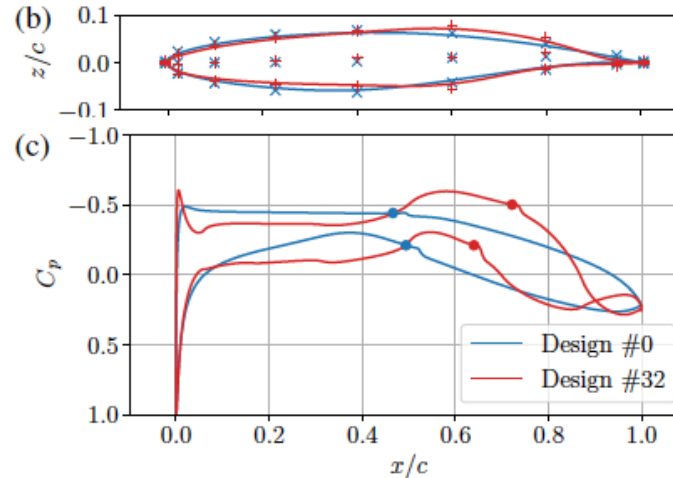
Aerodynamic Design Optimization for Natural Laminar Flow (NLF) Airfoils

- Preliminary demonstration of applying physics-based, CFD-integrated for drag reduction via NLF airfoil design
- Strategy: Integration of fully discrete adjoint linear stability theory (LST) sensitivities into design optimization with FUN3D/SFE
- Constrained optimization problem: Minimize Drag coefficient, C_D at specified lift coefficient, $C_L = C_{L,0}$
 - 16 design variables: AoA & vertical displacement of 15 free-form-deformation (FFD) control points
- Baseline configuration (Design #0): RAE 2822 airfoil at $M_\infty=0.19$, $Re_c=5.6E6$, $T_\infty=300$ K, $AoA_0=0.7498^\circ$
 - $C_{D,0}=0.00462$, $C_{L,0}=0.303$, $x_{tr,0,l}/c=0.494$, $x_{tr,0,u}/c=0.457$

➤ Design iterations



➤ Design #32 ($AoA_{32} = 1.057^\circ$): $C_{D,32}/C_{D,0}=0.696$



- Adjoint-based design complements existing knowledge-based design processes – can uncover potential optima beyond the subspace of knowledge-based designs
- Unique NASA capability based on higher fidelity transition modeling (direct stability computations as against lower fidelity models)



Release of Model Verification Data for $\gamma - Re_{\theta t}$ Transition Model



Why: Significant scatter in solutions by participants in AIAA and NATO workshops, even for simple configurations with identical or similar grids

❑ Lack of model verification prevents model validation!

Accomplishment: Code verification for LM2009 model for standard benchmark configurations with TS transition, separation bubble transition, and FST-induced bypass transition

- First successful verification of $\gamma - Re_{\theta t}$ transition model implementations in OVERFLOW and FUN3D for standard benchmark configurations with TS transition, separation bubble transition, and FST-induced bypass transition
- Verification data has been released to CFD community via NASA Turbulence Modeling Resource (2025)



Langley Research Center

Turbulence Modeling Resource

https://turbmodels.larc.nasa.gov/t3_transition_mainpage.html

Successful verification of transition model paves the way for model validation

VERIF/2DTFP: 2D T3A Transitional Flat Plate Verification - Intro Page

The purpose here is to provide a large sequence of nested grids of the same family, along with results from existing CFD codes that employ specific forms of particular turbulence models, in order to help programmers verify their implementations of these same models. On a given grid, there may be differences between the results from different codes, but presumably as the grid is refined the results should approach the same answer (if the flow conditions and boundary conditions are the same).

With **verification**, the purpose is not to establish the "goodness" of a model compared to experiment, but rather to establish that a model has been implemented correctly, as intended according to the equations and boundary conditions. (It is through **validation** that a model's "goodness" is established.) The purpose here is primarily verification.



