

Transition Analysis for Isolated Trips on BOLT-II Wind-Tunnel and Flight Configurations

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The BOLT-II configuration, designed for an upcoming flight experiment, exemplifies the complexities of hypersonic boundary-layer transition in the presence of multiple and potentially interacting instability mechanisms. The present paper is related to the NASA-led roughness experiment on the secondary side of the BOLT-II configuration. First, computations are performed to aid mean-flow-based correlations for the transition measurements acquired during an experimental campaign in the Ludwig Tube facility at the United States Air Force Academy. To that end, both laminar and turbulent flow computations are performed for selected conditions of the experiment with a 1:3 scale model. The variation in well-known correlation parameters for transition due to isolated roughness elements with respect to element position, height, and flow Reynolds number is delineated. Furthermore, the wake instability theory is used to examine the amplification of unstable disturbances behind the centerline trip at the design conditions of the BOLT-II flight experiment and for its dynamically scaled version on the 1:3 scale model of the wind tunnel experiment. To our knowledge, this study represents the first analysis of the wake instabilities in the presence of a prominent entropy layer outside the boundary layer. At the nominal flight design condition of $Re_\infty = 5.44$ and $Re_\infty = 2.5 \times 10^6/\text{m}$, a diamond planform (“pizza-box”) trip with $k/\delta = 0.70$ and planform-side-length-to-height ratio of $b/k = 3.0$ at $X/L = 0.254$ induces a strong distortion of the boundary-layer flow in the vicinity of the symmetry plane, such that the wake structure includes a centerline streak produced by the flow retardation behind the trip along with multiple additional, prominent vorticity structures representing the necklace vortex system. Stability results reveal that each of these streaks can support a strong amplification of wake instabilities within a frequency band of 80 kHz–280 kHz, with a peak N-factor of greater than 15 beyond $X/L \approx 0.42$. The dynamically-scaled wind-tunnel configuration with $Re_\infty = 20.25 \times 10^6/\text{m}$ is also found to support $N > 15$ at similar axial stations.

Nomenclature

AoA	=	angle of attack [deg]
b	=	length of each side of the diamond-planform trip
C_{ph}	=	phase velocity along boundary-layer edge streamline at the center plane [m/s]
$C_{orbiter,5}$	=	value of correlation constant for correlation 5 from transition data analysis for orbiter (Eq. 1)
$C_{orbiter,7}$	=	value of correlation constant for correlation 7 from transition data analysis for orbiter (Eq. 2)
f	=	frequency of instability waves [kHz]
h	=	specific enthalpy [J/kg]
k	=	trip height [m], often quoted with [mm] units
L	=	axial body length [m] (= 1.0 m for flight configuration, 1/3 m for wind tunnel configuration)
M	=	Mach number [nondimensional]
M_∞	=	freestream Mach number [nondimensional]
M_e	=	Mach number at the edge of the boundary layer [nondimensional]

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N	= logarithmic amplification ratio of a fixed frequency secondary instability mode [nondimensional]
p'	= pressure fluctuations [Pa]
P_∞	= freestream pressure [Pa]
Pr	= Prandtl number [nondimensional]
$\dot{q}$	= surface heat flux [W/m ²]
Q	= second invariant of velocity gradient tensor = $0.5 (\Omega^2 - S^2)$
Re	= Reynolds number [nondimensional]
Re_∞	= freestream unit Reynolds number [m ⁻¹]
Re_k	= $\rho_k U_k k / \mu_k$ [nondimensional]
Re_{kk}	= $\rho_k U_k k / \mu_w$ [nondimensional]
s	= specific entropy [J/(K kg)]
S	= norm of the rate of strain tensor [s ⁻¹]
St	= Stanton number [nondimensional] = $(\dot{q} / \rho_\infty U_\infty) / (h_{0,\infty} - h_{0,w})$
t	= time [s]
T_0	= stagnation temperature [K]
T_{ad}	= adiabatic wall temperature [K]
T_w	= wall temperature [K]
T_∞	= freestream temperature [K]
u	= streamwise velocity [m/s]
u'	= streamwise velocity fluctuation normalized to a peak value of unity at a given location [nondimensional]
U_∞	= freestream velocity [m/s]
X	= axial coordinate [m]
Y	= coordinate along major axis of the model cross section [m]
Z	= coordinate along minor axis of the model cross section [m]
α	= complex wavenumber of instability wave along the X direction [m ⁻¹]
β	= yaw angle [deg]
δ	= boundary-layer thickness based on $h_0/h_{0,\infty} = 0.995$
μ	= dynamic viscosity [kg/(m s ²)]
σ	= standard deviation
θ	= local momentum thickness of the boundary layer [m]
ρ	= fluid density [kg/m ³]
Ω	= vorticity magnitude [s ⁻¹]

