Assessment and Improvement of RANS-based Transition Models based on Experimental Data of the Common Research Model with Natural Laminar Flow

Balaji Shankar Venkatachari,* Pedro Paredes†
National Institute of Aerospace, Hampton, VA 23666

Joseph M. Derlaga,‡ Pieter Buning,§ Meelan Choudhari,** Fei Li,†† and Chau-Lyan Chang‡‡
NASA Langley Research Center, Hampton, VA 23681

Transition models based on auxiliary transport equations augmenting the Reynolds-averaged Navier-Stokes (RANS) framework often rely upon the correlations that were derived from a limited number of low-speed experiments and do not account for all of the transition mechanisms and/or their variation with the significant flow parameters. Available data from a recent experiment in the National Transonic Facility at the NASA Langley Research Center are used to assess the current transition modeling capability in NASA's OVERFLOW 2.2o code for a swept wing configuration at transonic cruise conditions. Specifically, the OVERFLOW solutions are used together with detailed stability analysis of the boundary layer flow over the new Common Research Model with Natural Laminar Flow (CRM-NLF) to evaluate the accuracy and the robustness of the transport-equation-based transition models, with the goal of proposing improvements that would help to strengthen the physical basis of these models for the important class of flows involving the combined effects of crossflow and flow compressibility. Results highlight the significant underprediction of the laminar flow extent within the inboard region of the wing, wherein the onset of transition may be attributed to a gradual amplification of Tollmien-Schlichting instabilities.

Nomenclature

C_p = surface pressure coefficient [nondimensional]
Re_{MAC} = Reynolds number based on freestream variables and mean aerodynamic chord [nondimensional]
x/c = chordwise coordinate scaled by reference chord length [nondimensional]
y^+ = near wall grid spacing in wall units [nondimensional]
α = angle of attack [deg]
η = semispan location nondimensionalized by semispan length [nondimensional]

I. Introduction

According to the CFD Vision 2030 [1], the most critical area in computational fluid dynamics (CFD) simulation capability that will remain a pacing item for the foreseeable future is the ability to adequately predict viscous flows with boundary layer transition and flow separation. A majority of the CFD

*Sr. Research Engineer, Email: balaji.s.venkatachari@nasa.gov, Senior member, AIAA
† Research Engineer, Email: pedro.paredesgonzalez@nasa.gov, Member, AIAA
‡ Research Scientist, Computational AeroSciences Branch, Email: joseph.m.derlaga@nasa.gov, Member, AIAA
§ Aerospace Technologist, Computational AeroSciences Branch, Email: pieter.g.buning@nasa.gov, Associate Fellow, AIAA
** Aerospace Technologist, Computational AeroSciences Branch, Email: m.m.choudhari@nasa.gov, Fellow, AIAA
†† Aerospace Technologist, Computational AeroSciences Branch, Email: Fei.Li@nasa.gov
‡‡ Aerospace Technologist, Computational AeroSciences Branch, Email: chau-lyan.chang@nasa.gov, Associate Fellow, AIAA

computations are carried out under the assumption that the flow is turbulent everywhere, and they often use the computationally efficient Reynolds-averaged Navier-Stokes (RANS) models. However, for certain applications such as wings with natural laminar flow (NLF) technology or unmanned aerial vehicle design, such strong assumptions can lead to significant errors in performance estimation. Furthermore, most of the RANS models are incapable of modeling the process of laminar-to-turbulent boundary layer transition because of the complexity involved in the physics of the transition onset process, and the inherent averaging process in the RANS procedure makes it difficult to capture the development of the linear disturbances and its subsequent nonlinear growth and eventual breakdown.

Direct numerical simulations (DNS) and wall-resolved large-eddy simulations (WRLES) are the only approaches capable of simulating the complete physical process of the onset of transition and the breakdown of laminar boundary layers into turbulent flow. However, even with the current state-of-the-art high performance computing tools, these approaches are too expensive to permit the analysis of realistic configurations at high Reynolds numbers due to the extreme requirements on spatio-temporal resolutions. Moreover, DNS and WRLES require accurate specification of the initial and boundary conditions to account for a correct representation of the factors that excite the instabilities in the flow, and this information is often not fully available from most wind-tunnel and flight tests.

