

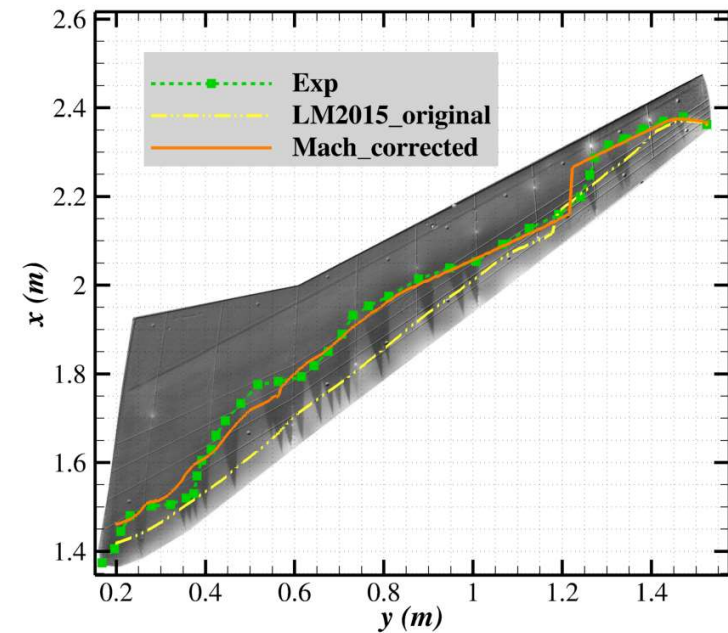
Transition Analysis for the CRM-NLF Wind Tunnel Configuration using Transport Equation Models and Linear Stability Correlations



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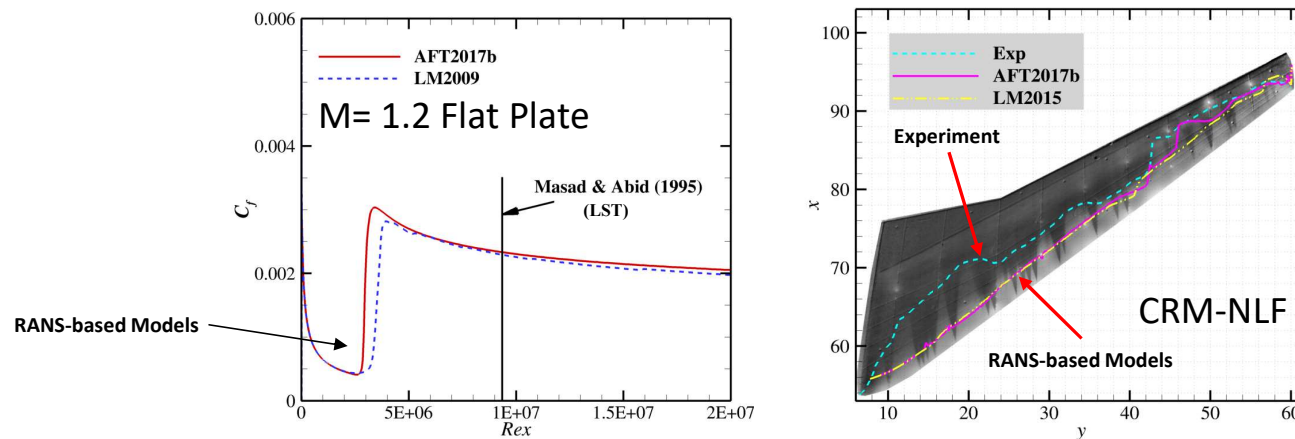
Outline



- Motivation & Objectives
- CFD and Stability Analysis Solvers
- Compressibility Corrections to LM and AFT models
- Results for CRM-NLF (CFD + Stability Analysis)
- Summary

Motivation

- Shortcomings of RANS-based transition models for the Common Research Model with Natural Laminar Flow (CRM-NLF) configuration (AIAA Paper 2021-1430)
 - significant underprediction of the laminar extent
 - Increased stability due to compressibility not accounted for in existing mainstream models (empirical transition correlations within these models were formulated for low-speed flows)



Big Picture:

Blend the “physics-based” methodology for transition modeling with the RANS-based approaches to create a robust, reliable, user-friendly, and cost-efficient approach for integrated modeling of laminar-turbulent transition (CFD Vision 2030 goal)

Objectives



- Modify selected correlations within these transport-equation-based transition models to account for compressibility effects
 - Models should return to their original behavior at low subsonic speeds and remain valid for original cases used in their calibration & validation
 - SST-based Langtry-Menter model and SA-based Amplification factor transport equation model as implemented in NASA's OVERFLOW CFD solver
 - Utilize previous works on linear stability analysis to achieve this
- Evaluate resulting improvements in transition modeling for transonic CRM-NLF configuration
 - Use reference data based on experiment + transition predictions based on stability analysis)
- Extend previously calibrated, stability-based dual N -factor criterion* to predict the transition front for all angles of attack from the experiment
 - Also: PSE marching carried along streamlines as opposed to grid lines in previous work for two AOAs (*Paredes et al. AIAA Paper 2021-1431*)

CFD Solver & Stability Analysis Solver

OVERFLOW 2.3b¹

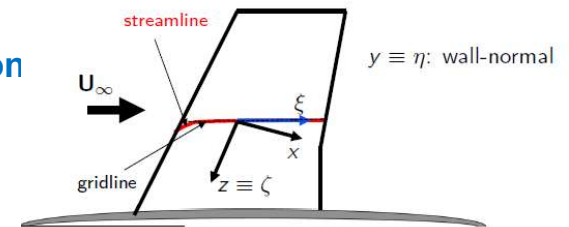
- Implicit structured overset grid Navier-Stokes solver