Subscripts

0	= stagnation condition
e	= boundary-layer edge
k	= wall-normal location corresponding to trip height
L	= based on reference length L [m]
w	= wall
∞	= freestream

Abbreviations

BOLT	= Boundary Layer Transition
DNS	= Direct Numerical Simulations
HIFiRE	= Hypersonic International Flight Research Experimentation
PSE	= Parabolized Stability Equations
WENO	= Weighted Essentially Nonoscillatory

I. Introduction

Laminar-turbulent boundary-layer transition has a major impact on the design and performance of hypersonic flight vehicles because of the increased skin friction and heat transfer rate of a turbulent boundary layer compared with a laminar one. Recent flight experiments on the HIFiRE-1 and HIFiRE-5b configurations have provided valuable data toward the calibration of stability-based transition prediction models for the laminar-turbulent transition due to Mack mode and crossflow instabilities, respectively. The HIFiRE-5b configuration also exhibited an additional, complex flow feature in the form of a centerline streak that is likely to have transitioned via shear layer instabilities concentrated within one or more localized regions of high shear adjacent to the minor axis plane of symmetry. Building upon the success of the HIFiRE-1 and HIFiRE-5b flight campaigns, the upcoming series of BOLT flight experiments will focus on a more complex geometric configuration that supports a significantly more complex basic state than either of the HIFiRE configurations. As described by Wheaton et al. [1], the objective of the BOLT program is to investigate boundary-layer transition mechanisms on a low-curvature concave surface with a swept leading edge at high Mach numbers of 5 to 7. A schematic of the BOLT configuration is shown in Figure 1. The top side of the BOLT configuration corresponds to the main test surface, denoted as side A, whereas the bottom surface (or side B that is also referred to as the “secondary” side) will be used to acquire additional measurements for the effects of a backward facing step [2]. The BOLT-II flight experiment will use an extended version of the BOLT model with the goal of investigating the turbulent boundary-layer characteristics on the primary side of the model surface. Accompanying measurements on the secondary side will focus on NASA’s roughness experiment involving isolated trips. The present computational study is targeted at supporting the secondary side experiment on BOLT-II.

The BOLT and BOLT-II configurations include a cylindrical nose-tip with four swept leading edges emanating from the corners of the tip. These four leading edges are joined by four laterally concave surfaces, each of which has a single plane of symmetry. One of the rationales behind this design was that the decoupling of the flow behavior over these four surfaces would allow multiple experiments to be carried out simultaneously. Since the conception of the BOLT configuration, considerable efforts have been devoted to both wind-tunnel testing and numerical computations. Among these, Berridge et al. [3] conducted experiments in the Boeing/AFOSR Mach 6 Quiet Tunnel (BAM6QT) and found what appeared to be spectral peaks associated with boundary-layer instabilities at sufficiently high Reynolds numbers and a nonzero angle of attack. They also carried out wind-tunnel tests in the LENS II facility at CUBRC and again found evidence of high frequency instability in the spectral measurements with one of the surface pressure sensors. In both experiments, the origin of the instabilities could not be ascertained because of the limited detail in the experimental measurements.