Release of Model Verification Data for $\gamma - Re_{\theta t}$ Transition Model



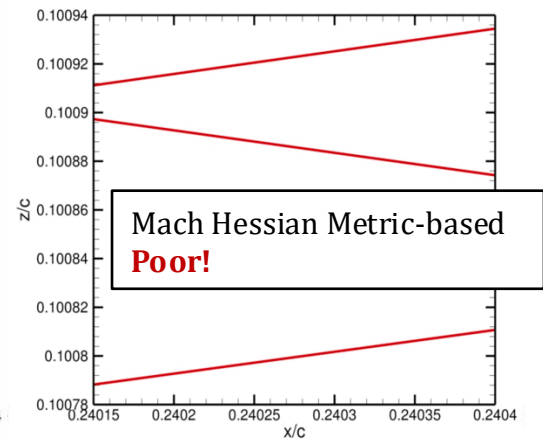
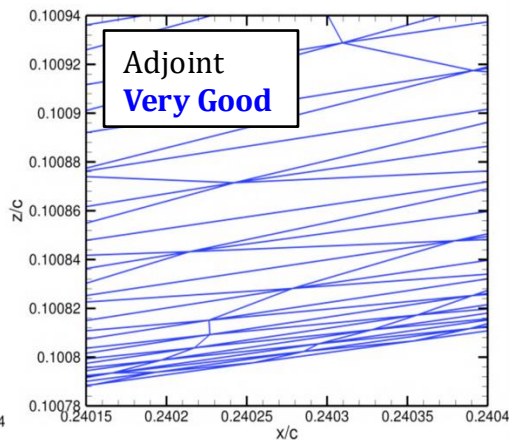
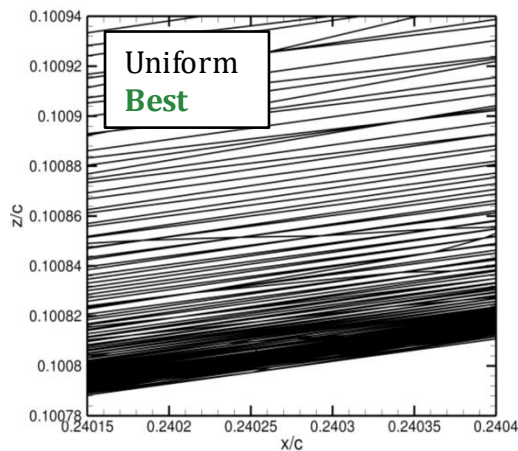
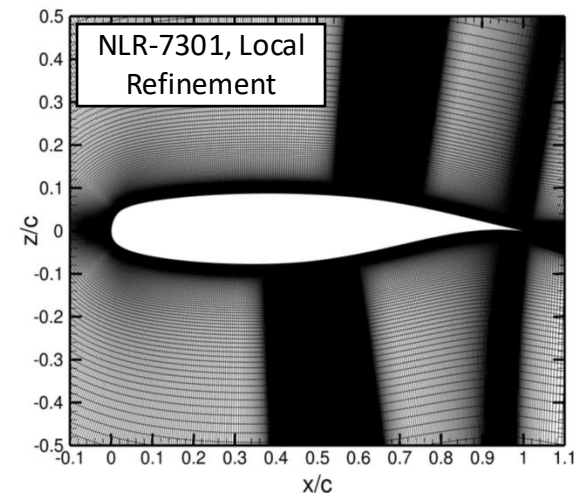
- **New Technology Reports filed to facilitate code release to OVERFLOW and FUN3D user communities**
- Successful model verification has paved the way for code verification of transition model implementations in other flow solvers and, hence, for model validation (subject to reliability of error bounds on measured data)

- However, very large mesh sizes (5761x3073 for flat plate and airfoils) required to achieve this verification and FUN3D GCIs for local metrics within transition zone can still exceed 1%
- **Show stopper for thorough model verification, especially 3D configurations!**

→ Initial assessment of multiple approaches for **adaptive grid refinement** toward efficient computation of grid converged solutions

Grid Refinement Strategies for RANS-based Transition Models with FUN3D

- **Reason:** Need adapted grids to achieve more accurate solutions/transition locations on coarser grids and eliminate the need to create well-crafted static grids. Recent workshops organized by AIAA and NATO-STO AVT panel demonstrated significant scatter, preventing meaningful model assessment.
- 3 Strategies: (i) local streamwise refinement of structured grid,
(ii) feature-based adaptation of unstructured grid via Sketch2Solution (S2S) + *refine* library,
(iii) adjoint-based grid adaptation
- **Findings** (Hildebrand et al. (AIAA 2024-2517), journal article published, March 2025)
 - Schubauer and Skramstad flat plate experiment: **69x grid savings via local streamwise refinement**
 - NLR 7301 airfoil: **26x grid savings** via local streamwise refinement for separation-bubble-driven transition
 - Adjoint-based adaptation works well, but will need to extend FUN3D adjoint capability to transition model(s)
 - For refine-based grid refinement, **Mach-number Hessian fails to refine nearwall portions of grid.**



$x/c = 0.24$

NLF-0416 Airfoil

Automatic Near-body Mesh Adaption for Transitional Flows using OVERFLOW

T³-RVLT collaboration

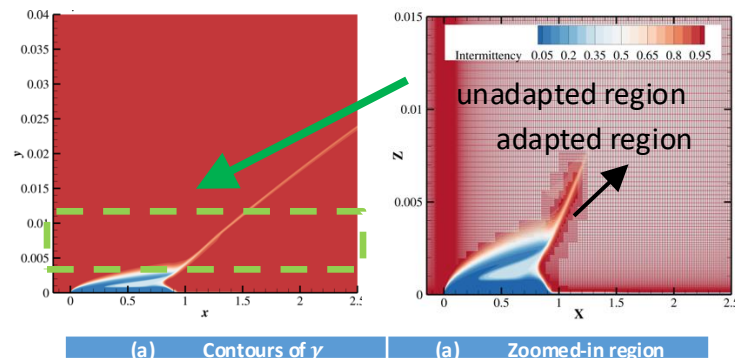
Goal

- Verification of RANS-based transition models revealed the need for highly dense grids to achieve asymptotic convergence of relevant metrics
- Identify best grid design practices for RANS-based transition models
- To enable practicing engineers to obtain reasonably accurate results in a computationally efficient manner

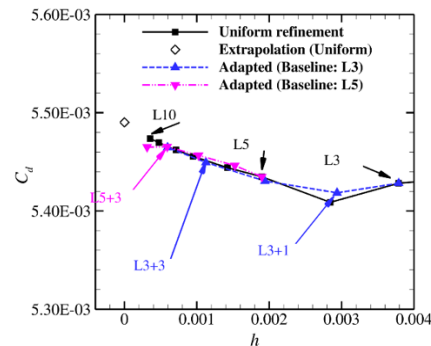
Progress

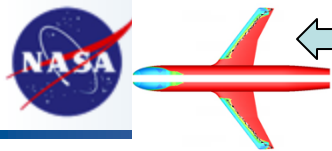
- Identified transition relevant sensor for automated near-body mesh adaptation of transitional flows: sensor function based on undivided difference of the vorticity magnitude, augmented to turn off grid refinement in regions that can be resolved with conventional grids (wake, freestream, fully turbulent region) but enable grid refinement near shocks.
 - Complements adjoint/metric-based adaption with FUN3D
- Assessment of new sensor for LM predictions of natural transition, separation-induced transition, and shock-induced transition
- Adaptation worked well, but savings were limited ($O(3-5\times)$) due to isotropic nature of adaptation.