Using semiempirical correlations based on the linear stability theory (LST), such as the e^N method introduced by Smith and Gamberoni [2] and van Ingen [3], remains one of the most widely used approaches for the prediction of transition onset locations in aircraft design computations. The LST equations are derived from the linearized Navier-Stokes equations to track the evolution of small amplitude, fixed frequency disturbances under the parallel flow assumption. The e^N method does require the specification of a critical N-factor that must be obtained from correlations against experimentally measured transition locations. Transition analysis using the parabolized stability equations (PSE) [4] has less-restrictive assumptions and can more easily account for the effects of a nonparallel basic state, curvatures in geometry, and nonlinear modal interactions of the laminar instabilities. Both LST and PSE can account for the amplification of the dominant primary instabilities encountered on aircraft wings, namely, the Tollmien-Schlichting waves and the stationary/travelling crossflow vortices. However, the application of these approaches toward a coupled computation of laminar, transitional, and fully turbulent parts of a flowfield entails an increased computational cost as well as complexity; it also suffers from a lack of robustness and often requires adequate understanding of transition physics and hydrodynamic stability theory that typical users of CFD codes may not know. To alleviate or circumvent these shortcomings, surrogate models are often used in lieu of the direct computation of stability characteristics based on the laminar flow information provided by the flow solver. There are a number of successful implementations of CFD codes that combine stability-based transition predictions with RANS-based turbulence modeling, for instance see Refs. [5–12]. However, a majority of these models suffer from the need to have sufficiently well resolved boundary layer profiles in the laminar baseflow computations, including the wall-normal derivatives of velocities and temperature, or at least, the need to compute integral boundary layer parameters that may be used as a proxy to the laminar profiles themselves. These restrictions are difficult to overcome in modern CFD codes that rely upon massive parallelization and the use of unstructured grids [13].

Given that the vehicle performance is often characterized in terms of integral quantities such as load/moment coefficients or through pressure/skin-friction distribution, capturing the detailed physics of the transition to turbulence in itself is less important than the overall impact of the transition on the development of the boundary layer and its impact on the aforementioned quantities. Due to the previously mentioned reasons and cheaper computational cost requirements, efforts to develop models that represent the transition physics and can be embedded into a RANS framework has gained substantial ground [14–23]. For reasons of computational cost, these models often require that only local information be used to model transition, instead of using detailed boundary layer profiles for stability analysis or even integral-boundary layer parameters that may be used in metamodels for the stability characteristics. The RANS-based transition models often rely on solving additional transport equations and using correlations that determine the onset of transition, allowing the codes to switch between operating in the laminar and turbulent modes. This approach clearly overcomes some of the aforementioned limitations of stability-based transition prediction and is well-suited for generalizing the established process for turbulent flow computations in a cost effective manner. However, by virtue of lacking an adequate representation of the complex transition process, such models are also less amenable to an extrapolation to new configurations and must be validated on a case by case basis in general. More details on the various approaches currently being used to predict/model transition can be found in Refs. [24, 25].

The present research seeks to blend the so-called physics-based approach for transition modeling with the RANS-based approaches, with the eventual goal of developing a reliable and cost efficient, yet robust and user-friendly approach for integrated modeling of laminar-turbulent transition. Towards achieving that goal, data obtained from NASA's recent experiments on the Common Research Model with Natural Laminar Flow (CRM-NLF) [26–29] that was carried out in the National Transonic Facility, provides an ideal platform for evaluating the performance of the existing RANS-based approach to modeling transition, especially those available within NASA's OVERFLOW 2.2o code [30]. In a typical transport aircraft wing with high sweep, transition occurs as a result of crossflow (CF) instability and/or Tollmien-Schlichting (TS) instability, provided that the attachment line remains laminar. The CRM-NLF wing has been designed to modify the surface pressure distribution in such a way that the overall amplification of both of these instabilities is reduced. CF growth is attenuated through a rapid acceleration near the leading edge (achieved via a sufficiently smaller leading edge radius), while the amplification of TS waves is controlled by creating a slightly favorable pressure gradient. The design also addresses attachment line contamination and transition due to attachment line instabilities, thereby allowing laminar flow to be maintained over a substantial region of the wings and thus helping reduce its drag. The earlier RANS-based transition models were designed to account for transition caused by either TS waves, or some form of bypass transition, or as a result of flow separation; however, they did not account for crossflow effects very well. In the last few years, however, there has been an increased interest to account for crossflow effects in transition models [31–36]. Also, many of these transition models, rely upon correlations that were based on low-speed flows. Hence, to understand the shortcomings of these models, it is important to see how these RANS-based transition models behave when: (i) multiple of the above-mentioned transition-inducing mechanisms are at work; and (ii) the speed regime is higher than what the models were calibrated for. The present paper also aims to improve these transition models, by attempting to inject a more physics-based approach into them drawing information from the accompanying work by Paredes et al. [37] — with focus on the detailed stability analysis of the boundary layer over the CRM-NLF. The information from the stability analysis will be used either in the form of a database lookup approach similar to that adopted in Ref. [12] or in the form of other reduced order models recently developed within our research group [38], to replace or augment some of the empirical correlations inside these models. Details about the model configuration, the flow solver and transition models, are given in the subsequent sections. That is followed by a short discussion of preliminary results and details about additional aspects of work that will be included in the final paper.