Kostak et al. [4] experimentally studied the effects of wind-tunnel disturbances on the process of boundary-layer transition on the BOLT configuration for a range of Reynolds numbers in four different wind tunnels. They did not find any prominent modal instabilities except for a 35-45 kHz wave that was noted in one of the wind tunnels used during their investigation. During experiments in the BAM6QT, Berridge et al. [5] noted that there were potential spectral peaks associated with instability waves at 40 kHz and 75 kHz, respectively. They suspected that the latter peak was related to a traveling crossflow instability; however, the origin of the former peak, which was observed in the unsteady pressure signals along the edge of the center vortex region, could not be identified. Berry et al. [6] tested a 0.3048 m long model in the LaRC 20-In Mach 6 Air Tunnel and used IR thermography to image a two-lobed transition pattern on either side of the centerline. The transition front was found to be strongly dependent on the flow Reynolds number. On the other hand, the transition pattern was not sensitive to the angle of attack; however, a nonzero side slip led to a loss of symmetry between the transition fronts on either side of the geometric plane of symmetry.

On the computational side, Thome et al. [7] carried out direct numerical simulations of BOLT by imposing distributed roughness on the model surface and found crossflow vortices as well as Mack’s second modes on the side of the centerline. Moyes et al. [8] analyzed the stability characteristics of the BOLT boundary layer and found significantly large N-factors for the Mack mode instabilities, especially in the region close to the leading edge where an adverse pressure gradient existed along with an acoustic impedance well. They also identified a strong amplification of crossflow instability modes within a wedge-shaped region on either side of the symmetry plane. Thome et al. [9] studied the response of the BOLT boundary layer to a sustained stochastic forcing and identified what appeared to be a high-frequency secondary instability of the stationary crossflow vortices on the side streaks in between the leading edge (or the attachment line) and the symmetry plane. Their simulations also uncovered a streak instability in the center bulging regions. Multidimensional instability analysis by Li et al. [10] led to encouraging agreement between the predicted frequency spectra of the streak instability in the region of increased boundary layer thickness and the

surface pressure spectra measured during the TAMU experiments suggests that these streak instabilities may play an important role during the transition process near the symmetry plane. The modest value of the predicted peak N-factor ($N_{\max} \approx 5$) for the streak instabilities also provided a potential explanation for why transition was not observed under quiet flow conditions, but may occur within a noisy wind tunnel.

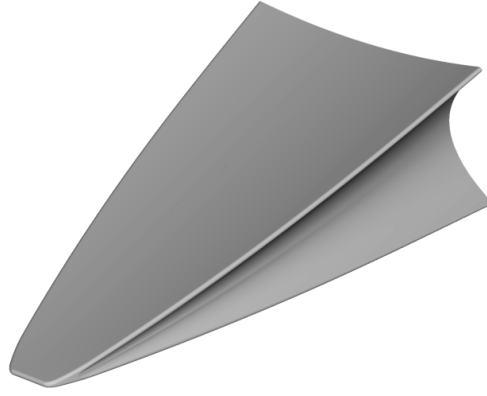


Figure 1. Schematic of the BOLT geometry.