Publications: Presented at ICCFD12 (2024), submitted for publication



Transition on a flat plate with mesh adaptation





NASA Juncture Flow Model:

Multiple instability mechanisms (TS, crossflow) contribute to transition process

Stability-based transition models

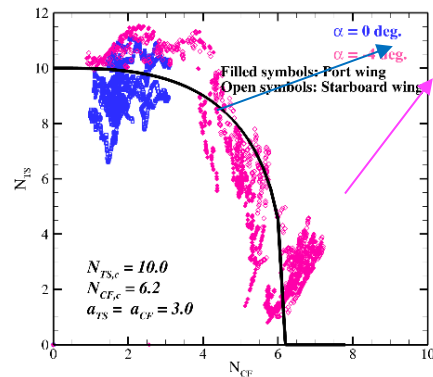
Intrinsic sensitivity of transition process to tunnel/model disturbance environment necessitates fine tuning of model parameters, particularly for transition due to crossflow (CF) and crossflow-TS mixed-mode instabilities interacting with each other.

Dual N-factor calibration

$$I(N_{TS}, N_{CF}) \equiv \left(\frac{N_{TS}}{N_{TS,c}} \right)^{a_{TS}} + \left(\frac{N_{CF}}{N_{CF,c}} \right)^{a_{CF}} = 1$$

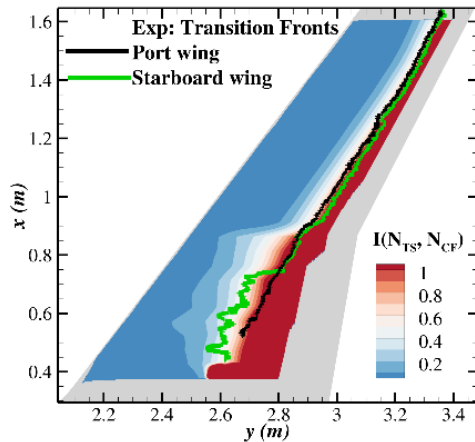
$$N_{TS,c} = 10, N_{CF,c} = 6.2$$

$$a_{TS} = a_{CF} = 3$$

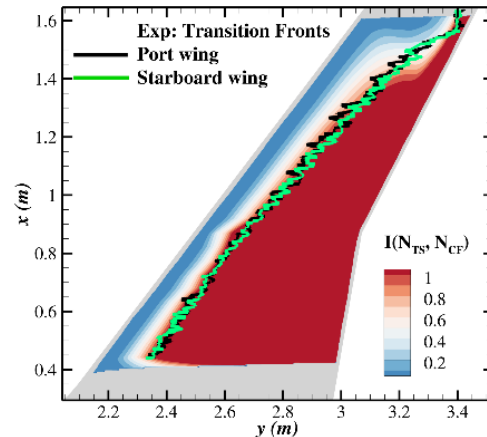


Predictions for calibrated model agree well with measurements for previously unseen cases.

$\alpha = -2.5^\circ$



$\alpha = -6^\circ$





Sensitivity to Surface Roughness

Stability-based model predicts

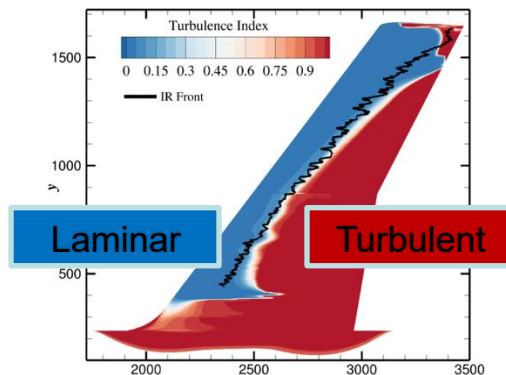
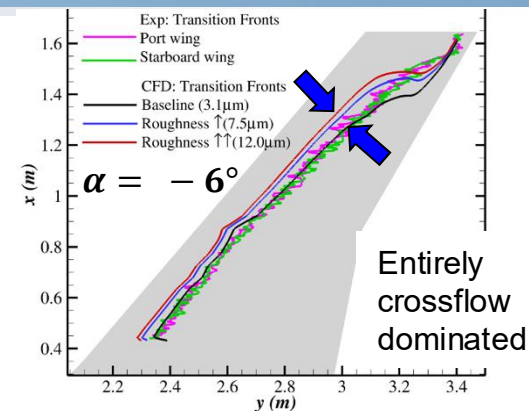
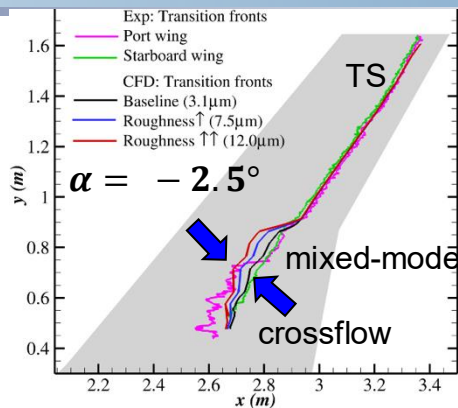
significant variations with change in surface finish from $3\text{ }\mu\text{m}$ to $12\text{ }\mu\text{m}$

- But, only onset predictions possible
- No model to predict transition zone!
- Major reason: sparsity of reliable benchmark datasets!