RANS-based transition models (studied in this work)

1. **Langtry-Menter (LM) model** : SST-2003 + LM2015 (LM2009 + Crossflow)
LM2009: Can model natural, bypass and separation-induced transition scenarios
2. **Amplification Factor Transport (AFT) model**: SA + AFT 2017b version
Accounts for TS instabilities alone and no crossflow

LASTRAC 3.d Solver²

- General purpose physics-based transition prediction tool: Linear stability theory (LST), Parabolized stability equations (PSE)
- **Mean flow computed using SA-turbulence model with imposed transition from**
- PSE along streamlines in nonorthogonal coordinate system
 - Includes surface curvature and nonparallel mean flow effects



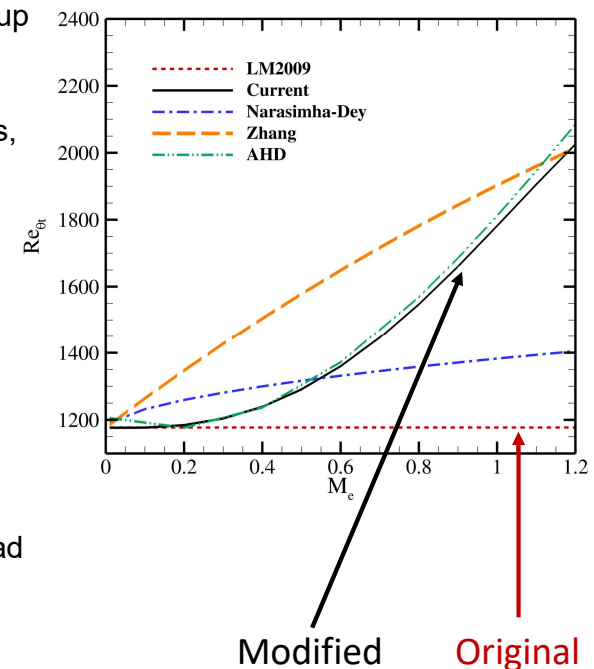
1. Nichols, R. H, and Buning, P. G., "User's Manual for OVERFLOW 2.3, Version 2.3," NASA Langley Research Center, Hampton, VA, Oct 2019.
2. Chang, C.-L., "LASTRAC 3d: Transition Prediction in 3D Boundary Layers," AIAA Paper 2004-2452, 2004.

Compressibility-related modifications (LM2009/2015)



- Important modifications from literature: Work by Pascal et al. (2020) and Stroer et al. (2021)
 - Based on AHD; Involved need for non-local terms that were overcome through additional transport equations
- New modification – a strictly local formulation and reverts to original model at low speeds
 - Applies for TS alone; No compressibility correction for crossflow terms (expected to be at least up to the transonic regime)
- Corrections to relationship between Vorticity Reynolds number and Re_θ (Compressibility BL profiles, Qiao et al.[2018])
 - Peak location of Re_v moves to edge of boundary layer with increase in Mach number
 - $Re_\theta = \frac{\max(Re_v)}{2.193 \cdot C(M_e)}$; $C(M_e)$ = function of edge Mach number M_e
- Modification of correlation for $Re_{\theta t}$
 - $(Re_{\theta t})_{\text{Original}} = f1(FSTI) \cdot f2(\lambda_\theta)$ (separate functions of FSTI & pressure gradient)
 - (Narasimha [1985]) : $(Re_{\theta t})_{\text{New/comp}} = (Re_{\theta t})_{\text{Original/incomp}} \cdot f3(M_e)$
 - $f3(M_e)$ determined using data from stability computations by Masad and Malik [1993] and Masad and Abid [1995] (investigated combined effects of pressure, suction/blowing and wall cooling)
 - See paper for limitations of approach & additional details

$Re_{\theta t}$ for ZPG Flat plate



Compressibility-related modifications (AFT)

- The AFT model developed by Coder and Maughmer is based on work by Drela and Giles [1987]
- Sturdza [2003] modified some of the correlations of Drela and Giles to account for compressibility effects so it is applicable to low supersonic speed flows
- We adopt the modifications proposed by Sturdza in this work to account for compressibility effects in AFT model

Modifications:

- Re_θ at critical point (i.e., onset of instability) : $(Re_{\theta 0})_{new} = (Re_{\theta 0})_{original} \cdot f1\left(\frac{T_w}{T_e}\right)$
- Slope of N-factor envelope: $\left(\frac{dN}{dR_\theta}\right)_{new} = \left(\frac{dN}{dR_\theta}\right)_{original} \cdot f2\left(\frac{T_w}{T_e}\right)$
- $\frac{T_w}{T_e} = f(Me)$

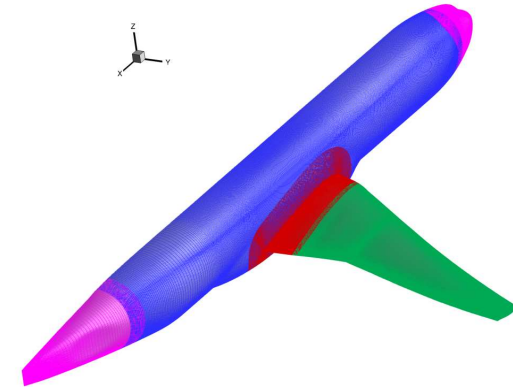
Estimation of edge Mach Number M_e

- Key parameter necessary for both models
- Nontrivial to obtain in an unstructured CFD solver and will make formulation non-local
- **Can be approximated via Bernoulli's equation + Isentropic relations (provided no shocks)**
- Deviations from isentropic relation expected to be small for $M < 1.2$ (Lee [2016] and Stroer [2020])