Transition in high-speed boundary layers due to discrete roughness elements has been a topic of intense research activity over the past decade [11, 12]. Following the successful deployment of ramp trips and pizza-box trips between wind tunnel and flight experiments involving the Hyper-X configuration [13, 14], experiments were also performed in the Mach 6 quiet tunnel at Purdue University to examine the effects of discrete roughness elements on boundary-layer transition over a circular cone [15] and the X-51 forebody configuration [16]. Computational research at the NASA Langley Research Center investigated the physical mechanisms behind the transition process. For moderate, i.e., post-critical roughness heights, the amplification of new instabilities in the spanwise localized wake behind the roughness elements was shown to have the potential to cause transition [17, 18] and the wake instability theory was validated in detail during subsequent experiments in the NASA Langley Supersonic Low Disturbance Tunnel [19]. For larger (near-effective to post-effective) roughness elements, an absolute instability in front of the trip element was predicted to play an important role as a precursor to the wake amplification [20] and this mechanism was clearly elucidated in subsequent direct numerical simulations [21]. An overview of this research on roughness induced transition may be found in Ref. [12]. A majority of the computations described therein were limited to nearly 2D or axisymmetric boundary layers without any effects of a surrounding entropy layer associated with a blunt leading edge (or nose). The BOLT configuration manifests both mean flow three-dimensionality and strong effects of an entropy layer. The present work seeks to include those effects in the context of the secondary side experiment on the BOLT-II model. Even though the flight experiment will include both a centerline trip at $(X, Z) = (0.254, 0.0)$ m and a downstream trip at $(X, Z) = (0.5, 0.15)$ m that is closer to the leading edge, the initial work described in this paper will focus on the effects of the centerline trip alone. Besides investigating the disturbance amplification characteristics behind the centerline trip at the design condition from the descent portion of the flight trajectory, we will also examine the wake instability behind a scaled version of the trip at wind tunnel conditions. Additionally, because of the importance of transition correlations based on mean-flow parameters for predicting roughness-induced transition in practical applications, we also investigate those correlations for the wind-tunnel testing of a 1:3 scale model (relative to the design of the flight article) in the Ludwig Tube Facility at the United States Air Force Academy in Colorado Springs.

An outline of the paper is as follows. In Section II, we outline the computations of both laminar and fully turbulent basic states over a smooth surface configuration for several test conditions from the wind tunnel experiment. First, the variation in surface heat flux distribution as a function of the flow Reynolds number and the state of the boundary layer is described. Next, the mean flow parameters relevant to the correlation of boundary-layer tripping are examined for selected conditions from the experiment. Computations to elucidate the effects of an isolated roughness element on the boundary-layer flow and its stability characteristics are presented in Sections III and IV for the wind-tunnel

model and the flight configuration, respectively. The locations and heights of the trip element are based on preliminary information that was under consideration by the flight project. In each case, the basic state distortion due to a diamond planform (i.e., “pizza-box”) trip is described first, followed by the modal instability analysis for disturbance amplification within the wake region. A summary of the main findings and concluding remarks are presented in Section V.

II. Basic State Solutions for Wind Tunnel Configuration

The subscale wind-tunnel model used during the experiments at the United States Air Force Academy (USAF) corresponds to a $1/3^{\text{rd}}$ -scale version of the BOLT-II flight-test article that is 1.0 meters long. Throughout this paper, we confine our attention to the nominal design conditions of $AoA = 0$ degrees and $\beta = 0$ degrees. The freestream conditions for the various test conditions from the wind-tunnel experiment are outlined in Table 1. The mean flow at each of these test conditions was computed by using the second-order, shock capturing code VULCAN-CFD (Viscous Upwind algorithm for Complex flow ANalysis) [22]. Our previous computations for a similar wind-tunnel case [10] shows that second-order Navier-Stokes solutions compare well with solutions obtained by using a 7^{th} -order DNS code. Table 1 outlines the total of 11 laminar and 5 turbulent cases, respectively. All of the basic-state computations assume the fluid to be a perfect gas (air) and the usual constitutive relations for a Newtonian fluid are used, namely, the viscous stress tensor is linearly related to the rate-of-strain tensor and the heat-flux vector scales linearly with the temperature gradient through Fourier's law. The coefficient of viscosity is computed from Sutherland's law and the coefficient of thermal conductivity is computed by assuming a constant Prandtl number ($Pr = 0.72$).

The VULCAN-CFD code solves the unsteady, conservation equations appropriate for a laminar or turbulent flow of calorically or thermally perfect gases or gases in thermal nonequilibrium with a spatially 2^{nd} -order accurate cell-centered finite-volume scheme. A variety of upwind schemes are available for fine-tuning of numerical dissipation and shock capturing in order to ensure solution accuracy for stability computations. In the present computations, the inviscid fluxes were constructed using the MUSCL $\kappa = 0$ scheme, the van Albada gradient limiter [23] and the Low Dissipation Flux Split Scheme (LDFSS) of Edwards [24]. The cell-face gradients required to construct the viscous fluxes were obtained using an auxiliary control-volume approach that results in a compact viscous stencil that produces a 2^{nd} -order accurate approximation of the full Navier-Stokes viscous fluxes. The solutions were relaxed in pseudotime to steady state by using the 3-D ILU(0) scheme [25] with a constant CFL number of 20. Due care was taken to ensure that the grid was aligned with the shock surface to avoid the generation of spurious flow features downstream of the shock. The grid distribution within the viscous region adjacent to the model surface is adjusted on a case-by-case basis to ensure a sufficient wall-normal resolution of the boundary-layer flow.