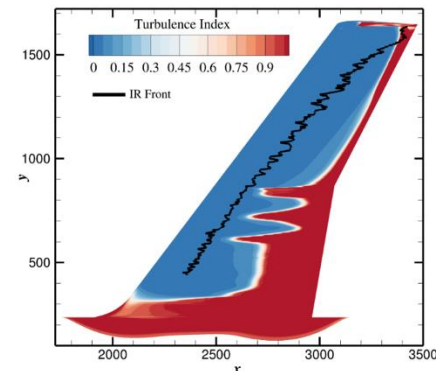
Transport-based empirical models fail to capture expected sensitivity to roughness!

- Major reason: sparsity of reliable experimental datasets!

➤ TTT funded experiment (Jenna Eppink presentation)



LM – CFHE model transparent to roughness level!

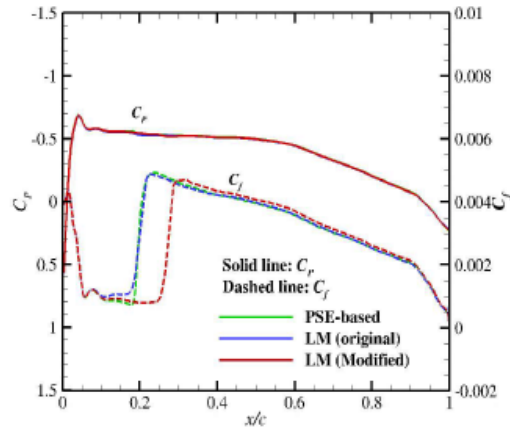


LM2015 model designed to capture roughness effects, but fails in this case !

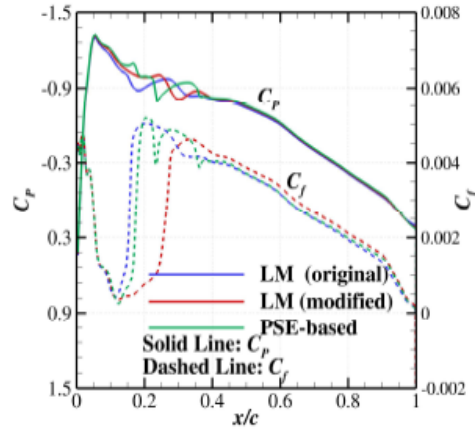


Compressibility Effects: RAE (NPL) 5212 Airfoil

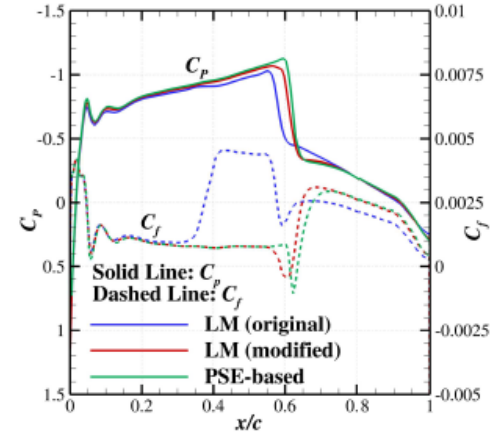
$$Re_c = 7.5 \times 10^6, Tu = 0.07\%, Ntr = 9 \text{ for PSE}$$



(a) $M = 0.5$ and $\alpha = 0.0^\circ$
(mildly adverse)



(b) $M = 0.7$ and $\alpha = 1.35^\circ$
(adverse)



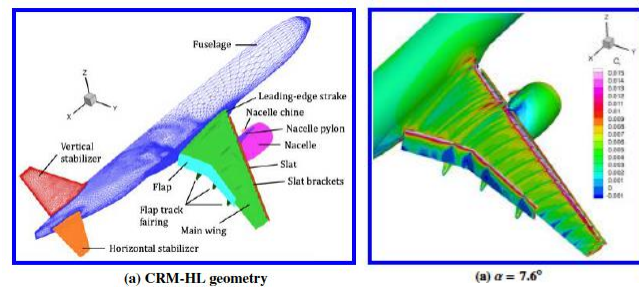
(c) $M = 0.75$ and $\alpha = 0.0^\circ$
(favorable)

No compressibility correction necessary under sustained, adverse pressure gradient

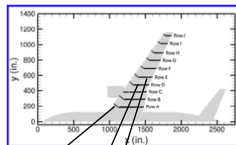
Correction required for sustained favorable pressure gradient

High-Lift Common Research Model (CRM-HL)

- Motivation:** Coupling between transition and flow separation can alter high-lift performance -- slat transition suspected to influence high-lift performance, especially C_{Lmax} behavior, on the CRM-HL model.
- Progress:** LM-CFHE model was applied to characterize CRM-HL configuration 2.4 for $\alpha = 7.6^\circ$
- Significant laminar regions on slat suction surface at $\alpha = 7.6^\circ$. Inboard transition due to chine vortex?**