CRM-NLF - Flow Conditions, Computation Details



- The CRM-NLF* wing has been designed such that the overall amplification of both TS and CF instabilities are reduced
- Fixed AoA runs instead of fixed C_L as per AIAA Transition Modeling and Prediction Workshop
- Steady-State computations using 3rd-order Roe Upwind Scheme and the unfactored successive symmetric overrelaxation (SSOR) implicit solution algorithm
- In-house generated fine grid (120 million near-body grid points, $y^+ \sim 0.5$) – See paper for details
- Surface roughness = 0.9 μ inch (measured in the CRM-NLF experiment; for use with the LM2015 model)



Condition	AOA (deg.)	Mach No.	T_∞ (K)	Re (per m)	Re_{MAC}
1	1.448 ± 0.001	0.856 ± 0.001	241.7	40.73M	14.84M
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3	2.461 ± 0.001	0.856 ± 0.001	242.0	40.56M	14.78M
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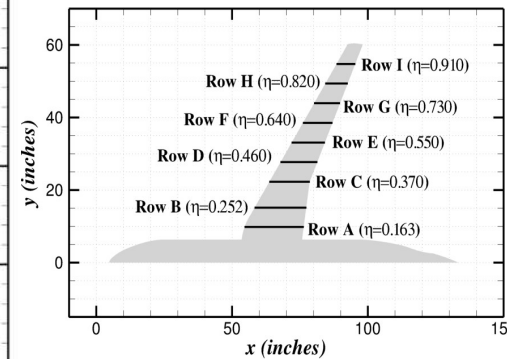
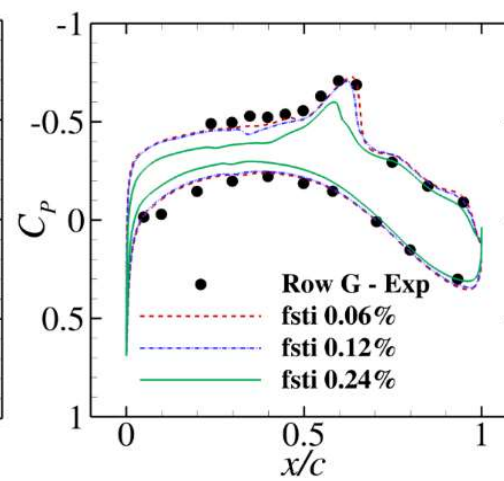
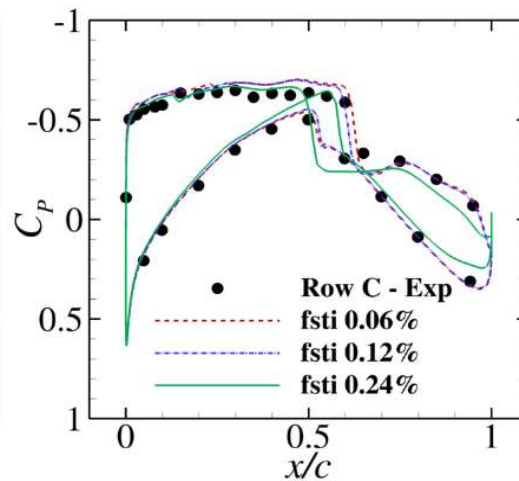
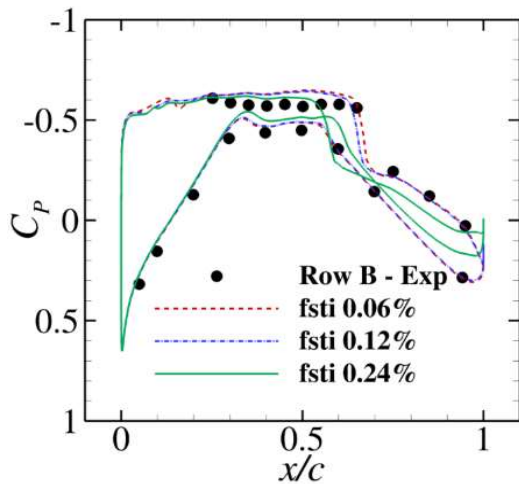
* Lynde, M. N., Campbell, R. L., and Viken, S. A., "Additional Findings from the Common Research Model Natural Laminar Flow Wind Tunnel Test," AIAA Paper 2019-3292, 2019.

Computation Details (contd.)

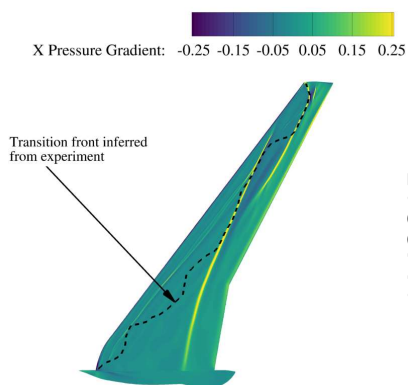


- Freestream Turbulence Intensity (FSTI) = 0.24% (NTF tunnel characterization)
 - Correct FSTI near the wing could only be achieved for SST-based models via use of turbulence sustaining terms
 - Turbulence sustaining terms interfered with the behavior of the model within the boundary layer (when FSTI=0.24%)
 - Incorrect pressure distribution
 - Reduction of FSTI to 0.12 % removed the issue for the SST-based LM model
 - No such sensitivity issues for SA-based AFT
 - Both models were run with FSTI = 0.12 % for consistent comparison

