Study of Laminar-Turbulent Transition Modeled by Amplification Factor Transport within the LAVA Solver

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The Amplification Factor Transport (AFT) transition model proposed by Coder and Maughmer[1] is implemented in the unstructured and curvilinear Reynolds-Averaged Navier-Stokes (RANS) solvers of the Launch Ascent and Vehicle Aerodynamics (LAVA) platform.[2] It is coupled to the Spalart-Allmaras (SA) turbulence model through a modified intermittency variable. As part of the model verification and validation phase, laminar-turbulent transition is studied over 2D flat plates, wind turbine and general aviation airfoils, as well as a 3D inclined prolate spheroid and the JAXA Standard Model (JSM).[3] This work will analyze the sensitivity of the results to grid refinement, grid paradigm, flow conditions and numerical schemes. The numerical efficiency of the unstructured and curvilinear solvers will be compared and convergence acceleration techniques will be explored to address a broad range of aerodynamics applications.

I. Introduction

Predictive laminar-turbulent transition modeling that does not require prescribed transition is a critical objective for the design and optimization of internal and external aerodynamic components beyond the limitations of a fully turbulent flow assumption. The Amplification Factor Transport (AFT) transition model proposed by Coder and Maughmer has made new strides towards this goal.[4,5] The model, henceforth labeled AFT2017a, is based on linear stability theory and relies on the approximate envelope method, wherein the envelope amplification factor is a measure of boundary layer instability growth.[6] Because it carries information about the upstream boundary layer history, it compares favorably with the local-correlation transition model of Langtry and Menter[7] for the computation of aerodynamic loads under pressure gradient. In a recent model extension, a modified intermittency transport equation based on Menter's model[8] was coupled to the amplification factor equation.[1] This newer version of the transition model, here labelled AFT2017b, was applied at the *3rd AIAA CFD High Lift Prediction Workshop (HLPW3)*,[9] where it was shown to significantly improve stall predictions compared to fully turbulent Spalart-Allmaras (SA) simulations. The present work offers a study of different implementations of the AFT2017b model into the LAVA unstructured and curvilinear solvers.

II. Numerical framework

The Launch Ascent and Vehicle Aerodynamics (LAVA) framework is a general purpose CFD solver suite that supports three types of grid paradigms: Cartesian with immersed boundaries and Adaptive Mesh Refinement (AMR), arbitrary polyhedral unstructured grids, and curvilinear body-fitted overset meshes.[2] Body-fitted grids are currently better suited for the study of transitional flow, therefore the last two solvers are used in this work. The LAVA-unstructured solver utilizes a cell-centered, 2nd order accurate MUSCL scheme with piecewise linear reconstruction to cell faces.[10] The gradient operators are computed by the Green-Gauss method with compact stencil.[11] The fluxes at the faces are evaluated using the AUSMPW+ or HR-SLAU2 flux functions.[12,13] First order backward differencing (BDF) implicit time integration is performed with the GMRES linear solver in PETSc.[14] The unstructured grids are generated using

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the StarCCM+ software.[15] In the curvilinear viscous RANS solver, the steady-state equations are solved with time-marching using a modified Roe scheme for the convective flux,[16] with 2nd order upwind scheme or a 6th order Hybrid Weighted Compact Nonlinear Scheme (HWCNS)[17,18] combined with 5th order upwind biased left and right state interpolation (WENO-Z).[19] A 2nd order accurate central difference scheme is used for the viscous terms. The solver uses high-order accurate free-stream preserving metric terms[20] and alternating line-Jacobi relaxation (2 sweeps). The grids are generated using Chimera Grid Tools.[21] In both solvers, the one-equation eddy-viscosity Spalart-Allmaras (SA) turbulence model[22] is combined with the Rotation and Curvature (RC)[23] and Quadradratic Constitutive Relation (QCR2000) corrections.[24] A version of the SA model allowing for negative turbulent eddy viscosity (SA-neg) is also available.[25] For transition simulation, the SA model is coupled to the two AFT transport equations for the amplification factor and the intermittency (= natural logarithm of the actual intermittency).[1] The SA-AFT equations can be solved sequentially within an outer iteration of the solver, or optionally in the unstructured solver as a combined linear system of three transport equations. The first implementation allows advancing the solution at different CFL numbers, which has proven useful in the unstructured solver where the SA-model tends to require smaller step sizes. The second approach improves coupling through the usage of same-iteration variables and cross-Jacobians terms, and eliminates the overhead associated with an extra GMRES solver call.