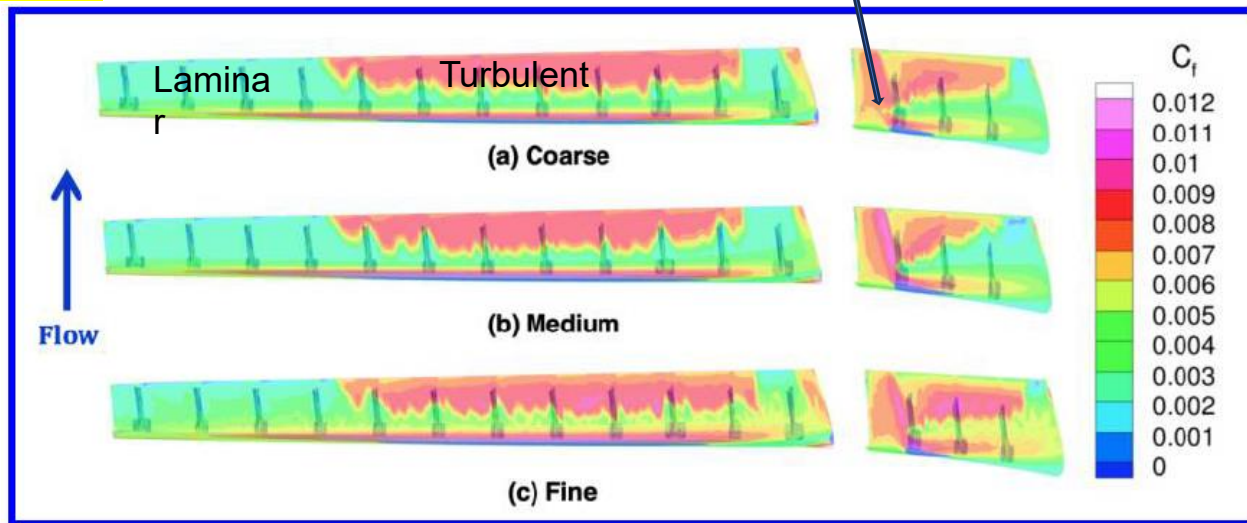
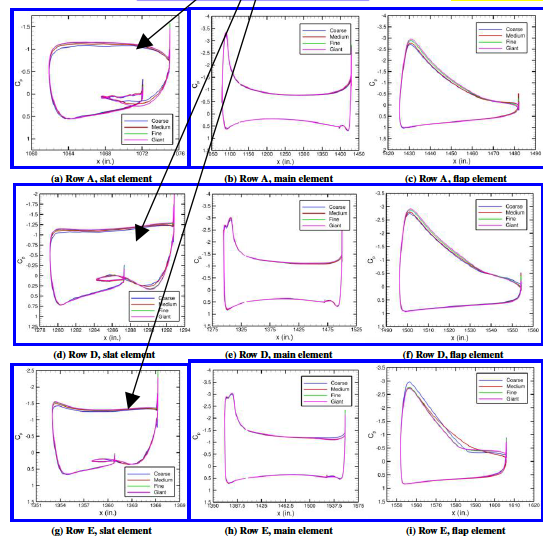
C_p :



$\alpha = 7.6^\circ$

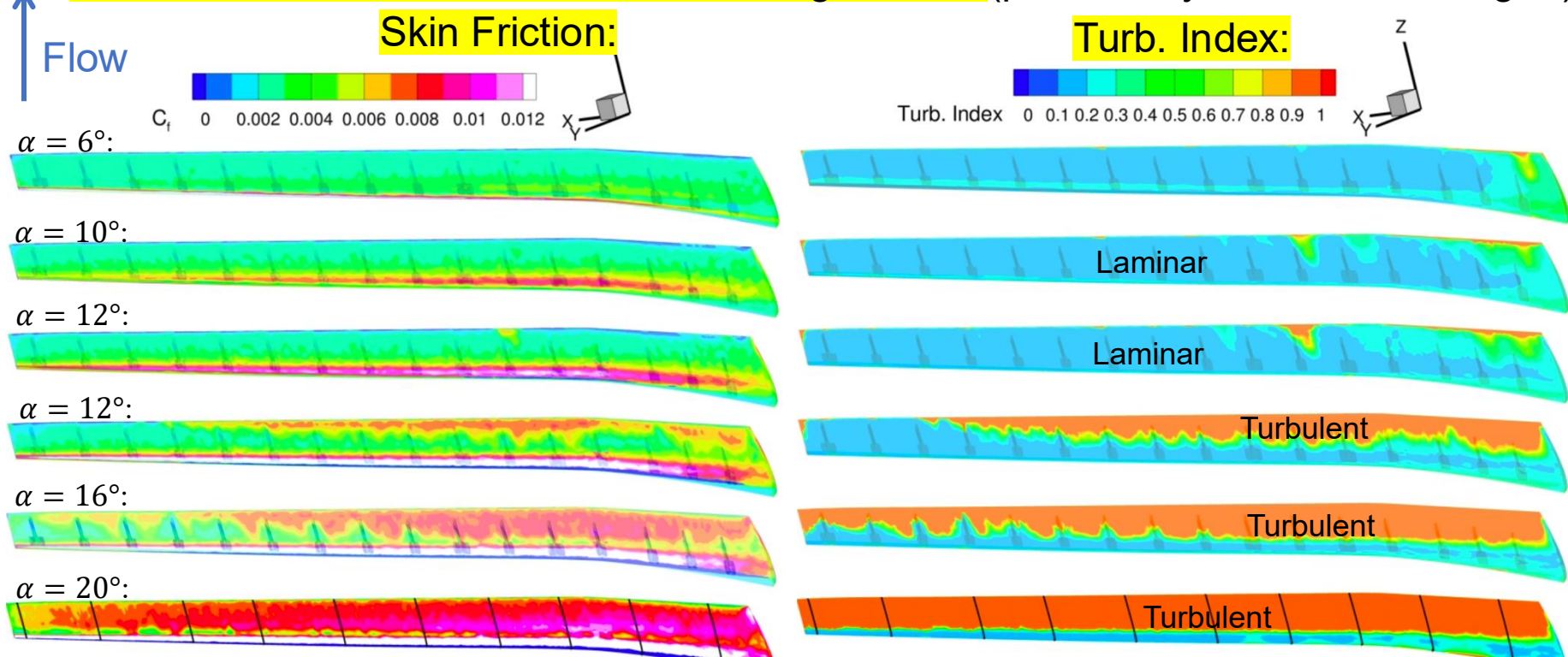
Skin Friction:

Impingement of chine vortex appears to cause transition on inboard slat?



High-Lift Common Research Model (CRM-HL): Configuration 2.2

- Slat transition with LM-CFHE model at higher AoA (preliminary results, coarse grid)



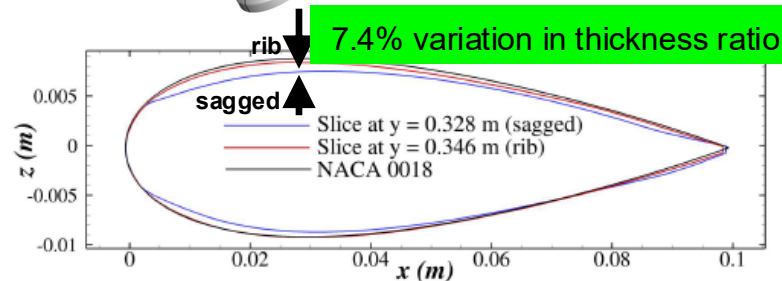
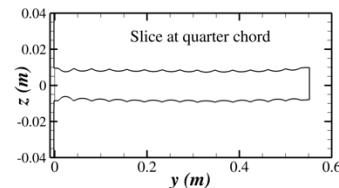
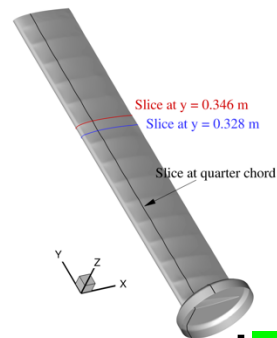
- Provides useful insights into slat transition behavior on an important configuration for TTT
 - **Complements large body of (fully turbulent) CRM-HL CFD**
- Basis for comparison with stability-based transition predictions (under way)
- CRM-HL is a challenging configuration for both classes of models, highlights required improvements!

Transition Analysis of the Sagged Pazy Wing (AIAA AEPW-3)

- Created as a benchmark for highly flexible wings subjected to substantial deformations
- Distinctive geometry with spanwise-varying static deformation and low Reynolds number flow conditions (NACA0018 airfoil being the baseline geometry)
- Complicated flow phenomena such as 3D laminar separation bubbles (LSBs) and intricate transition patterns

Objectives

- Assess the performance of mainstream RANS-based transition models such as the Langtry-Menter $\gamma - Re_{\theta t}$ model for flows with complex, 3D separation bubbles
- Evaluate the performance of transport-equations-based transition models to guide future aeroelastic computations using FUN3D