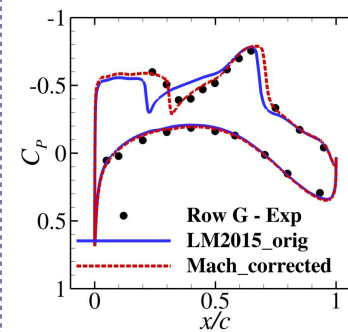
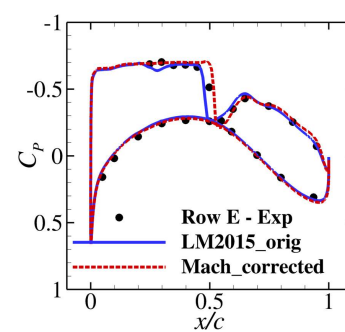
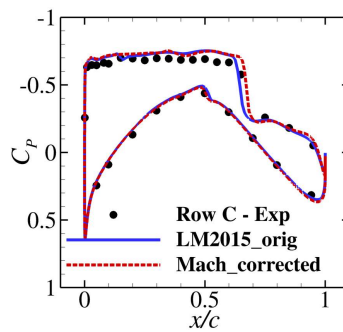
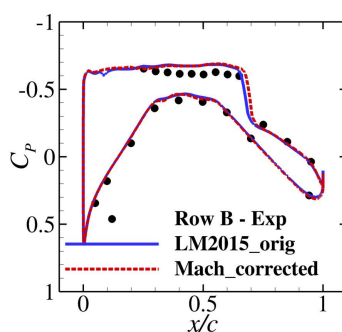
SST-2003-LM2015 (Influence of FSTI on C_p with turbulence sustaining terms)



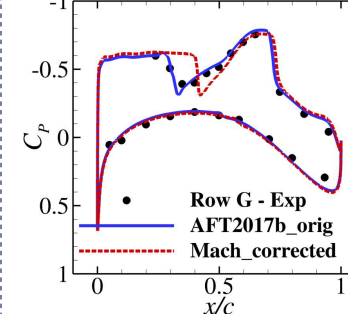
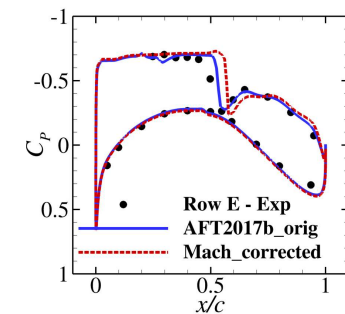
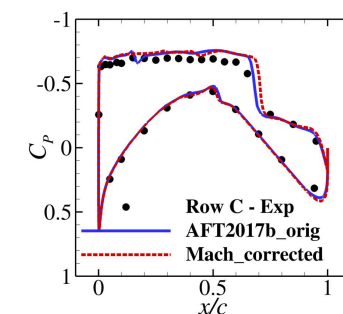
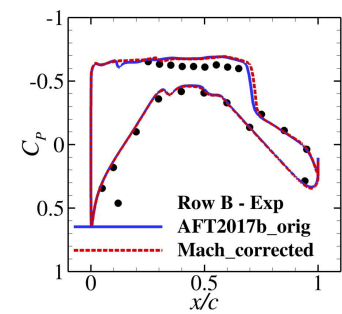
Sectional C_{ps} for AOA = 1.98 deg.



LM2015



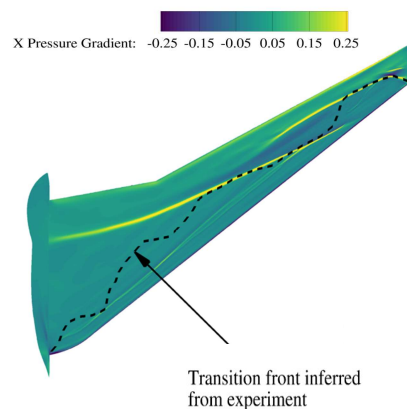
AFT2017b



Reasonable match at most spanwise locations

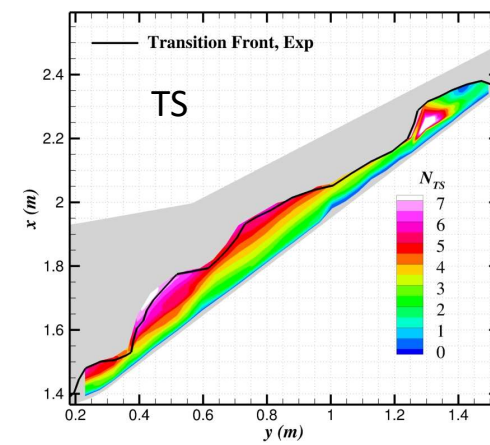
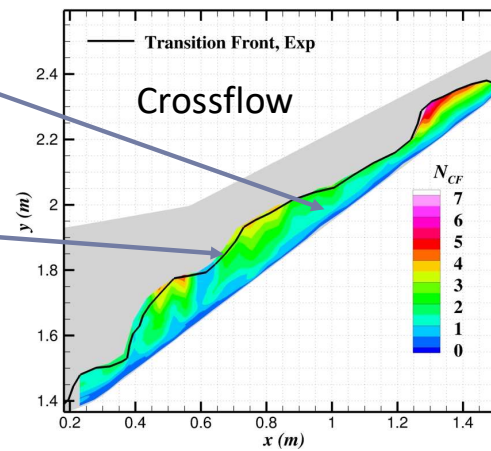
Shift in shock-location as one moves near wing-tip

Transition Fronts at AOA = 1.98 deg.