II. CFM-NLF Model

The CRM is an open geometry representation of a generic transport vehicle and has been used in a multitude of studies [39]. The CRM-NLF builds upon this geometry by replacing the CRM wing with a new outer mold line (OML) that supports a significant region of NLF on the upper surface of the wing. This modified wing configuration was designed by using the CDISC (Constrained Direct Iterative Surface Curvature) design process [40, 41]. The wind-tunnel model is a 5.2% scaled semispan model of the CRM-NLF. The model has a semispan length of 60.151 inches, mean aerodynamic chord (MAC) of 14.342 inches and a leading-edge sweep of 37.3 degrees over the majority of the wing span. The leading edge sweep is reduced to 12.9 degrees over the inboard 10% of the wing in order to avoid attachment line transition via turbulent contamination from the fuselage boundary layer. Data acquired during the test includes total forces and moments, surface static pressures, model deformation, and transition visualization data. More details on the model geometry and the wind tunnel measurements can be found on the CRM website.[§§]

III. Flow Solver and Transition Models

NASA's OVERFLOW 2.2o [30] is an implicit structured overset grid Navier-Stokes solver that is capable of computing time-accurate and steady-state solutions via a variety of options for spatial and temporal discretization. RANS-based transition models available in OVERFLOW 2.2o include: (i) the two-equation Langtry-Menter transition model (LM2009) [18] based on the year 2003 version of Menter's shear-stress transport (SST) RANS model [42,43], along with the modifications proposed by Langtry et al. [32] to account

[§§] https://Commonresearchmodel.larc.nasa.gov/crm-nlf/

for crossflow induced transition (LM2015); (ii) Coder's [22, 23] 2017b version of the amplification factor transport (AFT 2017b) equation-based model that uses the Spalart-Allmaras (SA) model [44]; and (iii) the Medida-Baeder model [19], which is a reformulation of the Langtry-Menter transition model to allow its integration with the SA model. There have been additional proposed modifications to the Medida-Baeder model that account for the effects of crossflow instability[45], but those have not yet been implemented into OVERFLOW.

IV. Selected Results

The illustrative computations described in this abstract were run at the flow conditions corresponding to a freestream Mach number of 0.856, a Reynolds number based on the mean aerodynamic chord (MAC) equal to 15 x 10^6, and an angle of attack of 1.5° that matches one of the relevant test conditions from the experiment. The free stream turbulence intensity was prescribed to be 0.24%, based on previous characterization of the NTF tunnel [46] and the surface roughness of the model was specified to be 1 µinch [28]. The conditions corresponding to higher angles of attack will be reported in the final paper. The solutions were obtained by running the flow solver in a steady-state manner by using the 3rd-order Roe upwind scheme [47] and the unfactored successive symmetric overrelaxation (SSOR) implicit solution algorithm [48]. The partial set of results presented herein are based on (i) the AFT 2017b transition model, (ii) the LM2009 model, and (iii) the LM2015 model that accounts for crossflow induced transition. As the Medida-Baeder model [19] is a variant of the Langtry-Menter transition model, it is not unreasonable to expect that any inference drawn about the performance of the Langtry-Menter transition model will carry over to the Medida-Baeder model as well.

The baseline mesh used in these computations had six overset near-body blocks (three on the fuselage including its nose and tail, one wing-body collar grid, and two on the wing, including its tip), as shown in Fig. 1. The generation of off-body grids and hole-cutting were carried out by using OVERFLOW's domain connectivity function (DCF) approach. The baseline grid, which was used for most of the results shown herein, had a near-wall spacing of $y+$ = 0.25, based on the conditions at 10% of the MAC of the wing, and has approximately 441 points around the wing in the chordwise direction. The near-body grid had an overall grid count of approximately 40 million points.

The computational results are evaluated against the measured data in terms of two separate metrics, namely, by comparing the measured surface pressure variation at six spanwise locations, indicated in Fig. 2, with the computed pressure distribution at the same locations and through a comparison of the predicted transition front against the locus of transition locations inferred from the experimental measurements (also shown in Fig. 2).

As seen from Fig. 3, the computed pressure distributions based on the AFT 2017b and LM2009 compare well with the measured data at all six spanwise location. Although not shown in Fig. 3, results obtained using the LM2015 model also matched the experimental data rather well. The rapid acceleration near the leading edge, the mild adverse pressure gradient in the midchord section of the upper surface, and the shock location are all captured accurately in the computations performed with the baseline grid. However, when one compares the predicted transition front (see Fig. 4) against those from the experiments, the differences between the models become apparent. Shown in Fig. 4 is the turbulence index contour (value above 0.5 indicates a turbulent region) as an indicator for transition in the CFD computations. The definition of this turbulence index was originally proposed by Spalart [44, 49]. Also indicated in the figure is the shock front inferred from the computed pressure distribution along the surface. Both variants of the Langtry-Menter model appear to agree with the measured transition front in the outboard section of the wing, wherein the onset of transition appears to be closely aligned with the shock front), as well as near the root of the wing, where transition was predicted to have been caused by the amplification of Tollmien-Schlichting waves [26, 28, 37]. Slightly beyond the root of the wing and until around the approach to a constant leading edge sweep, there is significant discrepancy in the predicted transition front when compared against the measurements from the experiment. Since crossflow is not expected to play a role for this design and flow conditions, one does not see a significant difference between the transition fronts predicted by the LM2015 and LM2009 models. On the other hand, the AFT2017b model appears to do very poorly except near the wing tip, predicting a very small laminar region across the entire span of the wing. One possible reason could be that the model heavily relies on the correlations derived for low speed flows, thereby not accounting for the stabilizing influence of the higher Mach number for the present transonic configuration. Another possible

