

Computational Study of Low-Speed Boundary-Layer Laminar-Turbulent Transition over a 30° Swept Plate in a Channel

Marie F. Denison¹, Jenna L. Eppink², and Joshua K. Smith³

¹NASA Ames Research Center, Moffett Field CA 94035

²NASA Langley Research Center, Hampton, VA 23681

³University of Arizona, Tucson AZ 85721

Reliable boundary-layer laminar-turbulent transition predictions are critical for the design of aircraft that use natural or controlled laminar flow to achieve low drag and better fuel efficiency. During cruise flight through low turbulence, the three-dimensional boundary layer over swept surfaces can transition prematurely due to stationary crossflow instabilities induced by surface roughness. Parabolized stability equations analyses have been successfully used to explain the different phases of the transition process under well controlled perturbations such as steps or discrete roughness elements. However, methodologies are still lacking to model the boundary layer receptivity to distributed random roughness, and the following non-linear instability stages leading to transition. For engineering applications, several semi-empirical methods based on linear amplification factors or local helicity have found growing adoption, but their reliability is limited by their level of simplification and the sparsity of data they are based on. To address this gap, a new study of the effect of distributed random surface roughness on crossflow transition was started, using a 30° swept plate as a test vehicle. The plate, which is mounted in the 2 Foot $\times$ 3 Foot Low-Speed Boundary-Layer Channel at the NASA Langley Research Center, has been tested with micro-scale roughness of varied geometry near the leading edge. In order to analyze the flow in the test section and prepare Direct Numerical Simulations with resolved roughness, Reynolds-Averaged Navier-Stokes (RANS) simulations of the flow over the plate installed in the wind tunnel test section were performed using the Langtry-Menter transition model with stationary crossflow extension. This paper presents the results of these simulations, with comparison to the experiment.

Nomenclature

c	=	Maximum chord length (2.54 m)
C_{dv}	=	Viscous drag coefficient
C_{dp}	=	Pressure drag coefficient
c_p	=	Pressure coefficient per unit span
h_{RMS}	=	Roughness root-mean-square height
i_t	=	Transition index
k	=	Turbulence kinetic energy
M	=	Mach number
T_s	=	Static temperature
Re_1	=	Reynolds number per grid unit (c)
Re	=	Reynolds number
$Re_{\theta t}$	=	Local transition onset momentum-thickness Reynolds number
Re_{SCF}	=	Stationary crossflow correlation number
Tu	=	Turbulence intensity $\sqrt{2k/3}/u$
u, v, w	=	Velocity components in Cartesian coordinates
u_τ	=	Viscous velocity
$\vec{U}$	=	Velocity vector

$\vec{\Omega}$	=	Vorticity vector
x, y, z	=	Cartesian coordinates
x_l	=	Streamwise coordinate of the plate leading edge
x/c	=	Shorthand notation for $(x - x_l)/c$
x_i	=	Streamwise coordinate of the inflow plane of the computational domain
x_{tr}	=	Streamwise coordinate of transition
β, β^*	=	Coefficients in dissipation terms of the SST model
γ	=	Intermittency
λ	=	Crossflow wavelength
ρ	=	Density
μ	=	Molecular viscosity
ν	=	Kinematic viscosity
μ_t	=	Turbulent viscosity
μ_{tr}	=	Turbulent-to-laminar viscosity ratio μ_t/μ
ω	=	Specific turbulence dissipation rate
∞	=	Subscript for values at the inflow plane of the computational domain

I. Introduction

Natural Laminar Flow (NLF), Laminar Flow Control (LFC) and Hybrid Laminar Flow Control (HLFC) are the three main design methods used to sustain laminar flow over part of an airframe to reduce its drag [1]. Under low turbulence intensity, as encountered during cruise flight or in quiet wind tunnels, the three-dimensional laminar boundary layer over swept surfaces (such as wings, control surfaces, or engine nacelles) can undergo premature laminar-turbulent transition due to stationary crossflow (CF) instabilities induced by surface irregularities such as panel junctures, rivets, or distributed surface roughness. Surface roughness can, for example, originate from material properties, such as paint or specialty coats, or from operating conditions leading to erosion, corrosion or accretion. Under favorable pressure gradient, typically near the leading edge, a predominantly inviscid inflectional instability leads to the exponential growth of small surface perturbations to form stationary crossflow vortices approximately aligned with the inviscid flow. The stationary CF instabilities saturate as mean flow alteration, non-linear instabilities and traveling crossflow vortices lead to the flow breakdown to a turbulent state [2, 3].

Crossflow transition driven by small-amplitude discrete and distributed perturbations has been studied extensively by means of experiments, linear stability, parabolized stability equations (PSE) and Direct Numerical Simulation (DNS) analyses [4–13]. However, we still lack models and methods to predict transition induced by random roughness of any given geometry, as characterized by parameters such as root-mean-square (RMS) height, solidity, skewness, wavelength spectrum, or auto-correlation length. So far, quantitative analyses of CF transition induced by random roughness have been challenged by the rich spectral content and three-dimensionality of the perturbation field [10], as well as a lack of experimental data and DNS validated by measurements to test hypotheses. Recently, Ustinov [14] proposed a method to compute the amplitudes and spectra of steady crossflow instability modes generated by random surface roughness, using adjoint parabolized stability equations to describe non-local receptivity to roughness elementary waves. Ustinov noted that when the roughness is unknown, the initial amplitude of most amplified modes is proportional to the product of the roughness amplitude and its characteristic length, but not to its amplitude only. In Ref. [15], the receptivity to micron-sized roughness elements was found to be a linear function of the roughness height, a behavior referred to as superlinearity. Theoretical work also suggests that specific wavenumbers may induce perturbations that cause resonant coupling between eigenmodes, in which case linear superposition does not apply [16]. A recent DNS parametric study of the interaction between the roughness-induced disturbance and free stream turbulence (FST) indicates that the spectral and spatial distribution of FST should be considered when modeling FST numerically [17]. Further analyses are needed to provide a comprehensive description of transition processes induced by micron-scale random surface roughness.

Given the complexity and limitations of PSE and DNS-based methods, engineering methods based on semi-empirical correlations have been developed in recent years for the study of CF induced transition in practical configurations. Such correlations have been implemented, for example, for the evaluation of linear amplification factors in e^N methods [18], and in the local helicity-based crossflow extensions of the Langtry-Menter model [19] and Coder and Maughmer's

Amplification Factor Transport (AFT) model [20]. These methods have been successfully applied to a number of cases, but lack consistency and generality as a result of simplifying assumptions and limited validation data. In particular, the empirical correlations are often based on a single roughness parameter such as the RMS roughness height. The Langtry-Menter model was calibrated based on the transition measurements over the 45° -swept wing NLF(2)-0415 by Radeztsky [4] assuming free-air flow, resulting in transition taking place too far downstream when considering the wind tunnel walls [21]. Missing information on the roughness wavelength spectrum, the flow turbulence intensity and decay, and the boundary layer along the wind tunnel walls further complicate the development and validation of transition models.