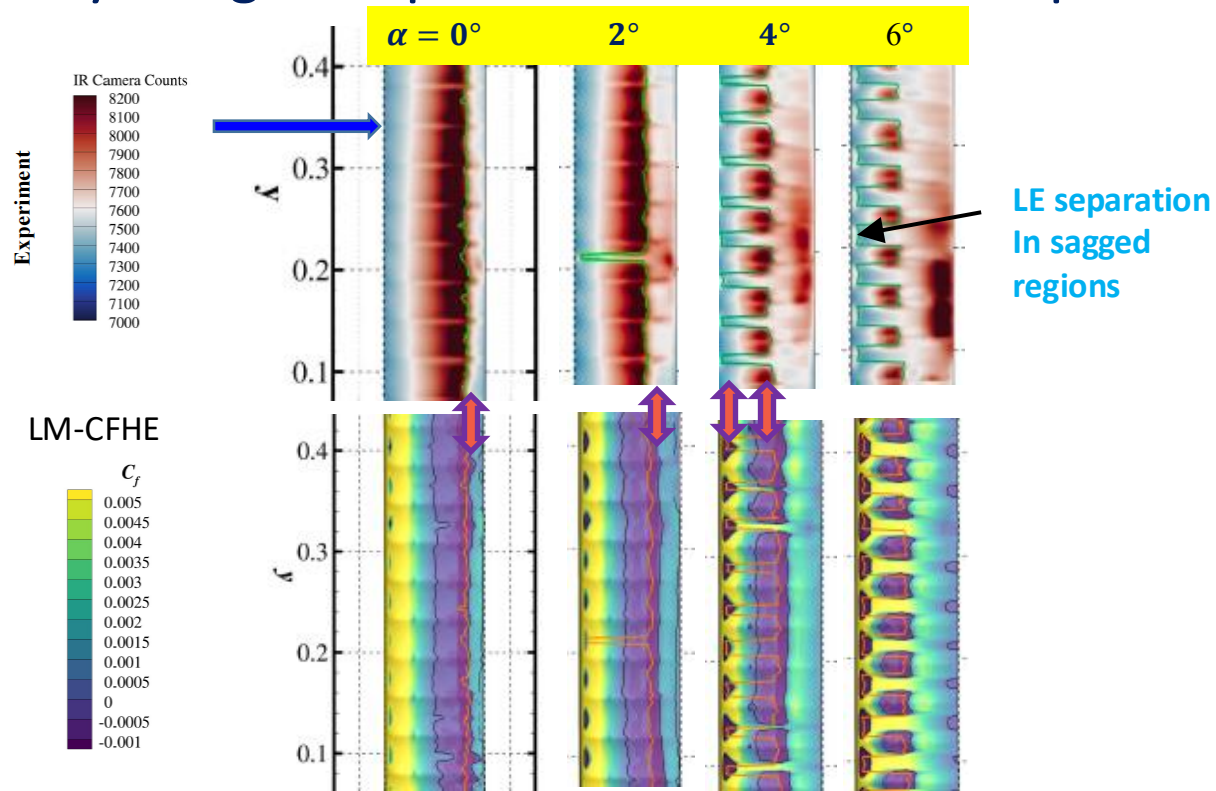


Publications:

AIAA 2024-2685; journal article in review

Pazy Wing: Comparison of Results with Experiment

($Re_c=1.2E5$)



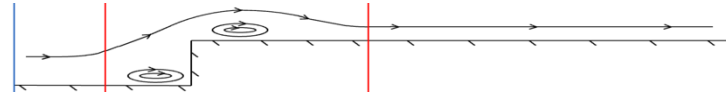
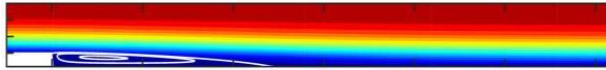
- Small thickness variations between rib & sagged regions $\rightarrow$ strong 3D variations in separation characteristics for $\alpha \geq 4^\circ$
- Both LM and AFT models mimic the separation characteristics and transition fronts from measured data
- Successful comparison with data $\rightarrow$ increased confidence in modeling separation bubble transition in complex scenarios



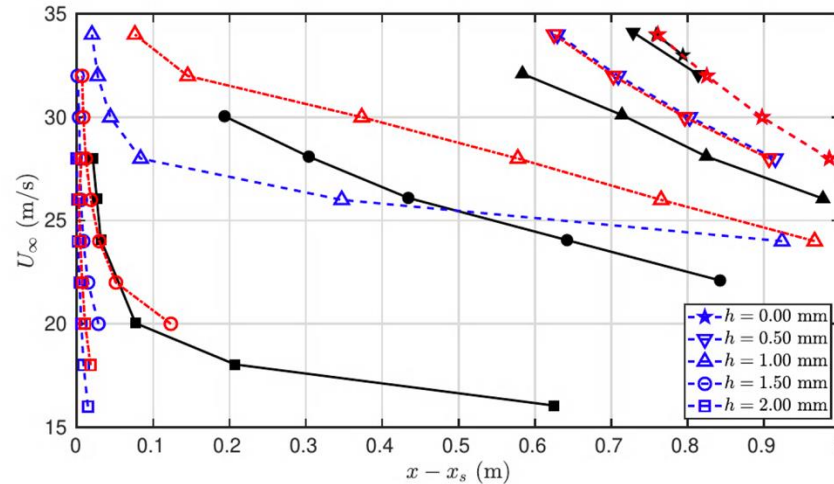
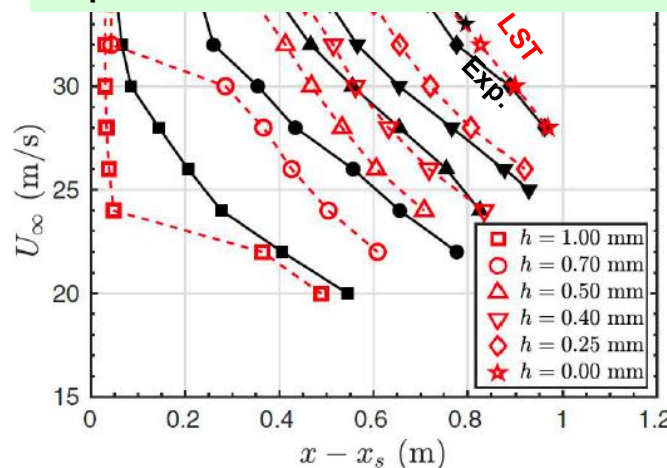
Effect of Backward/Forward Facing Step on Transition: Stability-Based Prediction

Why: Step excrescences lead to earlier transition

→ tolerance specification critical to achieving the benefits of laminar flow technology.