Exploiting the symmetry of the model geometry and the model attitude corresponding to $AoA = \beta = 0$ degrees, only one quarter of the model surface is included in the computational grid. A typical grid used for these computations consisted of a two-block topology, including a nose-region block with $(289 \times 109 \times 301)$ points in the streamwise, spanwise, and surface normal directions, respectively, and an aft block with $(1121 \times 417 \times 301)$ points. A finer grid with 50 percent higher resolution in each direction was also used to confirm the lack of grid sensitivity of the relevant flow metrics at the primary condition of interest with a unit Reynolds number of $2.5 \times 10^6/\text{m}$.

The turbulent flow computations are performed by solving the Reynolds-averaged Navier-Stokes equations in conjunction with the Spalart-Allmaras (S-A) model and the viscous spacing in wall units was verified to be substantially smaller than unity in all cases.

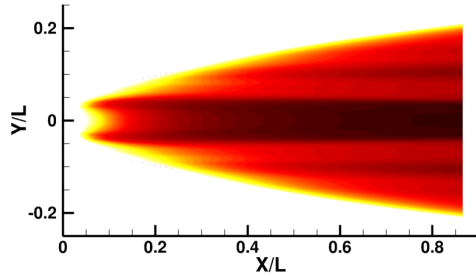
Figure 2 shows the Stanton-number distributions on the BOLT model surface for selected unit Reynolds numbers, with lighter colors indicating larger values of the Stanton number. Figures 2(a)–2(c) show the contours for the laminar cases. In general, the Stanton number is larger at the lower values of the unit Reynolds number, consistent with the well-known results for simpler, 2D boundary layers without any entropy-layer effects. The contours also indicate the presence of streamwise streaks. As the unit Reynolds number increases, the streaks become stronger, as previously seen in Ref. [10]. These streaks can lead to strong instabilities, especially at the higher Reynolds numbers as found in Ref. [10]. The dark band of lower Stanton number centered on the symmetry line of the test surface is a region where the boundary layer is appreciably thicker than that over the outboard region closer to the swept leading edge on either side. Similarly, Fig. 2(d) shows the Stanton number contours for the turbulent flow at $Re_\infty = 20.25 \times 10^6/\text{m}$, which was computed by using the SA model. The maximum Stanton number for the turbulent boundary layer is approximately twice that of the corresponding laminar cases. Although not shown, the turbulent Stanton number was again larger for lower unit Reynolds numbers. The low Stanton number band in the vicinity of the symmetry line is also seen for the

turbulent case, but the streaks over the entire surface become much weaker in comparison with the laminar cases, presumably as a result of the increased mixing in the laminar flow.

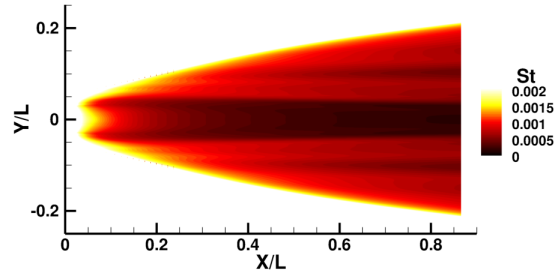
Table 1. Freestream conditions for the wind-tunnel configurations

(The row shaded in gray indicates the wind-tunnel configuration scaled from the flight case with a centerline trip as described in Section IV. In all cases, the model temperature is assumed to be fixed at $T_w = 300$ K.)