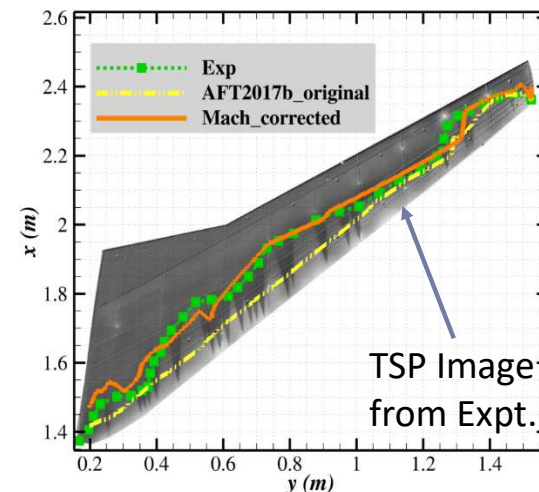
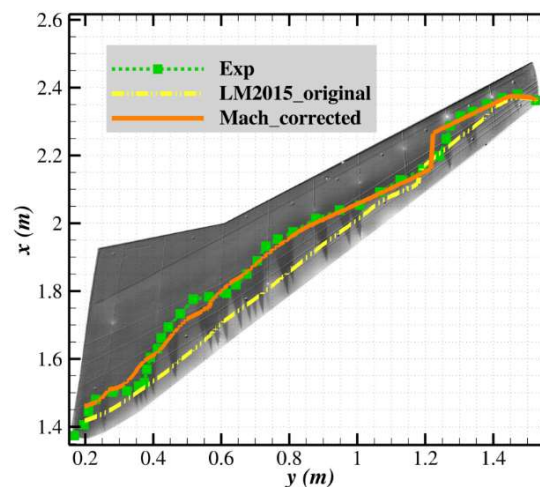


Envelope of N -factor contours

Transition Front from Expt.

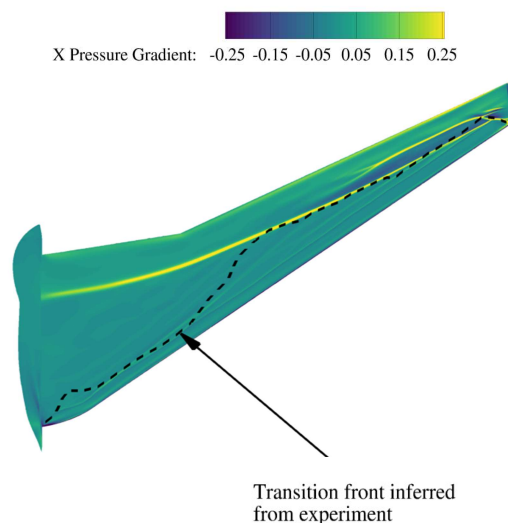


- Compressibility corrections -> Substantially improved match with experiment in relation to baseline LM and AFT models
- Exception: Small but visible differences in transition front over outboard section of the wing, where the front switches from one shock to another)
 - Accompanying shifts in pressure distribution highlight strong viscous-inviscid interaction in this case

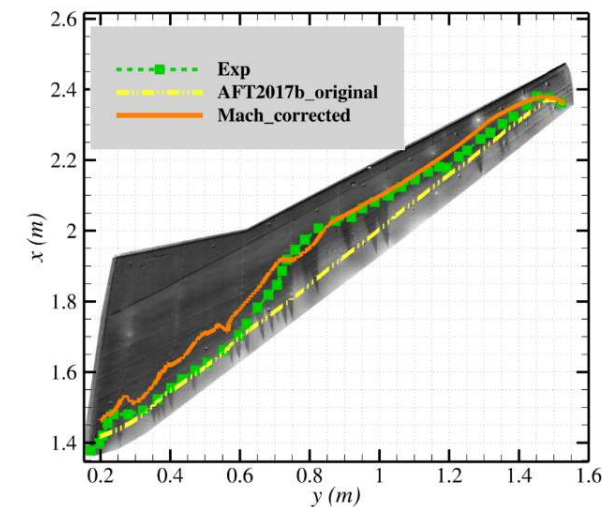
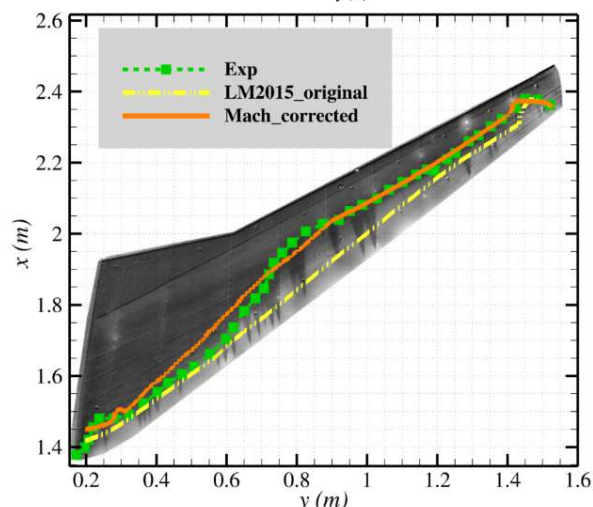
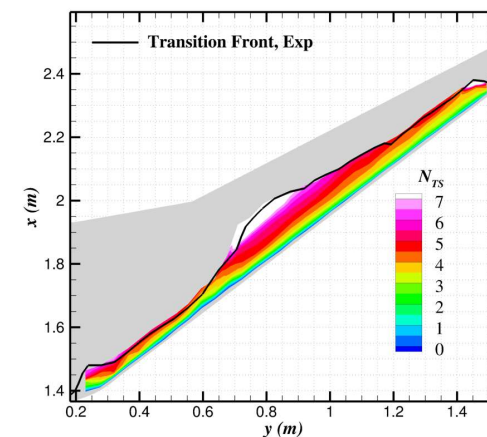
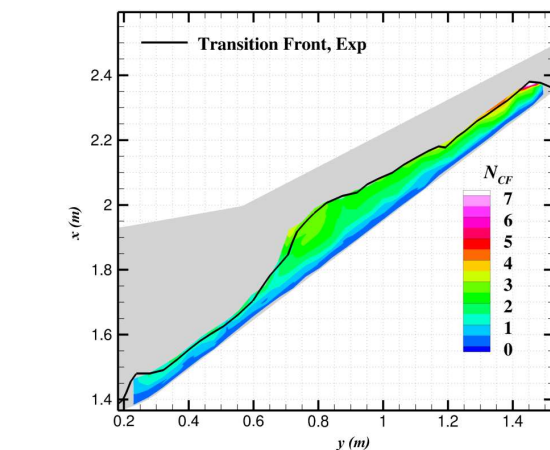


TSP Image from Expt.