Transition location for several step heights and flow speeds: **Stability-based prediction** vs. **Experiment**

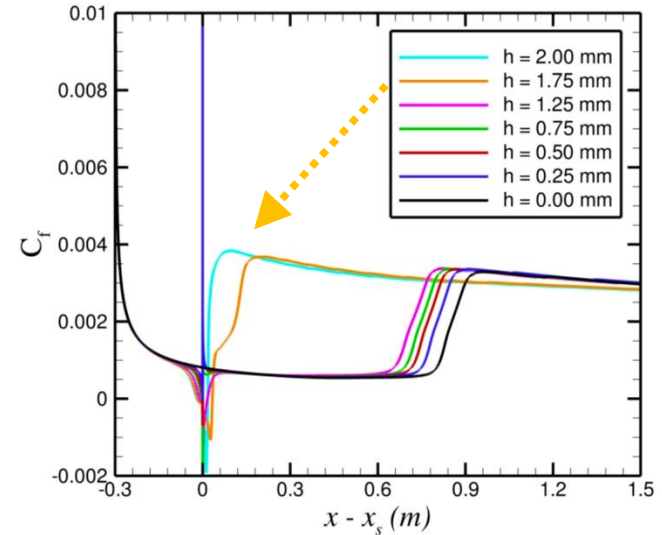
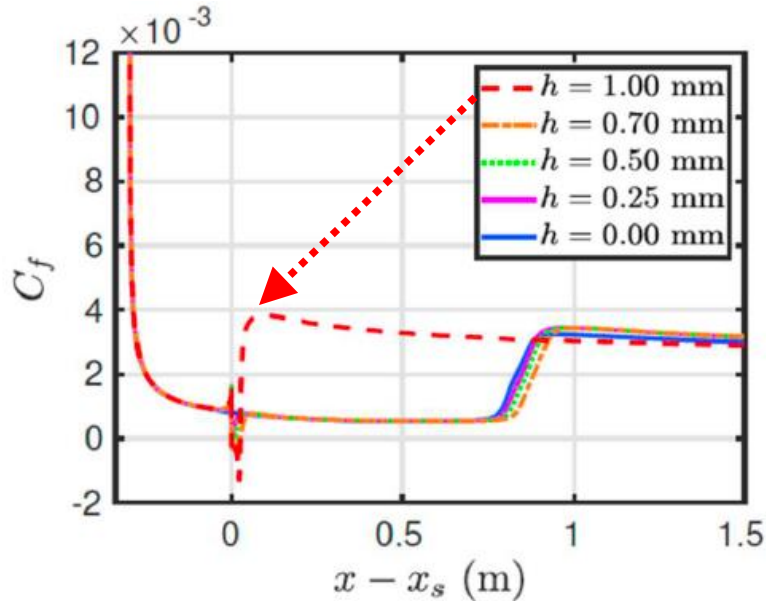


Stability-based predictions mimic the database trends until transition moves very close to step



Effect of Backward- and Forward-Facing Step on Transition: Transport-Based Transition Models (LM Model)

Low-Speed Flat-Plate Experiment (Wang and Gaster 2005): $U_\infty = 34$ m/s



- Transport-based models fail to account for gradual shift in transition location as step height is increased
 - Inability to account for history effects?

Enhanced implementation of turbulence sustaining terms in LM Model

Why

- Transition prediction significantly impacted by how freestream turbulence intensity (FSTI) is enforced in SST-based models

Current Approaches and Issues

(a) Set $[k, \frac{\mu_t}{\mu_\infty}]$ combination to achieve the desired FSTI levels near

the test article

- Not always feasible, without having to use unphysical values that may not be appropriate for the model

(b) Sustaining FSTI levels via source terms to offset decay upstream of test article (*Spalart and Rumsey, AIAA J 2007*)

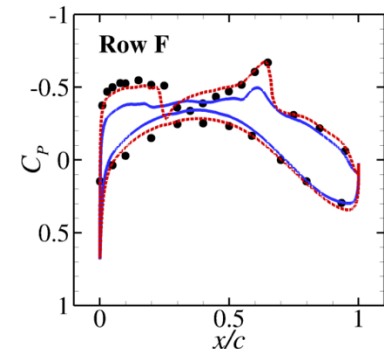
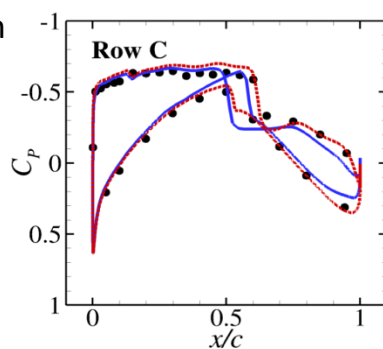
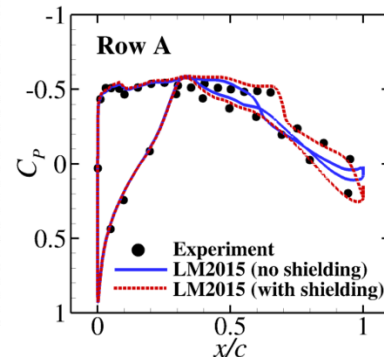
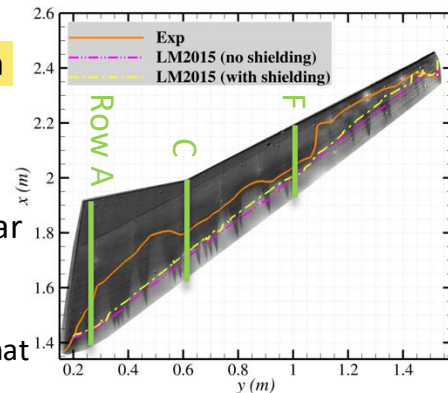
- Affects pressure distribution, boundary-layer behavior and transition-onset predictions

Accomplishment

- Successfully implemented shielding functions to prevent undesirable side-effects of FSTI-sustaining terms

→ Improved agreement with measured C_p and shock locations

(Results to be presented at the AIAA Aviation 2025 Conference)



CRM-NLF ($Re_c = 15M$; $AoA = 1.44$ deg.)