To address these shortcomings, new experiments were started on a 30° swept plate mounted in the 2 Foot $\times$ 3 Foot Low-Speed Boundary-Layer Channel at LaRC [22]. Rough surfaces of different geometric characteristics have been fabricated by nano-coating and applied to the plate leading edge. The flow over a plate with a smooth surface was characterized to establish a baseline, and so far the flow over two rough panels was characterized by Particle Image Velocimetry (PIV). This paper presents Reynolds Averaged Navier-Stokes (RANS) simulations of transition over the plate with and without surface roughness using the Langtry-Menter model with crossflow extension, with comparisons to measurements. The paper is organized as follows: Section 2 describes the test facility, article, conditions and methods including the newly implemented PIV setup. Section 3 describes the numerical methods, turbulence and transition models, computational domain and meshes. Section 4 presents the simulation results with comparison to experiments, followed by conclusions and an outlook on future work.

II. Geometry and Test

Fig. 1 shows a sketch of the plate and a CAD drawing of its installation in the 2 Foot $\times$ 3 Foot Low-Speed Boundary-Layer Channel at LaRC. The 0.0127-m thick flat plate model consists of a 0.41-m long leading edge piece, swept at 30° , and a larger downstream piece. The model is 0.91 m wide (thus, spanning the width of the test section) and 2.54 m long on the longest edge. The facility is a closed circuit wind tunnel with a 0.61-m high by 0.91-m wide by 6.1-m long test section that can reach speeds of up to 45 m/s ($Re_l = 2.87 \times 10^6/m$) in the test section. Freestream turbulence intensity levels were measured close to the leading edge using a crosswire in an empty test section to be less than 0.05% for the test speed of 26.5 m/s. The flow conditions for the tests are listed in Table 1.

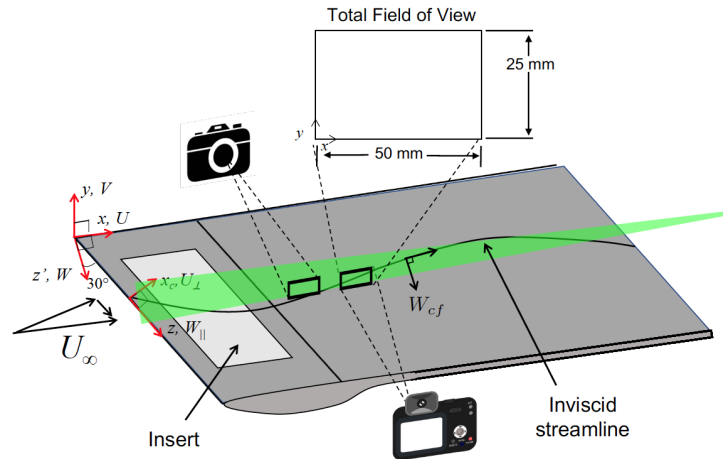


Fig. 1 Sketch of model coordinate system and time-resolved PIV setup. The white rectangle over the leading edge insert indicates the area where the roughness is applied.

Particle-Image Velocimetry measurements were done with a high-speed double-pulsed Nd:YLF laser (Fig. 1). The laser sheet was oriented in the streamwise direction, with two cameras in a 2D-PIV configuration, each with 300 mm lenses, achieving a total field of view of approximately 50 mm by 25 mm, and allowing measurement of the u - and

M_∞	u_∞	$T_{s\infty}$	Re	Tu_0	ρ_∞
0.077	26.5 m/s	294 K	$1.69 \times 10^6/\text{m}$	0.05%	$1.2 \times 10^{-5} \text{ kg/m}^3$

Table 1 Flow conditions for the wind-tunnel tests

v -velocity components. The in-plane spatial resolution was approximately 0.15 mm. All elements of the PIV system are mounted on traversing stages, which allows for streamwise and spanwise movements of the measurement plane. The system was traversed parallel with the leading edge, and the measurement domain covered approximately 100 mm or 10 wavelengths of the primary stationary-crossflow mode over 120 planes.

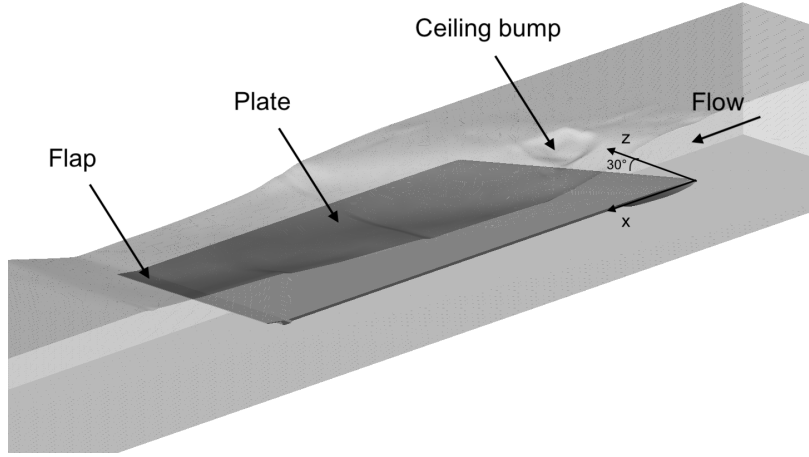


Fig. 2 Swept plate and wind tunnel test section geometry

A 3D pressure body along the ceiling was designed to induce a streamwise pressure gradient, which, along with the sweep, causes stationary crossflow growth (Fig. 2). A second purpose of the ceiling liner was to simulate infinite swept-wing flow within a midspan measurement region of width 0.3 meters. A flap was added to adjust the location of the attachment line, which in turn controls the streamwise pressure distribution. The boundary layer thickness along the ceiling was measured at a distance $(x - x_{le})/c = 0.55$ from the leading edge, and was estimated as $\delta_c \approx 8\text{ mm} \pm 1\text{ mm}$ at the centerline $z/c = 0.18$. Note that in the remaining of the paper, x/c is used as a shorthand notation for $(x - x_{le})/c$, unless specified otherwise. Since no pressure taps were included in the model, pressure belts were temporarily installed to measure the surface pressure distribution. The precision of these measurements is uncertain, and there is a possibility that the belts had a slight effect on the flow. The leading edge piece was designed to include an insert that could be used to study different random roughness coatings. This insert extends from approximately $x/c = 0.0185$ to $x/c = 0.14$ (after subtraction of a 1-inch mask applied before nano-particle coating) and spans a width of 457 mm (the middle half of the model). The roughness panels were fabricated by spraying the panel surface with nanoparticles of varying size and weight ratio to obtain different roughness parameters. While the fabrication of new rough panels is still underway, three panels have been characterized so far: a baseline (no-added roughness) panel, and two rough test panels, TP1 and TP2. The root-mean-square (RMS) values, peak-to-peak values, and correlation lengths obtained from contact profilometry scans of each surface are given in Table 1.