Transition Fronts at AOA = 2.46 deg.



- TS and shock-induced transition mechanisms at play
- Baseline models did well in inboard regions (small region of APG immediately downstream of suction peak)
 - Compressibility correction predicts larger laminar region here



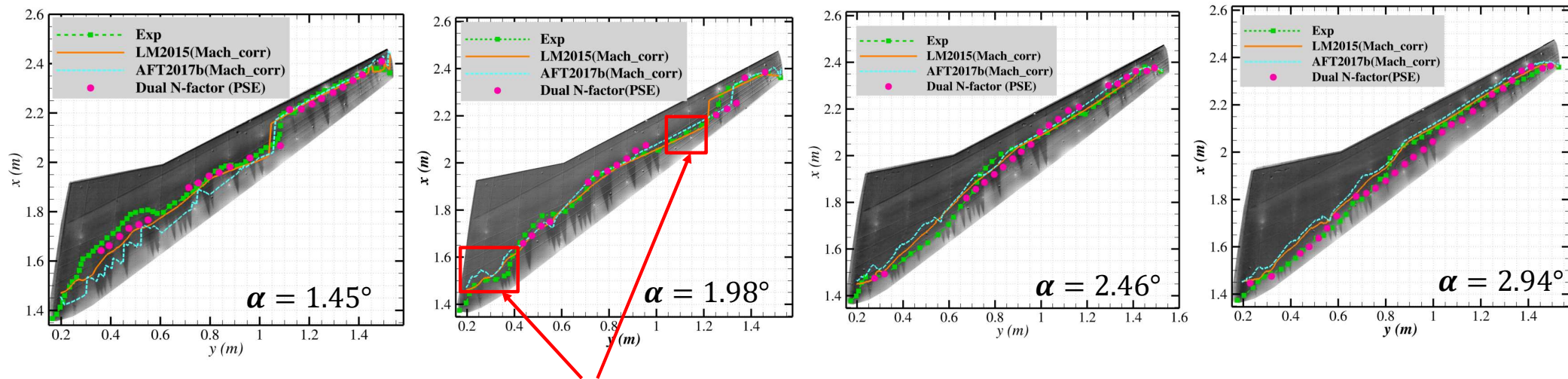
Linear PSE – Dual N_{TS} - N_{CF} Criterion

- Transit onset occurs when a function of N_{TS} and N_{CF} reaches a threshold

$$\left(\frac{N_{TS}}{N_{TS,c}}\right)^{a_{TS}} + \left(\frac{N_{CF}}{N_{CF,c}}\right)^{a_{CF}} = 1; N_{TS,c} = 6; N_{CF,c} = 6; a_{TS} = 3; a_{CF} = 3$$

- Critical N based on disturbance, roughness levels (See Paredes et al. AIAA Paper 2021-1431)

Transition front obtained with dual N-criterion superimposed with data from experiments and transition models



Does not reach critical N -values in these regions (end of specified laminar region or shock-limited)

Summary



- Proposed simple modifications to baseline SST-2003-LM2009/2015 and SA-AFT2017b to account for stabilizing effect of compressibility
 - The models returns to original form at low speeds
 - Applicability limited to $M_e < 1.2$ (validity of isentropic approximation to determine edge Mach number)
 - Substantial improvements in accuracy of predicting transition front for the transonic CRM-NLF configuration
- Stability analysis carried out with PSE marching along streamlines
 - Comprehensive assessment of transition in CRM-NLF based on nonparallel disturbance amplification
 - Stability-based dual N -factor criterion predicted transition fronts that matched well with those inferred from the CRM-NLF experiment for all the conditions studied
 - Provided additional evaluation for assessing the modifications to the RANS-based transition models

Future Work

- Careful evaluation of the compressibility correction and dual N -factor criterion across wide set of problems
- More reliable estimate of edge Mach number (extends applicability of model to $M_e < 2$)
- Improve some of the simplifications assumed while formulating compressibility corrections

Acknowledgments



- Research Funded by: NASA TTT Project under TACP
- NIA cooperative agreement 2A00 (Activity 201133)
- Joe Derlaga and Pieter Buning for help with OVERFLOW
- Richard Campbell, Michelle Lynde and Sally Viken of CRM-NLF Team
- NASA Advanced Supercomputing and LaRC K-Midrange Cluster resources

Backup Slides

Compressibility-related modifications

Modifications – a strictly local formulation and reverts to original model at low speeds (See paper for more details)

LM2009/LM2015 Model

- Corrections to relationship between Vorticity Reynolds number and Re_θ (Compressibility BL profiles, Qiao et al.[2018])
 - $Re_\theta = \frac{\max(Re_v)}{2.193 \cdot C(M_e)}$; $C(M_e)$ = function of edge Mach number M_e
- $(Re_{\theta t})_{\text{Original}} = f1(FSTI) \cdot f2(\lambda_\theta)$ (separate functions of FSTI & pressure gradient)
 - (Narasimha [1985]) : $(Re_{\theta t})_{\text{New/comp}} = (Re_{\theta t})_{\text{Original/incomp}} \cdot f3(M_e)$
 - $f3(M_e)$ determined using data from stability computations by Masad and Malik [1993] and Masad and Abid [1995]