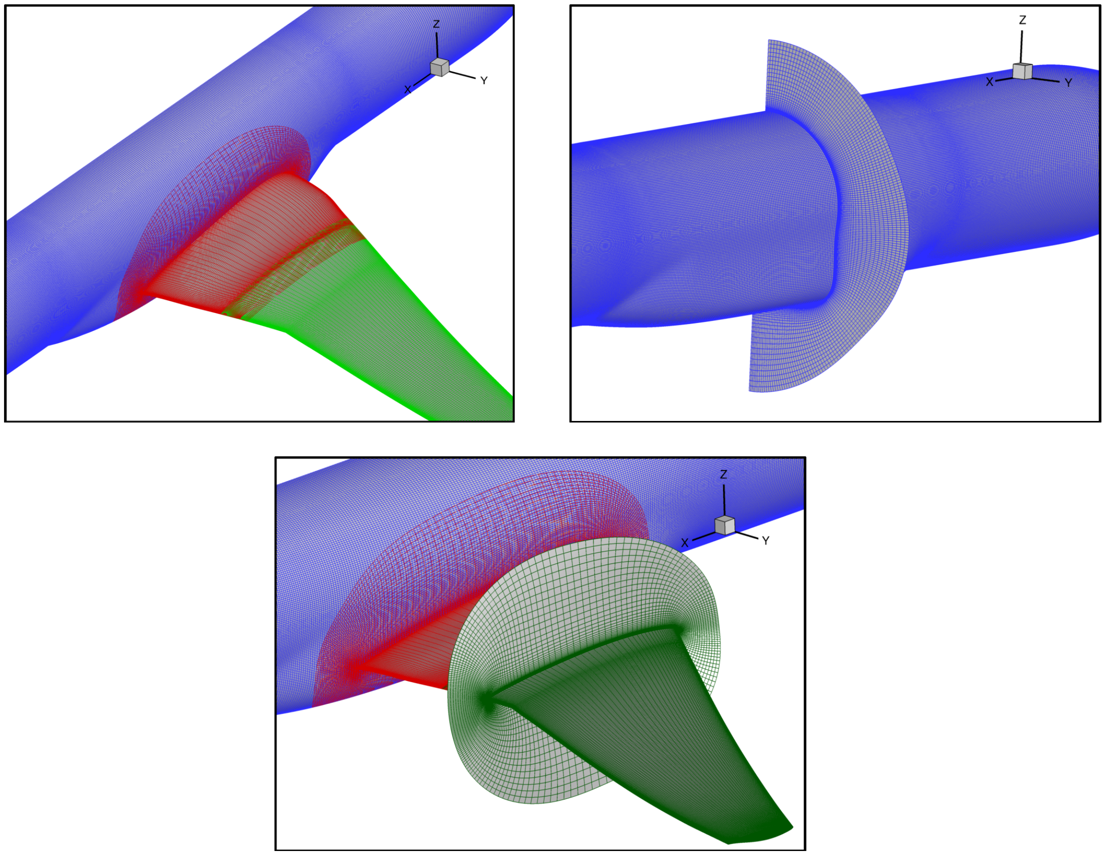


Fig. 1. Overview of the near-body mesh.

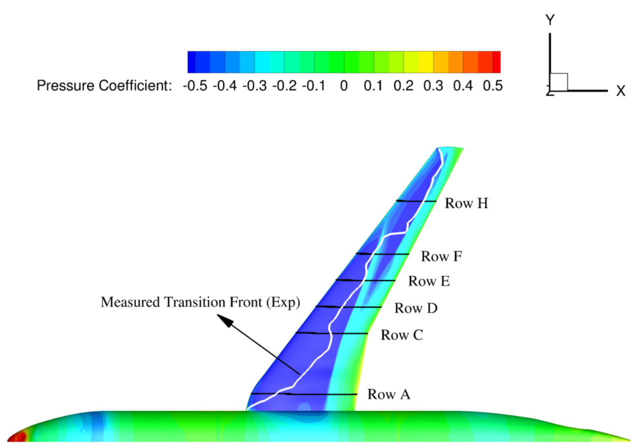


Fig. 2. Computed pressure distribution contour on the model shown along with measured transition front from the experiment and spanwise stations where pressure data were available from experiments.