Sublimating naphthalene was used to visualize the transition location. Since the sublimation rate of naphthalene is sensitive to shear stress, the chemical will sublimate faster in turbulent regions of the flow. Fig. 3 shows images obtained for the 3 panels. The wavelength of the crossflow vortices, which appear in the flow visualization as flow striations near the transition location, is $\lambda = 11.5 \text{ mm}$ in the direction parallel to the plate leading edge. The grid, which was drawn on the model and photographed prior to the tests, was unswept and undistorted to aid in visual interpretation of the results. Transition occurs close to mid-chord for all three panels, with little sensitivity to the roughness. On the other hand, analysis of the crossflow vortices indicate that their amplitude is significantly increased for

Panel	RMS height [μm]	Peak-to-peak height [μm]	Correlation length [m]	Mean x_{tr}
Baseline	0.42	1.79	153	0.5/0.5
TP1	8.64	39.36	385	0.498/0.474
TP2	4.78	20.68	1029	0.48/0.471

Table 2 Roughness Panel Parameters. The first value given for the mean transition location x_{tr} is averaged across the full measurement region from $z/c = 0.12$ to 0.24 . The second value is averaged across the PIV measurement region $z/c = 0.16$ to 0.20 .

the larger roughness of TP2. The reader is referred to Ref. [22] for detailed description of the tests, results and PSE analysis.

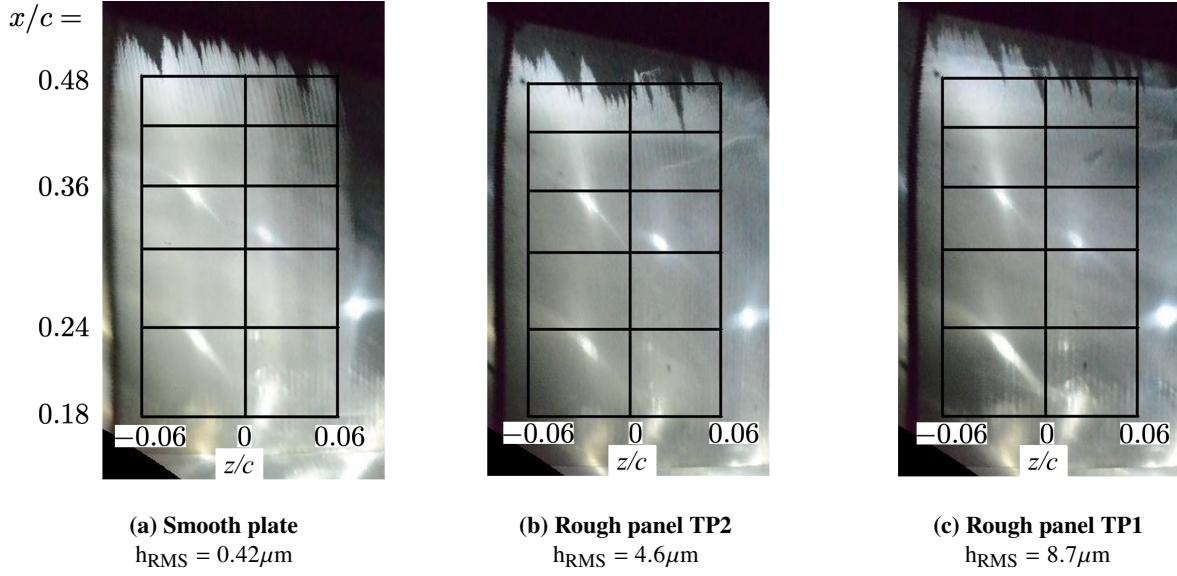


Fig. 3 Transition visualization by naphthalene sublimation. The leading edge of the plate is located on the bottom side.

III. Numerical methods

RANS simulations were run using the overset structured curvilinear solver OVERFLOW, version 2.3d [23]. Steady-state solutions were obtained by marching non-time accurately towards steady state, using the improved Successive Symmetric Overrelaxation (SSOR) implicit linear solver with CFL ramping, and the 3rd-order Roe upwind scheme to compute the explicit fluxes [24]. The Shear-Stress Transport turbulence model with rotation and curvature correction [25] and the Langtry-Menter 2-equation transition model with crossflow extension [19] were used. The two variables of the SST transport equations are the Turbulent Kinetic Energy (TKE) k , and the specific dissipation rate, ω . The turbulent viscosity is given by $\mu_t = \rho k / \omega$. The two variables of the Langtry-Menter transport equations are the intermittency, γ and the local transitional Reynolds number, Re_{θ_t} . In Langtry's crossflow model, the crossflow effect is implemented as a stationary crossflow sink term in the Re_{θ_t} transport equation, defined as follows:

$$DSCF \propto \min(Re_{SCF} - Re_{\theta_t}, 0) F_{\theta_t, 2}, \quad (1)$$

where the term $F_{\theta_t, 2}$ confines the crossflow sink term DSCF so that it is only active inside the laminar boundary layer. DSCF is active only when the stationary crossflow correlation Reynolds number Re_{SCF} drops below the transported onset criteria. Re_{SCF} is a decreasing function of the RMS roughness height derived from an empirical correlation to

Radeztsky's experiments on the 45° swept NLF(2)-0415 wing [4], augmented by linear stability calculations for other sweep angles. Re_{SCF} is also a function of a non-dimensional crossflow strength indicator based on the normalized local streamwise vorticity:

$$H_{CF} = \frac{y|\vec{\Omega} \cdot \vec{U}|}{U} \quad (2)$$

The model was calibrated using measurements over fully rough surfaces. In the present study, transition was observed at $x/c \approx 0.5$, downstream from the roughness patch, which ends at $x/c = 0.14$. Given the lack of validation of the model for cases with localized roughness patches, and considering that the region near the leading edge downstream of the attachment line typically is most receptive to the roughness, with little effect of the roughness farther downstream, the top side of the plate was modelled as a rough surface up to $x/c = 0.9$, unless specified otherwise.

The location of transition fronts was extracted using the turbulent index that Carnes recently refactored for the Langtry-Menter model [26]:

$$i_t = 6.1 \frac{1}{u_\tau^{2.346}} \frac{d(\nu k^{0.673})}{dy}, \quad (3)$$

where u_τ is the friction velocity and ν is the laminar kinematic viscosity. The threshold $i_t = 0.5$ was used.