AFT 2017b Model

- Based on the modifications to correlations of Drela and Giles [1987] by Sturdza [2003] (applicable to low supersonic speeds)
- Re_θ at critical point (i.e., onset of instability) : $(Re_{\theta 0})_{\text{new}} = (Re_{\theta 0})_{\text{original}} \cdot f1\left(\frac{T_w}{T_e}\right)$
- Slope of N-factor envelope: $\left(\frac{dN}{dRe_\theta}\right)_{\text{new}} = \left(\frac{dN}{dRe_\theta}\right)_{\text{original}} \cdot f2\left(\frac{T_w}{T_e}\right)$; $\frac{T_w}{T_e} = f(M_e)$

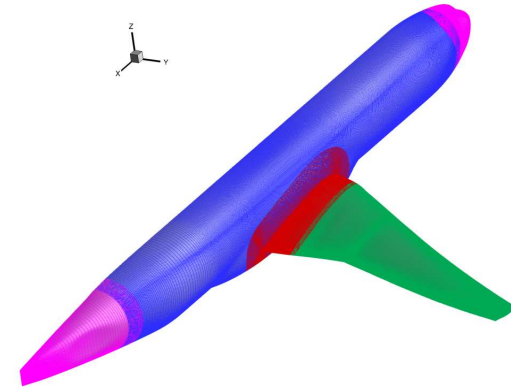
Edge Mach Number M_e

- Can be approximated via Bernoulli's equation + Isentropic relations (provided no shocks)
- Deviations from isentropic relation expected to be small for $M < 1.2$ (Lee [2016] and Stroer [2020])

CRM-NLF - Flow Conditions, Computation Details



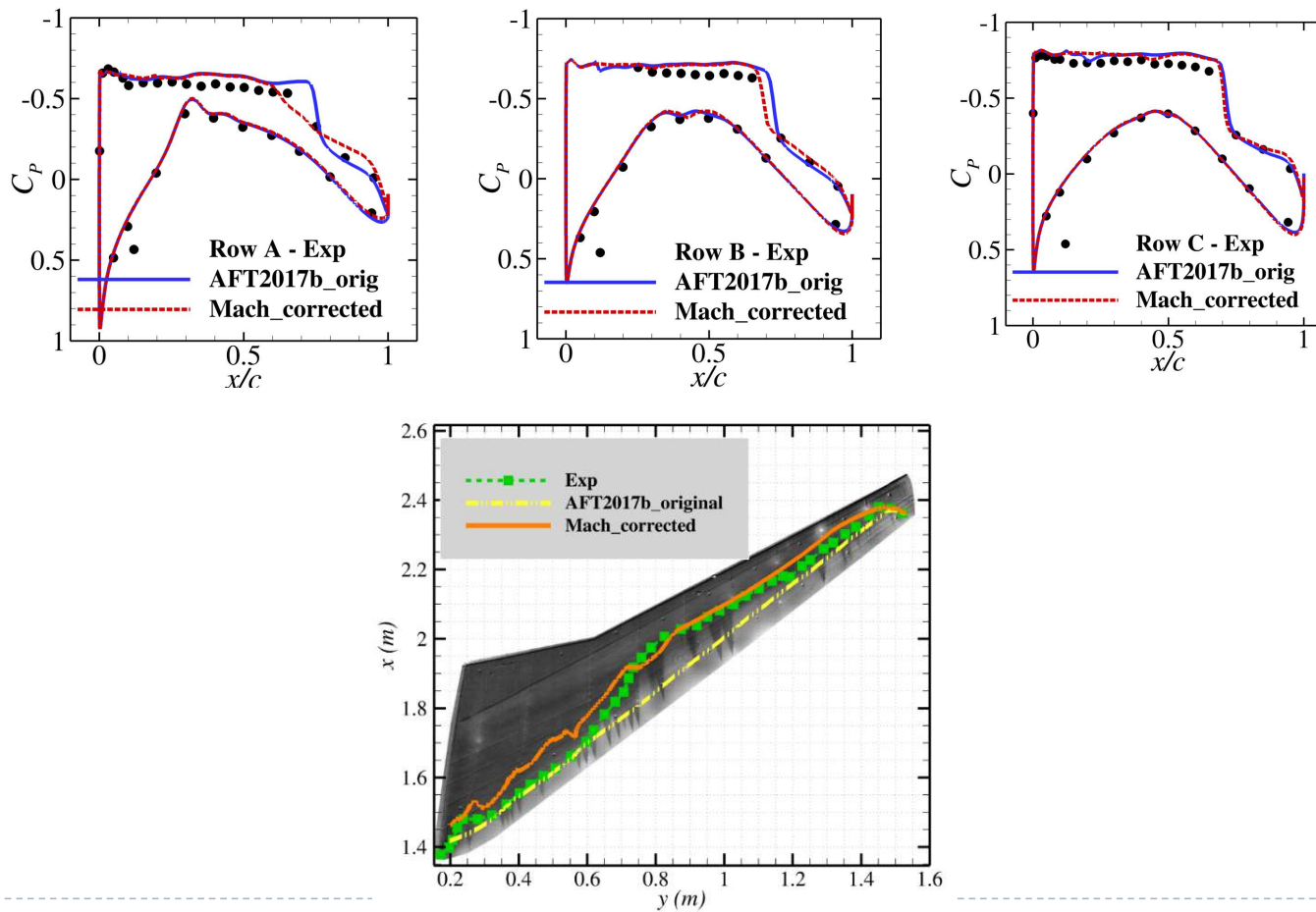
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- In-house generated fine grid (120 million near-body grid points, $y^+ \sim 0.5$) – See paper for details
- Surface roughness = 0.9 μ inch (measured in the CRM-NLF experiment; for use with the LM2015 model)
- Both models were run with FSTI = 0.12 % for consistent comparison (sustaining turbulence with SST-based model)
 - See details in paper regarding reduced FSTI and influence of sustain terms on pressure distribution (with SST)