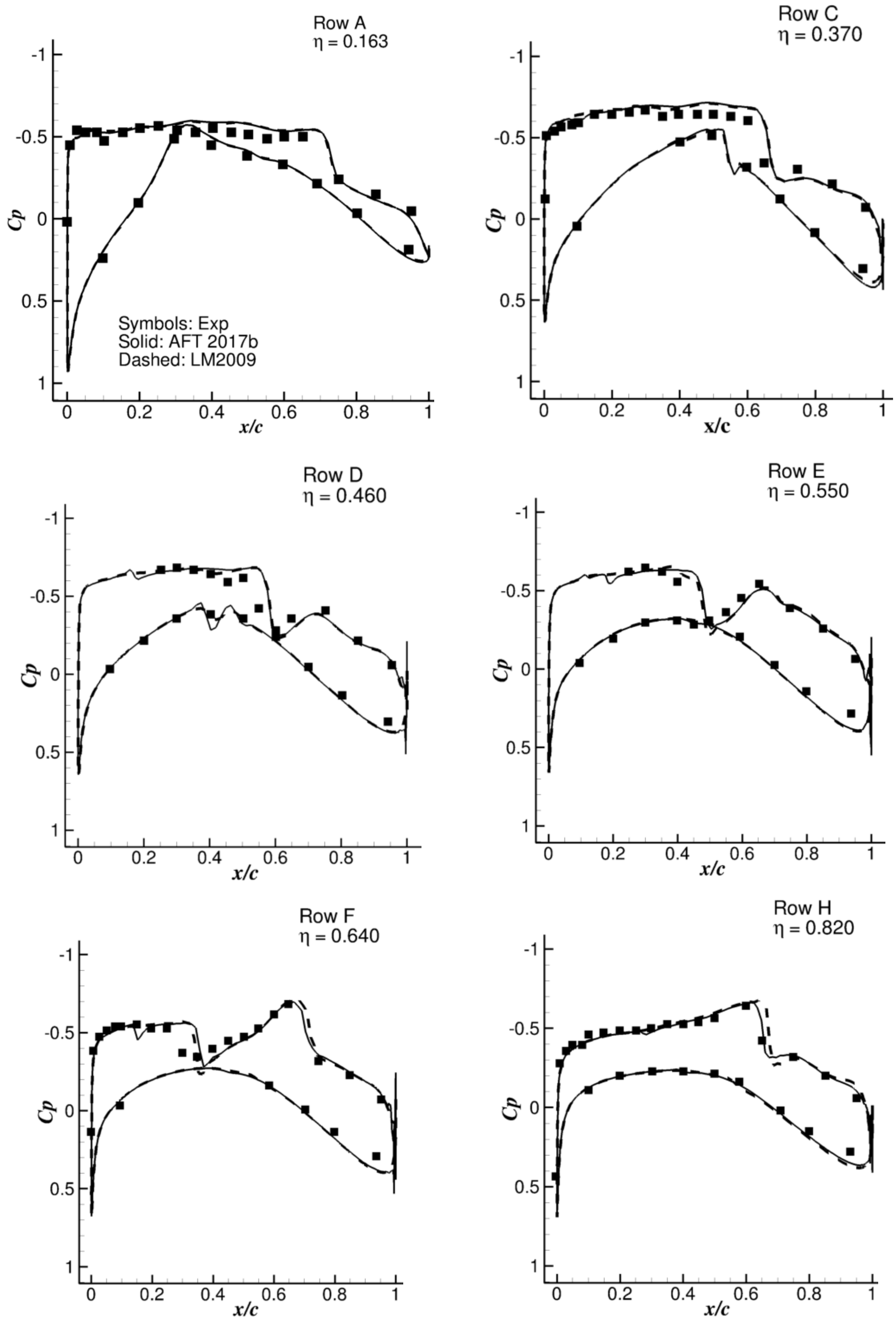


Fig. 3. Comparison of measured and computed pressure distributions at various stations on the CRM-NLF wing obtained using different transition models for $\alpha = 1.5°, M = 0.856$ and $Re_{MAC} = 15 \times 10^6$. Square symbols: Experiment; Solid line: AFT2017b; Dashed: LM2009.

reason could be that the AFT model requires, in general, a significantly higher grid resolution compared to the other models, because it is anchored to an estimation of the approximate N-factor envelop. A more thorough investigation into the results from the AFT 2017b model and possible fixes toward an improved agreement with the measured transition front will be discussed in the final paper. As a quick evaluation of the transition predictions at the baseline grid resolution, all models were tested against another grid that contained fewer grid points around the wing while retaining the same near-wall spacing. The results for the LM2009 model as shown in Fig. 5 clearly highlight the sensitivity of the predicted transition front to the chordwise resolution. The same conclusion was found to carry over to the other two models as well. Although not shown here, the computed pressure distributions did not deviate significantly from the experimental data in all cases. A comprehensive and systematic grid resolution study using a sequence of grids will be reported in the final paper.

Paredes et al. [37] have carried out a linear stability analysis of the boundary-layer flow computed herein and the results of that analysis will be reported in an accompanying submission. Their complete study will focus on a comprehensive analysis of disturbance amplification in the swept wing boundary layer, based on multiple levels of fidelity such as quasiparallel LST without and with curvature effects, PSE, and with different assumptions regarding disturbance trajectories along the wing surface. The findings from that study are expected to inform the current set of computations by providing detailed insights into the transition mechanisms over different parts of the CRM-NLF wing and how the RANS-based models do or do not capture each of those mechanisms. Furthermore, the stability database can be used to augment these RANS-based transition models to improve their performance. As an example, given that the AFT model relies on the correlations derived by Drela and Giles [5] to approximately determine the N-factor envelope, which in turn were based on Falkner-Skan type flows, incorporating the evolution of amplitude growth factors on realistic airfoils, and at the higher speed regime of interest, is definitely expected to improve the performance of the model. More details on how these improvements can be achieved and incorporated into these models will be provided in the final paper.