Assuming the measured turbulence intensity $Tu_0 = 0.05\%$ at the leading edge of the plate x_l at the centerline, and a specific dissipation rate $\omega_0 = 5U_\infty/c$ [27], the boundary conditions for the SST variables at the inflow plane x_i were obtained from the decay functions [28]

$$\begin{aligned} Tu_\infty &= Tu_0 \left(1 + \frac{3Re_1(x_i - x_l)\beta Tu_0^2}{2\mu_{tr0}} \right)^{\frac{-0.5\beta^*}{\beta}} \\ \mu_{tr\infty} &= \mu_{tr0} \left(1 + \frac{3Re_1(x_i - x_l)\beta Tu_0^2}{2\mu_{tr0}} \right)^{1 - \frac{\beta^*}{\beta}} \end{aligned} \quad (4)$$

where $\mu_{tr} = \mu_t/\mu$, μ is the dynamic viscosity, and Re_1 is the unit Reynolds number. Measurements of the turbulence intensity decay are planned at the end of the test campaign to verify the range of specific dissipation rate and with it, μ_{tr} .

Adiabatic viscous boundary conditions based on pressure extrapolation were used at the walls. The outflow to inflow static pressure ratio was adjusted to align the pressure profile over the laminar boundary layer with the pressure belt measurements. At the inflow plane, total pressure and temperature boundary conditions were specified based on the reference flow conditions of Table 1.

The CAD geometry of the computational domain is shown in Fig. 2. An earlier version was used in preliminary simulations, but it became clear that some features were not represented with sufficient fidelity, notably the bump in the ceiling over the plate. As the shape of the ceiling is critical to reproduce the pressure gradient over the laminar region, a laser scan of the facility was arranged. Frame elements supporting the plate were omitted and small irregularities in the ceiling profile were smoothed, while keeping larger scale features.

Overset curvilinear grids were generated using Chimera Grid Tools (CGT) [29]. The inflow plane of the test section starts at 0.5 chord upstream from the leading edge of the plate. The mesh is comprised of 9 overset grids: the top of the plate, the grid over the top plate where the leading edge panel surface roughness is imposed, the bottom of the plate, a capping grid at the trailing edge of the flap, a refinement grid along the bump in the ceiling, and four tunnel grids (under, over, upstream and downstream of the plate, respectively). The grid where roughness is applied at the wall extends from the start of the rough insert at $x/c = 0.0185$ and ends at $x/c \approx 0.9$. X-ray bodies are used to blank grid cells from the tunnel grids inside of the plate and bump grids, with a minimum of 5 overlapping points. The plate and wind tunnel wall boundary layer grids were grown normally to the wall over a marching distance of the order of the boundary layer thickness, with a ratio of 1.2 or less depending on the grid refinement level, starting from the 5th grid point above the wall on the top side of the plate. Four grid refinement levels were generated, with the refinement parameters and resulting total grid sizes listed in Table 3. The baseline grid point spacing $\Delta s/c$ from which other spaces were computed is halved between each level. The stretching ratio in the boundary layers and the factor applied to the distance of the first

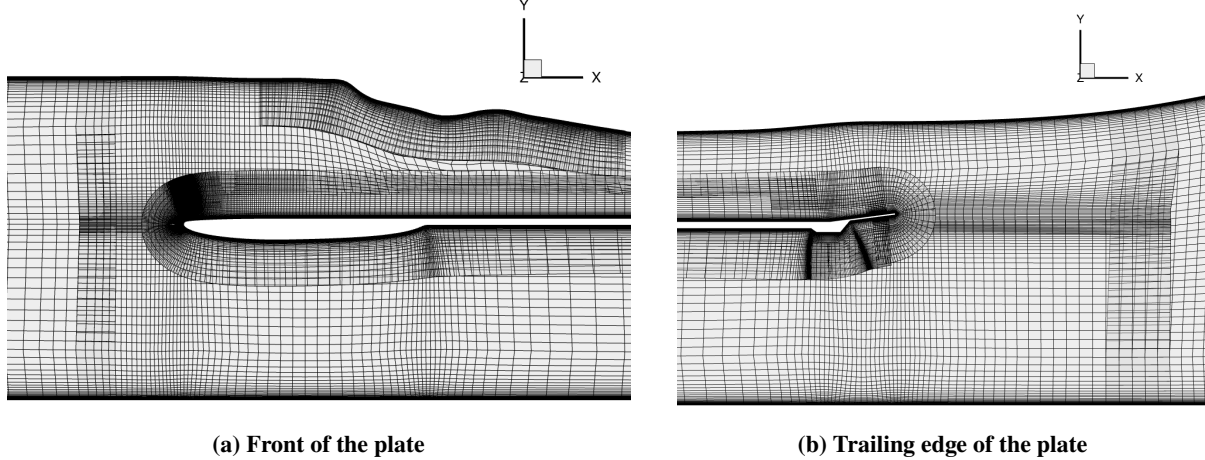


Fig. 4 Overset curvilinear structured mesh (coarse level)

Refinement	N	$\Delta s/c$	stretching ratio	Δy_w^+ factor
coarse	2.4×10^6	2×10^{-2}	1.2	1.0
Medium	6.7×10^6	1×10^{-2}	1.15	0.75
Fine	23.3×10^6	5×10^{-3}	1.1	0.5
Extra-fine	111×10^6	2.5×10^{-3}	1.05	0.25

Table 3 Total number of grid points and refinement parameters.

grid point from the wall Δy_w^+ are decreased linearly. The total number of grid points N is approximately 50 times larger than the coarsest grid. Fig. 4 shows views of the front and aft parts of the coarse grid system at the spanwise coordinate $z/c = 0.1$.

IV. Results and Discussion

Fig. 5 shows monotoneous convergence of the drag coefficient of the plate with grid refinement. The transition front computed for the smooth plate is located at $x/c > 0.6$ on the inboard side of the plate, downstream of the measured mid-chord location (Fig. 6). The results show little sensitivity to grid refinement for the three finest levels. The next results are shown for the fine grid.

Early design iterations of the grid system caused significant unsteadiness in the wake of the plate, due to poor resolution and mesh quality around the flap edges. In contrast, the final grids show good iterative convergence. The streamwise distribution of surface pressure is shown in Fig. 7, for different spanwise locations at $z/c = 0.12, 0.18$ and 0.24 . The static outflow to inflow pressure ratio was set to 0.9991 to capture the front of the measured c_p curve. The pressure is slightly higher than the pressure belt measurements over the second half of the plate. The thickness of the boundary layer over the center of the plate is about 5mm thick (Fig. 8), which is a few millimeters smaller than the measured value of $8 \pm 1mm$. Either a larger distance between the inflow plane of the computational domain and the leading edge of the plate, or an inflow boundary condition with boundary layer, will be implemented to increase the boundary layer thickness along the ceiling.