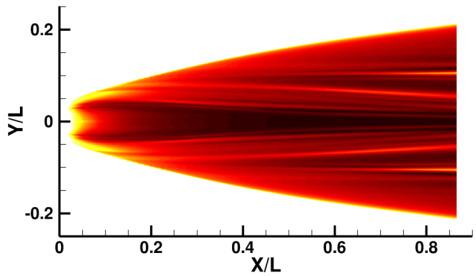
Re_∞ ($10^6/m$)	P_∞ (Pa)	T_∞ (K)	M_∞	Flow State
2.5	203.57	62.29	5.9	Laminar
3.0	244.28			
3.5	284.00			
4.0	325.71			
4.5	366.43			
5.0	407.14			
6.0	488.57			
7.0	569.00			
8.0	651.42			
9.0	732.85			
10.0	814.28			
20.25	1648.9	62.29	5.9	Laminar
2.5	203.57	62.29	5.9	Turbulent
4.0	325.71			
6.0	488.57			
8.0	651.42			
10.0	814.28			
20.25	1648.9	62.29	5.9	Turbulent



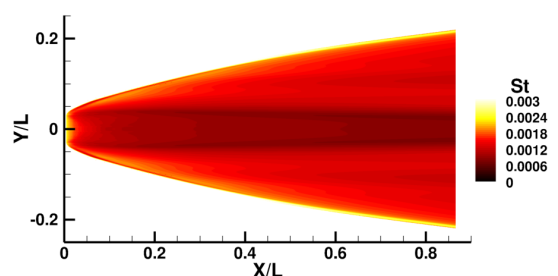
(a) $Re_\infty = 2.5 \times 10^6/m$, laminar



(b) $Re_\infty = 3.5 \times 10^6/m$, laminar



(c) $Re_\infty = 20.25 \times 10^6/m$, laminar



(d) $Re_\infty = 20.25 \times 10^6/m$, turbulent

Figure 2. Stanton number contours over the surface of scaled wind-tunnel configuration

Figures 3 illustrates the basic-state solutions for $Re_\infty = 20.25 \times 10^6/m$ by depicting the cross-sectional streamwise velocity distributions in the neighborhood of the symmetry plane ($Y/L = 0$). Velocity contours of the flow near the

symmetry plane are plotted for three selected streamwise stations, with the fully laminar solution shown on the left in Figs. 3(a), 3(c), and 3(e), whereas the fully turbulent solutions at the same stations are plotted in Figs. 3(b), 3(d), and 3(f), respectively, in the right-hand column. Regardless of the state of the boundary layer, the contours adjacent to the symmetry plane indicate a considerably thicker boundary layer that develops underneath the entropy layer behind the quasi-2D nose region. In contrast, one observes a thinner boundary layer on the right side of each plot that is wetted by the flow coming from the swept leading edges of the model. In the laminar case, however, the rapid spanwise change in the boundary layer thickness is accompanied by prominent, rolled-up vorticity structures. The internal regions of high mean-flow gradients associated with these structures can sustain flow instabilities that are localized within one or more such regions [10]. The turbulent-flow solutions from the right column of Figure 3 also indicate a thickening of the near wall streamwise velocity contours in the vicinity of the symmetry plane. However, the most prominent difference from the laminar solutions is the absence of rolled-up structures in the turbulent case. Further computations with more advanced turbulence models and eddy resolving simulations of turbulent flow, potentially including a realistic transition front, are necessary to provide further insights into this behavior.