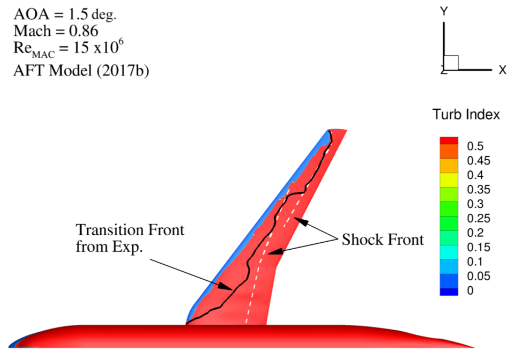
V. Additional Contents of the Final Paper

The final paper will include the following additional results and a discussion of the findings based upon them:

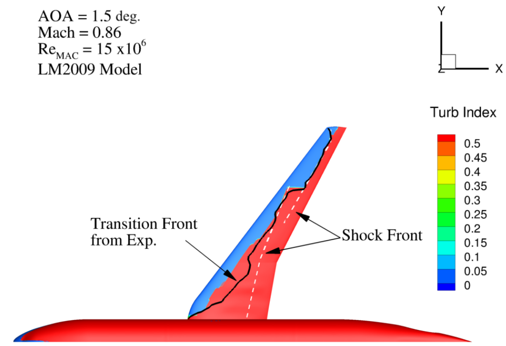
1) A comprehensive grid sensitivity study, using a sequence of grids with refinements in all three directions.
2) Computations for multiple angles of attack for which experimental data are available and assessment of the models in terms of the predicted transition front, as well as force and moment coefficients.
3) Detailed assessment of the transition models supplemented by stability analysis, which will be used in conjunction with the wind tunnel data to identify the shortcomings of the models and possible ways to remediate those shortcomings. It is envisioned that the details form the stability analysis (which are described in an accompanying paper by Paredes et al. [37]) will be utilized to replace some of the empirical correlations embedded within these models.

Acknowledgments

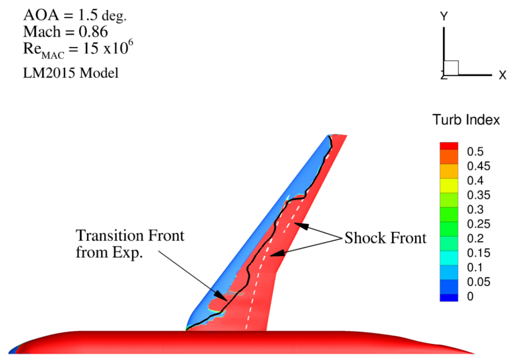
This research is sponsored by the NASA Transformational Tools and Technologies (TTT) project of the Transformative Aeronautics Concepts Program under the Aeronautics Research Mission Directorate. The first two authors' research is funded through the National Institute of Aerospace (NIA) under the cooperative agreement 2A00 (Activity 201133).



(a) AFT 2017b Model

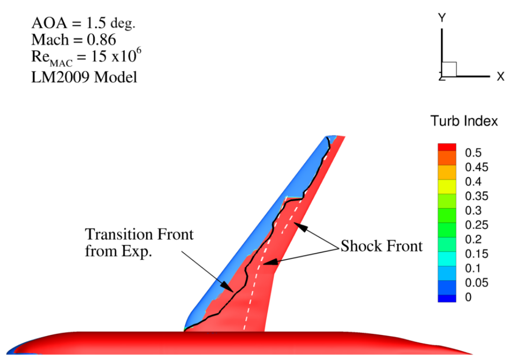


(b) LM2009 Model

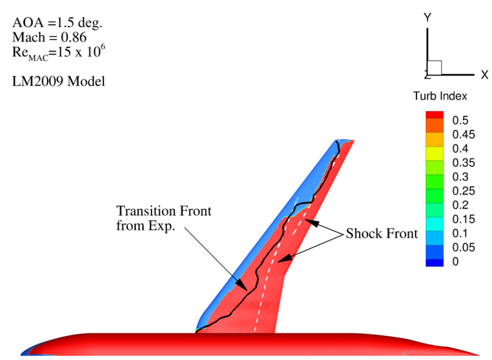


(c) LM2015 Model

Fig. 4. Comparison of the predicted transition behavior on the suction surface of the wing as depicted via turbulence index contours for selected transition models.



(a) Baseline Mesh



(b) Coarser mesh in chordwise resolution

Fig. 5. Assessment of the influence of chordwise grid spacing on the accuracy of the Langtry-Menter transition model (LM2009).

References

[1] Slotnick, J., Khodahoust, A., Alonso, J., Darmofal, D., Gropp, W., and Mavriplis, D., "CFD Vision 2030 Study: A Path to Revolutionary Computational Aerosciences," NASA/CR-2014-218178, 2014.

[2] Smith, A. M. O., and Gamberoni, N., "Transition, Pressure Gradient and Stability Theory," Douglas Aircraft Company, Long Beach, Calif. Rep. ES 26338, 1956.

[3] van Ingen, J. L., "A Suggested Semi-Empirical Method for the Calculation of the Boundary Layer Transition Region," University of Delft, Dept. of Aerospace Engineering, Delft, The Netherlands, Rep. VTH-74, 1956.