In Fig. 9, simulated streamwise velocity profiles at 3 midspan locations ($x/c = 0.27, 0.37$ and 0.41) are compared to the velocity range measured in the interval $z/c = [0.16, 0.2]$, for the smooth plate and the panel TP1 of larger roughness ($h_{RMS} = 8.7\mu m$). The simulated velocity is in the measured range. As expected, the spread in the experimental data increases downstream, as crossflow vortices increasingly deform the velocity profile. The crossflow vortices are not

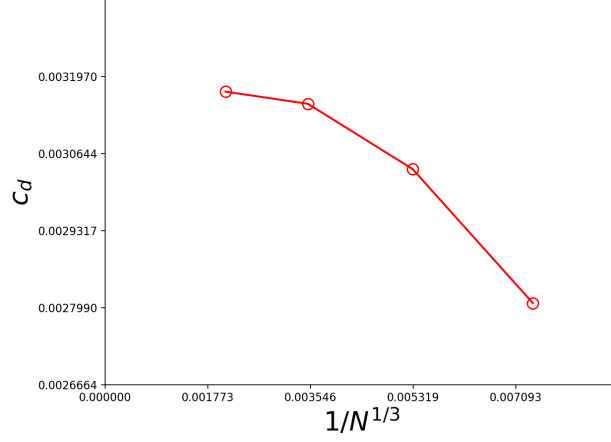


Fig. 5 Drag coefficient dependence on average grid resolution

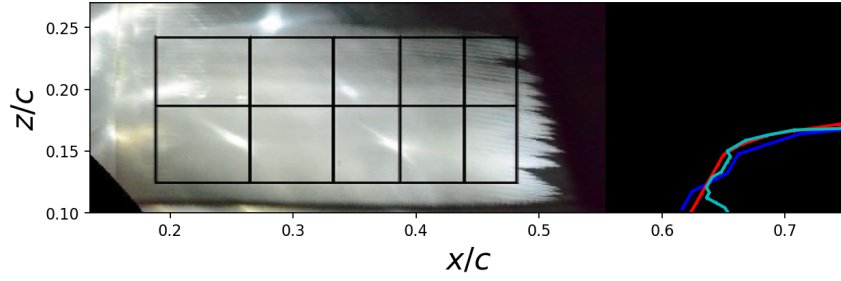


Fig. 6 Transition location over the smooth plate for the medium (blue), fine (red) and extra fine (cyan) grids, overlaid on the sublimation image.

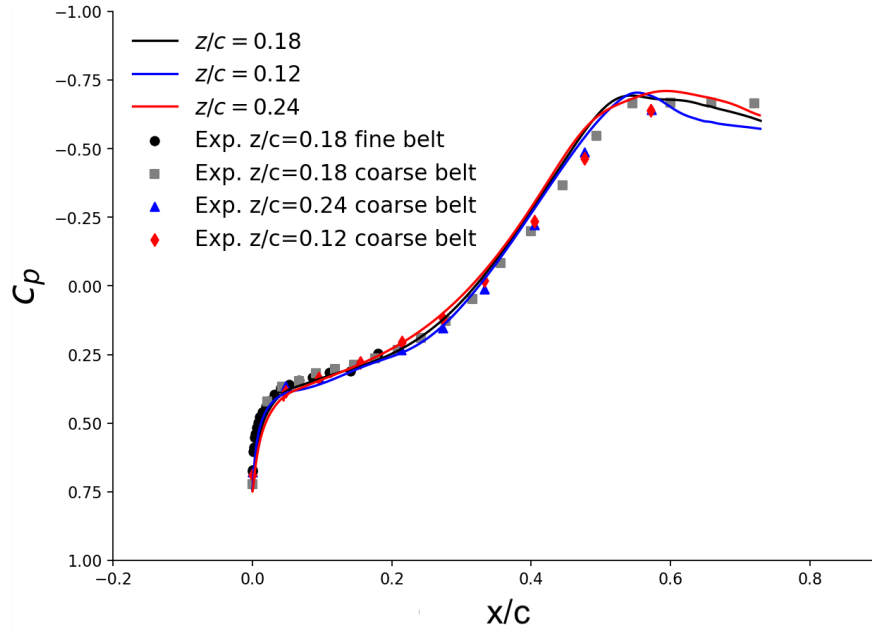


Fig. 7 Pressure Coefficient along the top of the plate at different spanwise locations.

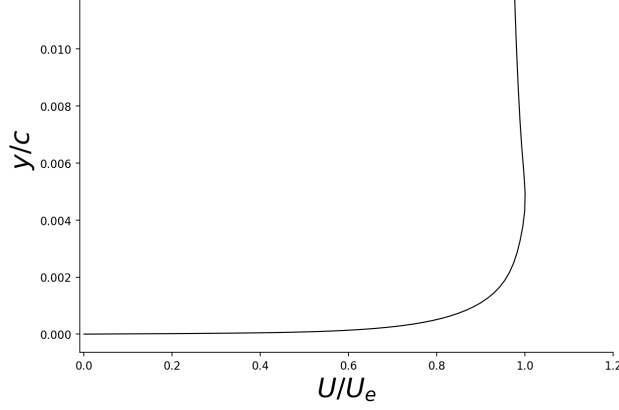


Fig. 8 Ceiling boundary layer profile at $x/c = 0.55$ at midspan.

modeled in the RANS simulations, which provide only the laminar baseflow solution upstream of the transition location. At $x/c = 0.27$, the roughness seems to cause larger amplitude crossflow deformations of the base flow than for the smooth case, whereas the flow deformations are comparable at $x/c = 0.37$.

Fig. 10 shows the transition fronts obtained for the smooth plate, panel TP1 and panel TP2, and an additional simulation case with $27\mu m$ RMS roughness height. Transition takes place on the inboard side of the plate. As the roughness increases, the transition front moves upstream, but remains downstream of $x/c = 0.55$. Transition downstream of the measurements is consistent with the observation made by Venkatachari in Ref. [21] when comparing predictions for the NLF(2)-0415 wing in free air and in the test section. Whereas predictions were close to the measurements in the free air case for which the model was calibrated, the transition front moved downstream when considering the wind tunnel with inviscid upper and lower walls. In the present study, the boundary layer along the wind tunnel walls was resolved, and the influence of the ceiling possibly caused additional departure from the free-air based calibration. In the experimental results, the location of the transition front shows little sensitivity to the roughness, and there is no spanwise transition asymmetry. Fig. 11 shows the crossflow strength indicator H_{CF} (III) at $x/c = 0.5$ and $x/c = 0.7$ for different spanwise coordinates, for panel TP2 with $h_{RMS} = 4.6\mu m$. At $x/c = 0.5$, H_{CF} is larger inboard, where the simulated transition takes place. At $x/c = 0.7$, H_{CF} is lower inboard due to the eddy viscosity increase accompanying transition. The model accounts for this effect through counteracting terms in the Re_{SCF} function so that it does not delay transition [19].