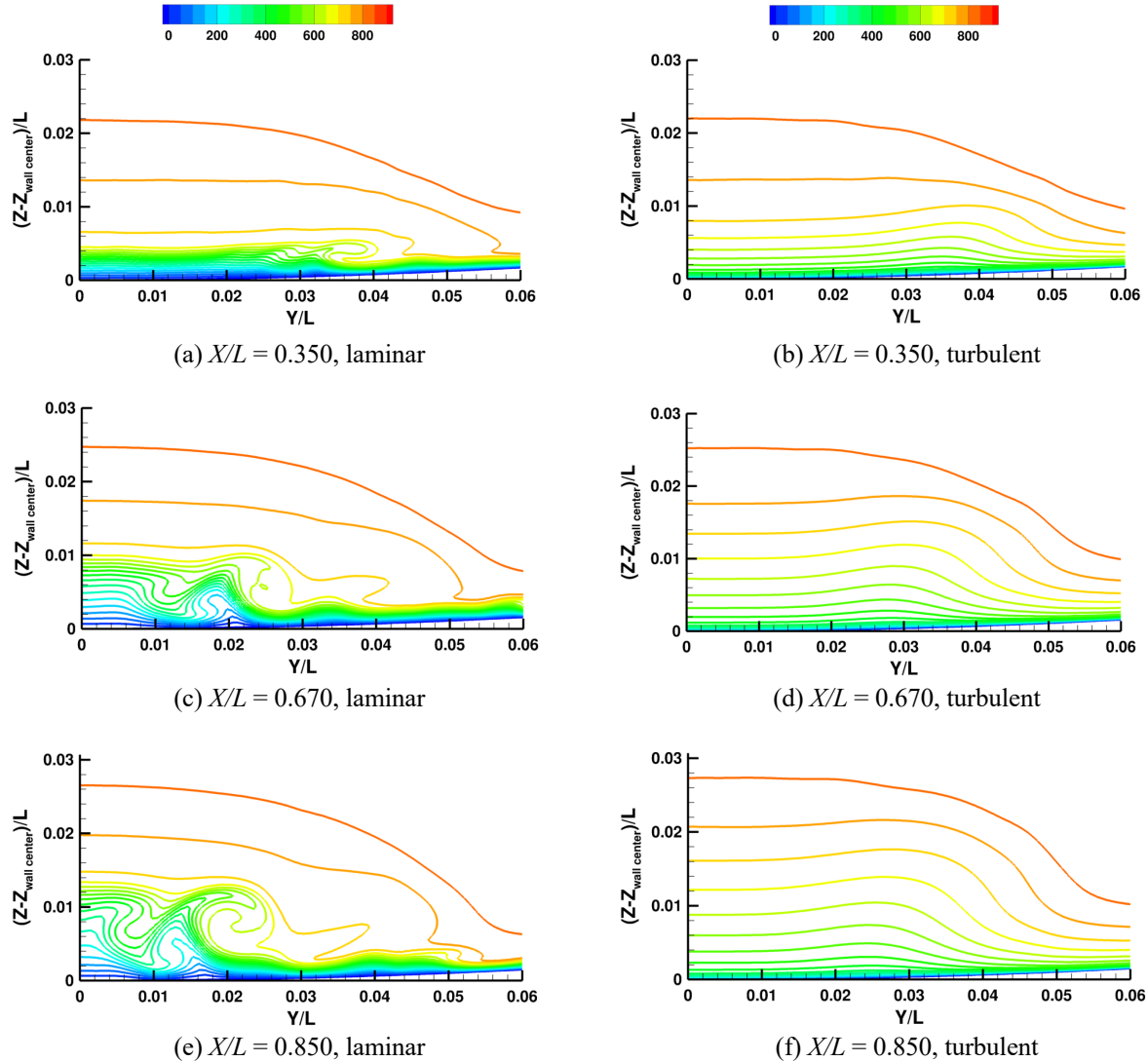


Figure 3. Streamwise velocity contours at selected streamwise locations, $M_\infty = 5.9$ and $Re_\infty = 20.25 \times 10^6/m$.