[4] Herbert, T., "Parabolized Stability Equations," *Annu. Rev. Fluid Mech.,* 29:245-283, 1997.

[5] Drela, M. and Giles, M. B., "Viscous-Inviscid Analysis of Transonic and Low Reynolds Number Airfoils," *AIAA Journal*, Vol. 25, No. 10, 1987, pp. 1347–1355.

[6] Drela, M., "Implicit Implementation of the Full e^N Transition Criterion," AIAA Paper 2003-4066, 2003.

[7] Cliquet, J., Houdeville, R., and Arnal, D., "Application of Laminar-Turbulent Transition Criterial in Navier-Stokes Computations," *AIAA Journal*, Vol. 46, No. 5, 2008, pp. 1182-1190.

[8] Perraud, J., Arnal, D., Casalis, G., Archambaud, J.-P., and Donelli, R., "Automatic Transition Predictions Using Simplified Methods," *AIAA Journal*, Vol.47, No. 11, 2009, pp. 2676-2684.

[9] Krumbein, A., Krimmelbein, N., and Schrauf, G., "Automatic Transition Prediction in a Hybrid Flow Solver – Part 1: Methodology and Sensitivities", *Journal of Aircraft*, Vol. 46, No. 4, 2009, pp. 1176 – 1190.

[10] Krumbein, A., Krimmelbein, N., and Grabe, C., "Streamline-Based Transition Prediction Techniques in an Unstructured Computational Fluid Dynamics Code", *AIAA Journal*, Vol. 55, No. 5, 2017, pp. 1548–1564.

[11] Campbell, R., Campbell, M., and Streit, T., "Progress Toward Efficient Laminar Flow Analysis and Design", AIAA 2011-3527.

[12] Davis, M. B., Reed, H. L., Youngren, H., Smith, B., and Bender, E., "Transition Prediction Method Review Summary for the Rapid Assessment Tool for Transition Prediction (RATTraP)," Technical Report AFRL-VA-WP-TR-2005-3130, Air Force Research Lab, Wright-Patterson AFB, OH, 2005.

[13] Stock, H. W., and Haase, W., "Navier-Stokes Airfoil Computations with e^N Transition Prediction Including Transitional Flow Regions," *AIAA Journal,* Vol. 38, No. 11, 2000, pp. 2059–2066.

[14] Warren, E. S., and Hassan, H. A., "Transition Closure Model for Predicting Transition Onset," *Journal of Aircraft*, Vol. 35, No. 5, September- October 1998, pp. 769-775.

[15] Edwards, J. R., Roy, C. J., Blottner, F. G., and Hassan, H. A., "Development of a One-Equation Transition/Turbulence Model," *AIAA Journal*, Vol. 39, No. 9, 2001, pp. 1691-1698.

[16] Walters, D. K., and Leylek, J. H., "A New Model for Boundary-Layer Transition Using a Single-Point RANS Approach," *ASME J. of Turbomach*, Vol. 126(1), 2004, pp. 193–202.

[17] Menter, F. R., Langtry, R. B., and Völker, S., "Transition Modelling for General Purpose CFD Codes," *J. Flow, Turbulence and Combustion,* Vol.77, 2006, pp.277–303.

[18] Langtry, R. B., and Menter, F. R., "Correlation-Based Transition Modeling for Unstructured Parallelized Computational Fluid Dynamics Codes," *AIAA Journal*, Vol. 47, No. 12, 2009, pp.2894–2906.

[19] Medida, S., and Baeder, J., "Application of the Correlation-based the γ-$\mathrm{Re}_{\theta t}$ Transition Model to the Spalart-Allmaras Turbulence Model", AIAA Paper 2011-3979, 2011.

[20] Ge, X., Arolla, S., and Durbin, P., "A Bypass Transition Model Based on the Intermittency Function," *J. Flow Turbulence and Combustion,* Vol.93, 2014, pp. 37–61.

[21] Song Fu, A., Wang, L., "RANS modeling of high-speed aerodynamic flow transition with consideration of stability theory", *Progress in Aerospace Sciences*, Vol. 58, 2013, pp. 36-59.

[22] Coder, J.G., and Maughmer, M.D., "Computational Fluid Dynamics Compatible Transition Modeling Using an Amplification Factor Transport Equation," *AIAA Journal*, Vol. 52, No. 11, 2014, pp.2506–2512.

[23] Coder, J.G., "Further Development of the Amplification Factor Transport Transition Model for Aerodynamic Flows," AIAA Paper 2019-0039, 2019.

[24] Medida, S., "Correlation-based Transition Modeling for External Aerodynamic Flows," University of Maryland PhD Dissertation, 2014.

[25] Krumbein, A., Krimmelbein, N., Grabe, C. and Shengyang, N., "Development and Application of Transition Prediction Techniques in an Unstructured CFD Code," AIAA Paper 2015-2476, 2015.

[26] Lynde, M. N., and Campbell, R. L., "Computational Design and Analysis of a Transonic Natural Laminar Flow Wing for a Wind Tunnel Model," AIAA Paper 2017-3058, 2017.