V. Conclusions

RANS simulation results were presented for transition over a 30° smooth swept plate with two micro-scale surface roughnesses characterized in the 2 Foot $\times$ 3 Foot Low-Speed Boundary-Layer Channel at the NASA Langley Research Center. The simulations were performed using the Langtry-Menter transition model with crossflow extension, coupled to the Shear-Stress Transport turbulence model. In this first part of the study, the roughness was applied over the top side of the plate up to $x/c = 0.9$ to avoid introducing effects from localized roughness areas for which the model has not been evaluated yet. Good overall agreement to the experiments was obtained for the pressure profile and velocity profiles in the laminar region. Transition was found to occur inboard only, consistently with the larger amplitude of the crossflow strength indicator in this region. The computed transition location was sensitive to the roughness RMS height in the measured range ($4.7 - 8.6\mu m$), with the most upstream point moving from $x/c = 0.635$ to $x/c = 0.55$. This differs from the experiment, where transition along the plate centerline was observed within $\Delta x/c = 0.02$ of mid-chord for all three panels. Transition predictions too far downstream relative to the experiments are qualitatively consistent with installation effects evaluated in Ref. [21] for the NLF(2)-0415 wing.

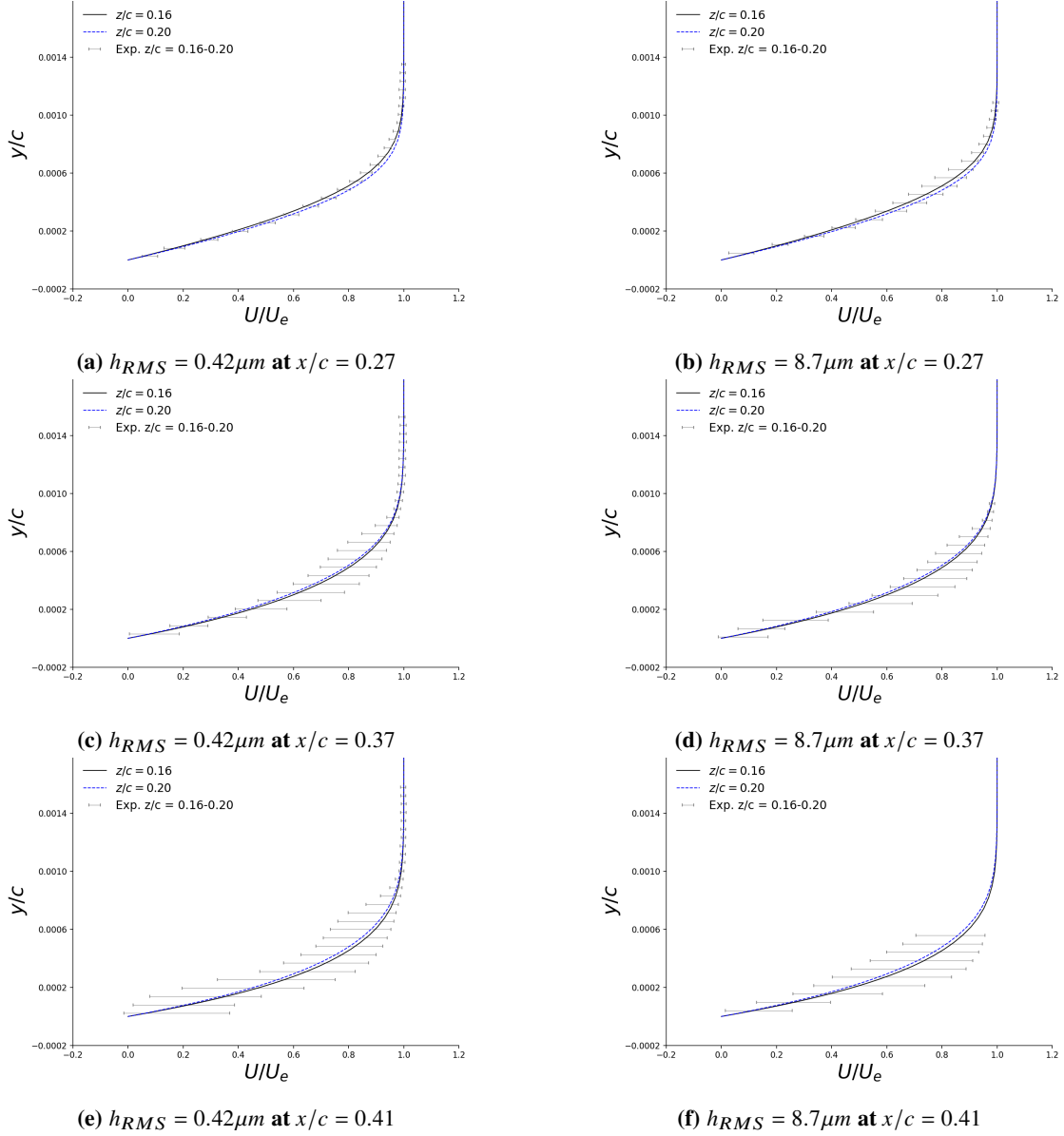


Fig. 9 Streamwise velocity profile at different streamwise locations (black line: simulation at $z/c = 0.16$, blue line: simulation at $z/c = 0.20$, horizontal bars: range of measurements in the interval $z/c = [0.16, 0.20]$ (measurement bands enlarged by outliers are not shown)).

Before revisiting the calibration of the crossflow model and evaluating it with rough regions of limited extent, the sensitivity of the results to possible sources of uncertainty needs to be assessed. For example, inspection of the flow field in the tunnel indicates that it is highly non-uniform, with large areas of streamwise vorticity along the ceiling and side walls of the test section. Adaptive mesh refinement will be used to ensure sufficient resolution of critical flow features. The inflow boundary condition will be adjusted so that the boundary layer thickness under the ceiling better matches the measurement at the centerline near mid-chord. Until turbulence decay data become available to calibrate μ_{tr} , the effect of the turbulent-to-laminar viscosity ratio will also be assessed. While the crossflow model is being evaluated on this new configuration, RANS simulations with the Spalart-Allmaras model with trip line [30] at the measured location will be used to inform boundary condition settings in upcoming DNS with resolved roughness.