III. Test cases and grids

The cases under study are listed in Table 1. They are run at a freestream temperature of 300K and freestream pressure of 1.01353×10^5Pa, except for the HLPW3 case C.[9] Most of these cases were recommended for the *AIAA Applied Aerodynamics CFD Transition Modeling and Predictive Capabilities Special Session* (TMS) at the Scitech Forum 2018.[26] A grid refinement study is conducted for each case. For the 2D bump in a channel and the flat plate, the structured and unstructured hexahedral grids from the Turbulence Modeling Resource (TMR) homepage[27] were used. Custom 2D bump grids were also generated. For case 0B the TMR grids were used as well, and for cases 1A-B we used the grids provided by the TMS Committee. For the airfoils of cases 2 and 3, the LAVA-curvilinear simulations were run on the TMS grids, whereas hexahedral versions of these grids were derived for LAVA-unstructured. Additionally, custom polyhedral grids with wake refinement were generated using StarCCM. The spheroid was only simulated with the unstructured code. Because LAVA is currently optimized for generalized polyhedral grids, the tetrahedral grids provided by the TMS Committee were converted to polyhedral grids using the ANSA software.[28] For case C, the overset and unstructured grids that we previously generated for the HLPW3 were used. A description of these grids and simulation results can be found in Ref. [29].

Table 1: Case list

Label	Case	Description	M	Re_1
0A	2D bump in channel	Turbulence model verification study	0.2	3×10^6
0B	2D zero-pressure-gradient flat plate	AFT model implementation verification	0.2	5×10^6
1A,B	2D zero-pressure-gradient flat plate	2 different turbulence intensities and eddy viscosity ratios	0.2	2×10^5
2	2D S809 wind-turbine airfoil	Grid refinement study at AOA = 1°, 6° and 9°	0.1	2×10^6
3A,B	2D NASA NLF(1)-0416 general aviation airfoil	Grid resolution study at AOA = 0° and 5°; AOA sweep $[-4° : 2° : 8°]$	0.2	4×10^6
4	3D Inclined, 6:1 prolate spheroid	AOA = 5°, 10° and 15°	0.13	6.5×10^6
C	3D JAXA Standard Model (JSM)	AOA = 4 to 21°	0.172	1.7×10^6

IV. Outline of the work

The 2D bump in a channel is used to verify the baseline turbulence model, in our case the SA-RC-QCR2000 with negative option. The first flat plate case is used to verify our code implementation against the results reported in the Ref. [5]. Fig. 1 shows a preliminary comparison of the skin friction coefficient from LAVA simulations with the

AFT2017b model, Overflow[30] simulations with the AFT2017a model, and from experiments. The next four cases (1-4) will be used in an extensive sensitivity study including grid refinement, grid and element type, angle of attack, freestream inflow turbulence and eddy viscosity ratio. The effect of limiters and flux functions will also be investigated, as we observed a variation of the transition location when comparing AUSMPW+ with HR-SLAU2. The 3D prolate spheroid is intended for the study of cross-flow, for which the AFT model in its current form is expected to show some limitations. Finally, the JSM will be used as a vehicle to test the readiness of our code for engineering-type applications. In particular, rate of convergence and robustness are current areas that require further optimization. Different types of acceleration methods will be investigated.

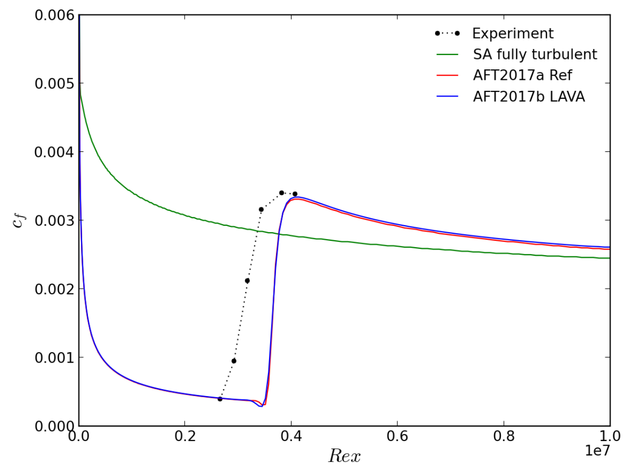

Figure 1: Flat plate simulation at a unit Reynolds number of 5×10^5, $M = 0.2$ at $T = 300K$ using the second finest TMR grid with 273x193 grid points. The experimental data are from Schubauer and Skramstad[31] and the AFT2017a results are taken from Ref. [5]

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