[27] Rivers, M., Lynde, M., Campbell, R., Viken, S., Chan, D., Watkins, A., and Goodliff, S., "Experimental Investigation of the NASA Common Research Model with a Natural Laminar Flow Wing in the NASA Langley National Transonic Facility", AIAA Paper 2019-2189, 2019.

[28] Lynde, M. N., Campbell, R. L., Rivers, M. B., Viken, S. A., Chan, D. T., Watkins, A. N., and Goodliff, S. L., "Preliminary Results from an Experimental Assessment of a Natural Laminar Flow Design Method," AIAA Paper 2019-2298, 2019.

[29] 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 2019-2298, 2019.

[30] Nichols, R. H, and Buning, P. G., "User's Manual for OVERFLOW 2.2, Version 2.2," NASA Langley Research Center, Hampton, VA, Aug 2010.
[31] Choi, J. H., and Kwon, O. J., "Recent Improvement of a Correlation-based Transition Model for Simulating Three-Dimensional Boundary Layers", *AIAA Journal*, Vol. 55, No. 6, 2017, pp. 2103–2108.
[32] Langtry, R. B., Sengupta, K., Yeh, D. T., and Dorgan, A. J., "Extending the γ-$\mathrm{Re}_{\theta t}$Correlation based Transition Model for Crossflow Effects," AIAA Paper 2015-2474, 2015.
[33] Medida, S., and Baeder, J., "A New Crossflow Transition Onset Criterion for RANS Turbulence Models," AIAA Paper 2013-3081, 2013.
[34] Nie, S., Krimmelbein, N., Krumbein, A., and Grabe, C., "Extension of a Reynolds-Stress-Based Transition Transport Model for Crossflow Transition," *Journal of Aircraft*, Vol. 55, 2018, pp. 1641–1654.
[35] Grabe, C., Shengyang, N., and Krumbein, A., "Transport Modeling for the Prediction of Crossflow Transition," *AIAA Journal*, Vol. 56, No. 8, 2018, pp. 3167–3178.
[36] Choi, J., and Kwon, O. J., "Enhancement of a Correlation-Based Transition Turbulence Model for Simulating Crossflow Instability", AIAA Paper 2014-1133, 2014.
[37] Paredes, P., Venkatachari, B., Choudhari, M., Li, F., Hilderbrand, N., and Chang, C. L., "Transition Analysis for the CRM-NLF Wind Tunnel Configuration," submitted to AIAA Scitech Forum, 2021.
[38] Paredes, P., Venkatachari, B., Choudhari, M., Li, F., Chang, C. L. and Xiao, H., "Toward Transition Modeling in a Hypersonic Boundary Layer at Flight Conditions," AIAA Paper 2020-0103, 2020.
[39] Vassberg, J.C., DeHaan, M.A., Rivers, M.S. and Wahls, R.A., "Retrospective on the Common Research Model for Computational Fluid Dynamics Validation Studies," *Journal of Aircraft*, Vol. 55, 2018, pp.1325–1337.
[40] Campbell, R. L., "Efficient Viscous Design of Realistic Aircraft Configurations," AIAA Paper 1998-2539, 1998.
[41] Campbell, R. L., and Lynde, M. N., "Natural Laminar Flow Design for Wings with Moderate Sweep," AIAA Paper 2016-4326, 2016.
[42] Menter, F. R., "Two-Equation Eddy-Viscosity Turbulence Models for Engineering Applications," *AIAA Journal*, Vol. 32, No. 8, 1994, pp. 1598-1605.
[43] Menter, F. R., Kuntz, M., and Langtry, R., "Ten Years of Industrial Experience with the SST Turbulence Model," *Turbulence, Heat and Mass Transfer*, Vol. 4 (1), 2003, pp. 625 - 632.
[44] Spalart, P. R. and Allmaras, S. R., "A One-Equation Turbulence Model for Aerodynamic Flows," *Recherche Aerospatiale*, No. 1, 1994, pp. 5-21.
[45] Medida, S., and Baeder, J., "A New Crossflow Transition Onset Criterion for RANS Turbulence Models", AIAA Paper 2013-3081, 2013.
[46] Crouch, J., Sutanto, M., Witkowski, D., Watkins, A., Rivers, M., and Campbell, R., "Assessment of the National Transonic Facility for Natural Laminar Flow Testing," AIAA Paper 2010-1302, 2010.
[47] Roe, P. L., "Approximate Riemann Solvers, Parameter Vectors, and Difference Schemes," *J. Comput Phys.,* Vol. 43, No. 2, 1981, pp. 357–372.
[48] Nichols, R. H., Tramel, R. W., and Buning, P. G., "Solver and Turbulence Model Upgrades to OVERFLOW 2 for Unsteady and High-Speed Applications," AIAA Paper 2006-2824, 2006.
[49] Sclafani, A., Slotnick, J., Vassberg, J. and Pulliam, T., "Extended OVERFLOW Analysis of the NASA Trap Wing Wind Tunnel Model," AIAA Paper 2012-2919, 2012.