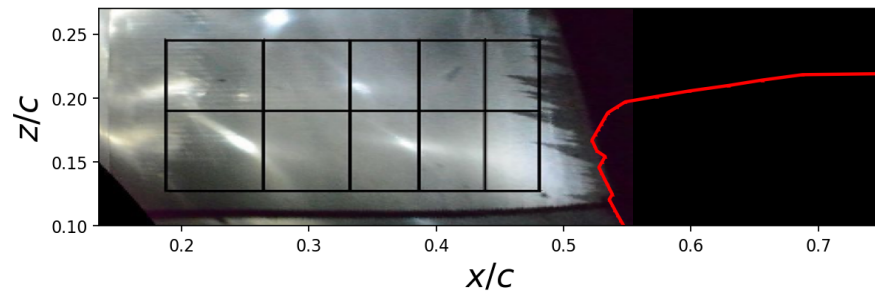
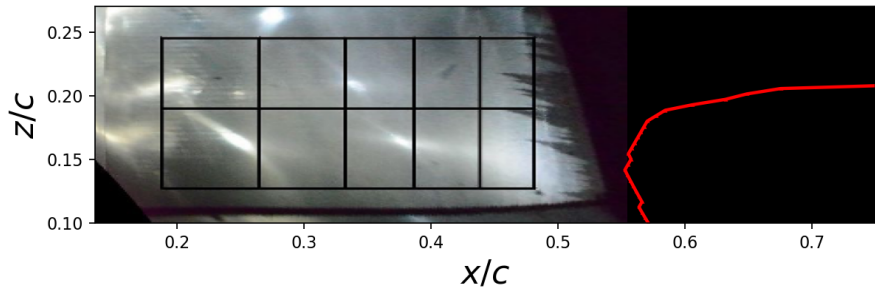
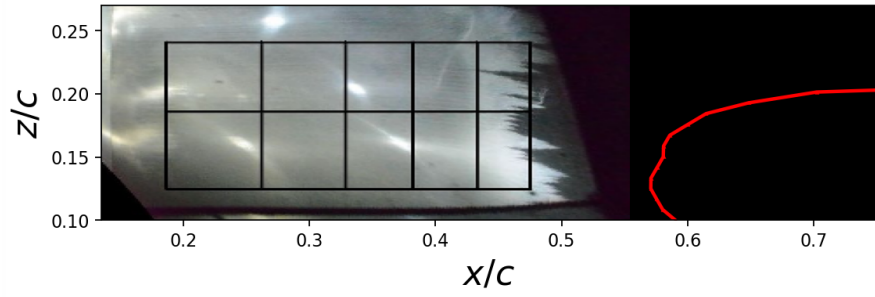
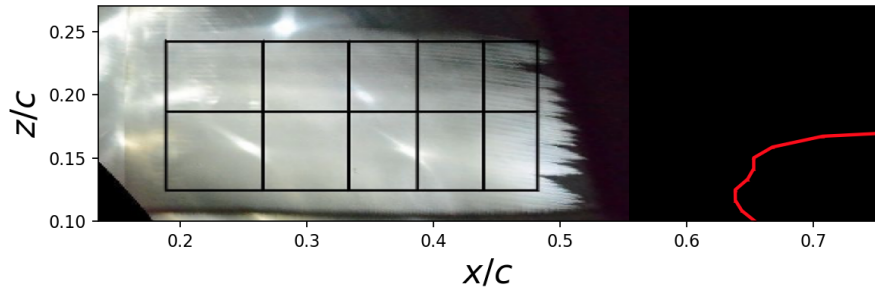


Fig. 10 Overlay of the simulated transition location (red line) with sublimation measurements

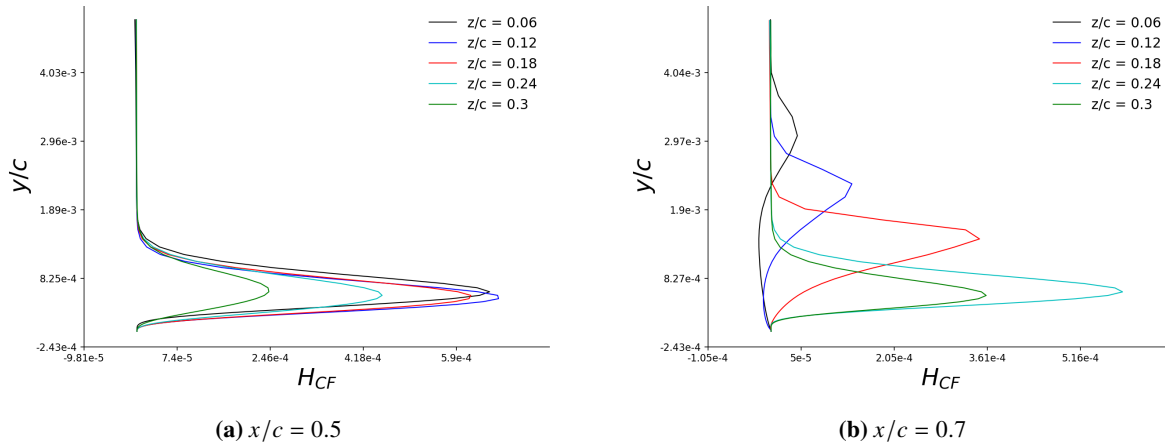


Fig. 11 Simulated crossflow strength H_{CF} at two streamwise coordinates for the rough panel TP2 with $h_{RMS} = 4.6\mu m$.

VI. Acknowledgements

This work was funded by the Revolutionary Computational Aerosciences discipline in the Transformational Tools and Technologies Project of the NASA Transformative Aeronautics Concepts Program. Computational resources were made available by the NASA Advanced Supercomputing (NAS) center. The authors would like to thank Dr. Thomas Pulliam and Dr. Karim Shariff at the NASA Ames Research Center for helpful discussions.