Condition	AoA (deg.)	Mach No.	T_∞ (K)	Re (per m)	Re_{MAC}
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Compressibility-related modifications (LM2009/2015)



- Corrections to relationship between Vorticity Reynolds number and Re_θ (Compressibility BL profiles, Qiao et al.[2018])
 - Peak location of Re_v moves to edge of boundary layer with increase in Mach number

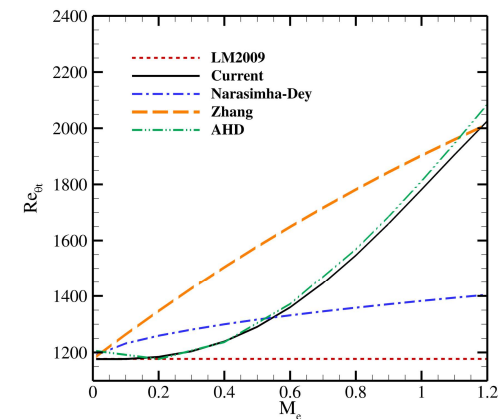
$$Re_\theta = \frac{\max(Re_v)}{2.193} \longrightarrow Re_\theta = \frac{\max(Re_v)}{2.193 \cdot C(M_e)} \quad C(M_e) = 1.0 - 0.06124M_e + 0.2402(M_e)^2 - 0.00346(M_e)^3$$

- Modification of correlation for $Re_{\theta t}$

- $(Re_{\theta t})_{\text{Original}} = f(FSTI) \cdot f(\lambda_\theta)$ (separate functions of FSTI & pressure gradient)
- Narasimha [1985] : $(Re_{\theta t})_{\text{New/comp}} = (Re_{\theta t})_{\text{Original/incomp}} \cdot f(M_e)$
- $f(M_e)$ determined using data from stability computations by Masad and Malik [1993] and Masad and Abid [1995] (investigated combined effects of pressure, suction/blowing and wall cooling)

$$f(M_e) = 1.0105 - 0.3046M_e + 1.1646(M_e)^2 - 0.3605(M_e)^3$$

- Ideally compressibility correction should be just not function alone of M_e but also involve pressure gradient
 - Current modifications will still be applicable for the CRM-NLF configuration due its predominantly flat pressure distribution across the span of the wing



Compressibility-related modifications (AFT)



➤ Re_θ at critical point (i.e., onset of instability)

Original:
$$\log_{10} \left(\frac{Re_{\theta 0}}{1.0} \right) = \left(\frac{1.415}{H_k - 1} - 0.489 \right) \tanh \left(\frac{20}{H_k - 1} - 12.9 \right) + \frac{3.295}{H_k - 1} + 0.44$$

New:
$$\log_{10} \left(\frac{Re_{\theta 0}}{K_0} \right) = \left(\frac{1.415}{H_k - 1} - 0.489 \right) \tanh \left(\frac{20}{H_k - 1} - 12.9 \right) + \frac{3.295}{H_k - 1} + 0.44$$

$$K_0 = \frac{2}{\pi} \operatorname{atan} \left(10 \frac{T_w}{T_e} - 10 \right) + 1$$

➤ Slope of N-factor envelope

Original:
$$\frac{dN}{dRe_\theta} = \frac{0.01}{1.0} \left\{ \left[2.4H_k - 3.7 + 2.5 \tanh(1.5(H_k - 3.1)) \right]^2 + 0.25 \right\}^{0.5}$$

New:
$$\frac{dN}{dRe_\theta} = \frac{0.01}{K_b} \left(2.4H_k K_a - 3.7 + 2.5 \left(\frac{T_w}{T_e} \right) \tanh[1.5(H_k - 3.1)] + 0.125 + K_d - K_m \right)$$

$$K_a = 1 + 0.2(H_k - 2.5918) \left(1 - \frac{T_e}{T_w} \right); K_b = 4.7 \left(\frac{T_w}{T_e} - 1 \right); K_d = 1.2 \left(\frac{T_w}{T_e} - 1 \right)^{1.5}; K_m = 0; \frac{T_w}{T_e} = f(Me)$$

Compressibility-related modifications



- Estimation of edge Mach Number M_e
 - Key parameter necessary for both models
 - Nontrivial to obtain in an unstructured CFD solver and will make formulation non-local
 - Can be approximated via Bernoulli's equation + Isentropic relations
 - Limited application as isentropic relations fails when shocks are involved
 - Deviations from isentropic relation expected to be small for $M < 1.2$ (making it suitable for transonic applications) (Lee [2016] and Stroer [2020])

$$|u_e| = \sqrt{u_\infty^2 + \frac{2\tilde{\gamma}}{\tilde{\gamma} - 1} \left[1 - \left(\frac{p}{p_\infty} \right)^{1-1/\tilde{\gamma}} \right] \frac{p}{\rho_\infty}}$$

$$a_e = \sqrt{\tilde{\gamma} R T_\infty \left(\frac{p}{p_\infty} \right)^{\frac{\tilde{\gamma}-1}{\tilde{\gamma}}}}$$