References

- [1] Krishnan, K., Bertram, O., and Seibel, O., "Review of laminar flow control systems," *Progress in Aerospace Sciences*, Vol. 93, 2017, pp. 24–52. <https://doi.org/dx.doi.org/10.1016/j.paerosci.2017.05.005>.
- [2] Malik, M., Li, F., Choudhari, M., and Chang, C.-L., "Secondary instability of crossflow vortices and swept-wing boundary layer transition," *Journal of Fluid Mechanics*, Vol. 399, 1999, pp. 85–115. <https://doi.org/10.1017/S0022112099006291>.
- [3] Saric, W., Reed, H., and White, E., "Stability and transition of three-dimensional boundary layer," *Annual Review of Fluid Mechanics*, Vol. 35, 2003, pp. 413–440. <https://doi.org/10.1146/annurev.fluid.35.101101.161045>.
- [4] Radeztsky Jr., R., Reibert, M., and Saric, W., "Effect of micron-sized roughness on transition in swept-wing flows," *31st Aerospace Sciences Meeting and Exhibit*, Reno, NV, 2013. <https://doi.org/doi.org/10.2514/6.1993-76>.
- [5] Choudhari, M., "Roughness-induced generation of crossflow vortices in three-dimensional boundary layers," *Theoretical Computational Fluid Dynamics*, Vol. 6, 1994, pp. 1–30. <https://doi.org/10.1007/BF00417924>.
- [6] Reibert, M., Saric, W., Carrillo, R., and Chapman, K., "Experiments in nonlinear saturation of stationary crossflow vortices in a swept-wing boundary layer," *34th Aerospace Sciences Meeting and Exhibit, Aerospace Sciences Meetings*, 1996. <https://doi.org/10.2514/6.1996-184>.
- [7] Collis, S., and Lele, S., "Receptivity to surface roughness near a sweptleading edge," *J. Fluid Mechanics*, Vol. 380, 1999, pp. 141–168. <https://doi.org/doi.org/10.1017/S0022112098003449>.
- [8] Downs R.S. III, E., White, and Denisse, N., "Transient growth and transition induced by random distributed roughness," *AIAA Journal*, Vol. 46, No. 2, 2008, pp. 451–462.
- [9] Nishino, T., and Shariff, K., "Direct numerical simulation of a swept-wing boundary layer with an array of discrete roughness elements," *7th UTAM Symposium on Laminar-Turbulent Transition*, IUTAM Bookseries, Vol. 18, Springer, Dordrecht, 2010, pp. 289–294. https://doi.org/10.1007/978-90-481-3723-7_46.
- [10] Carpenter, M., Choudhari, M., Li, F., Streett, C., and Chang, C.-L., "Excitation of crossflow instabilities in a swept wing boundary layer," *48th AIAA Aerospace Sciences Meeting*, 2010.

- [11] Li, F., Choudhari, M., Duan, L., and Chang, C., “Nonlinear development and secondary instability of traveling crossflow vortices,” *Physics of Fluids*, Vol. 26, 2014, pp. 064104 1–19. <https://doi.org/10.1063/1.4883256>.
- [12] Paredes, P., Hanifi, A., Theofilis, V., and Henningson, D., “The nonlinear PSE-3D concept for transition prediction in flows with a single slowly-varying spatial direction,” *Procedia IUTAM*, Vol. 14, 2015, pp. 36–44. <https://doi.org/10.1016/j.piutam.2015.03.02>.
- [13] Borodulin, V., Ivanov, A., and Kachanov, “Experimental and theoretical study of swept-wing boundarylayer instabilities. Unsteady crossflow instability,” *Physics of Fluids*, Vol. 29, No. 094101, 2017, pp. 1–31. <https://doi.org/10.1063/1.5094609>.
- [14] Ustinov, M., and Kachanov, Y., “Comparison of amplitude method of roughness-induced swept-wing transition prediction with experiment,” *Physics of Fluids*, Vol. 33, No. 094105, 2021, pp. 1–16. <https://doi.org/10.1063/5.0057853>.
- [15] Butler, A., and Wu, X., “Stationary crossflow vortices near the leading edge of three-dimensional boundary-layers: the role of non-parallelism and excitation by surface roughness,” *J. Fluid Mech.*, Vol. 845, 2018, pp. 93–140. <https://doi.org/10.1017/jfm.2018.226>.
- [16] He, J., Butler, A., and Wu, X., “Effects of distributed roughness on crossflow instability through generalized resonance mechanisms,” *Journal of Fluid Mechanics*, Vol. 858, 2019, pp. 787–831. <https://doi.org/10.1017/jfm.2018.817>.
- [17] Nakagawa, K., Tsukahara, T., and Ishida, T., *Aerospace*, Vol. 128, No. 10, 2023, pp. 1–22. <https://doi.org/10.3390/aerospace10020128>.
- [18] 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. <https://doi.org/10.2514/1.J054990>.
- [19] Langtry, R., Sengupta, K., Yeh, D., and Dorgan, A., “Extending the $\gamma - Re_{\theta l}$ local correlation based transition model for crossflow effects,” 45th AIAA Fluid Dynamics Conference, 2015. <https://doi.org/10.2514/6.2015-2474>.
- [20] Carnes, J., and Coder, J., “Effect of crossflow on the S-76 and PSP rotors in hover,” *AIAA SciTech Forum 2020*, Orlando, FL, 2020. <https://doi.org/10.2514/6.2020-0773>.
- [21] Venkatachari, B., Paredes, P., Derlaga, J., Buning, P., Choudhari, M., Li, F., and Chang, C., *Assessment of transition modeling capability in OVERFLOW with emphasis on swept-wing configurations*, AIAA 2020-1034, 2020. <https://doi.org/10.2514/6.2020-1034>.
- [22] Eppink, J., “Effects of random micron-sized roughness on swept-wing transition,” *AIAA Aviation Forum 2023*, San Diego, CA, 2023.
- [23] Nichols, R. H., and Buning, P. G., “Users Manual for OVERFLOW 2.3,” , 2021. URL overflow.larc.nasa.gov.
- [24] Derlaga, J., Jackson, C., and Buning, P., *A Parallel Symmetric Successive Overrelaxation Method for OVERFLOW*, AIAA 2021-2747, 2021. <https://doi.org/10.2514/6.2021-2747>.
- [25] Smirnov, P., and Menter, F., “Sensitization of the SST turbulence model to rotation and curvature by applying the Spalart-Shur correction term,” *Journal of Turbomachinery*, Vol. 131, No. 4, 2009, pp. 041010–1–8. <https://doi.org/10.1115/1.3070573>.
- [26] Carnes, J., and Coder, J., “Analyzing the near-wall behavior of the Langtry–Menter transition model,” *Flow, Turbulence and Combustion volume*, Vol. 108, 2022, p. 683–715. <https://doi.org/10.1007/s10494-021-00288-5>.
- [27] Spalart, P. R., and Rumsey, C. L., “Effective inflow conditions for turbulence models in aerodynamic calculations,” *AIAA Journal*, Vol. 45, No. 10, 2007, pp. 2544–2553. <https://doi.org/10.2514/1.29373>.
- [28] Langtry, R., “A correlation-based transition model using local variables for unstructured parallelized CFD codes,” Ph.D. thesis, University of Stuttgart, Germany, May 2006.
- [29] Chan, W., “The Overgrid interface for computational simulations on overset grids,” *32nd AIAA Fluid Dynamics Conference*, 2002. <https://doi.org/10.2514/6.2002-3188>.
- [30] Spalart, P., and Allmaras, S., “A one-equation turbulence model for aerodynamic flows,” *Recherche Aerospatiale*, Vol. 1, 1994, pp. 5–21.