The streamwise velocity contours at selected cross-planes across the full width of the model are shown in Figs. 4(a) and 4(b) for the laminar and turbulent cases at $Re_\infty = 20.25 \times 10^6/\text{m}$. While this Reynolds number is larger than the highest Reynolds number from the tests at USAFA, namely, $Re_\infty = 10 \times 10^6/\text{m}$, it has been used herein as a prelude to the wind-tunnel case considered in Section III. As one moves downstream along the model, the spanwise extents of the bulge regions remain relatively constant in comparison with the accompanying increase in the spanwise width of the model. Boundary-layer thicknesses are extracted on two streamwise lines, one along the symmetry line (red line in Fig. 4) and another outside the bulge region (green line); and are shown in Fig. 5 for all of the cases listed in Table 1. For both the laminar and the turbulent cases, the boundary layer becomes thinner with an increasing unit Reynolds number, as seen in Figs. 5(a) and 5(c). The boundary-layer thicknesses normalized by $x/Re_x^{1/2}$ and $x/Re_x^{1/5}$ for the laminar and turbulent boundary layers, respectively, are shown in Figs. 5(b) and 5(d). Observe that the boundary layer thickness along the model centerline (a candidate location for one of the trips to be used during the flight experiment) increases approximately linearly with the axial coordinate x , regardless of the state of the boundary layer. Yet, this variation is seen to be consistent with the scaling based on quasisimilarity, as seen from the reasonable collapse of the laminar boundary-layer thickness along the centerline (Fig. 5 (b)). The undulations in the boundary-layer thickness along the outboard section are believed to be caused by the modulation of the boundary-layer flow due to the underlying streaks (Fig. 2).

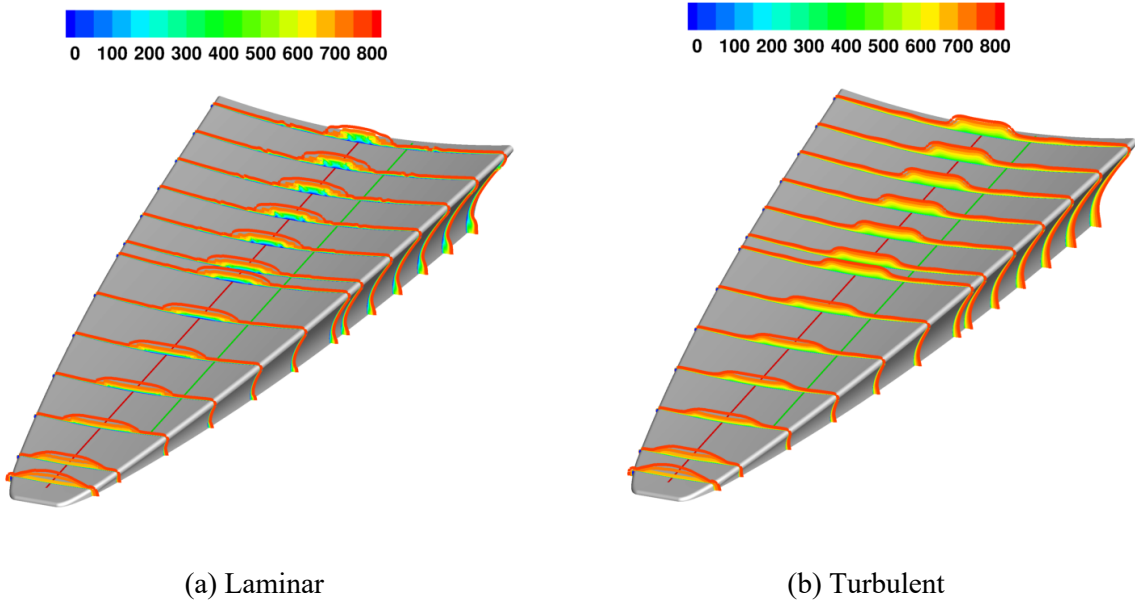
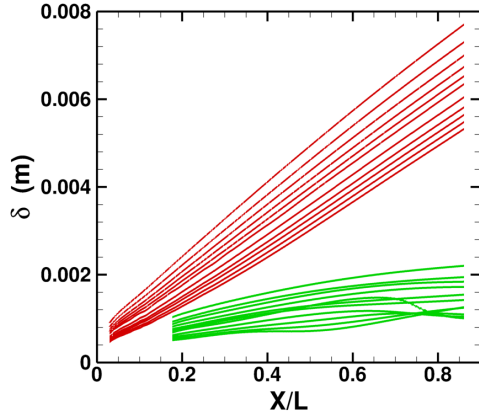
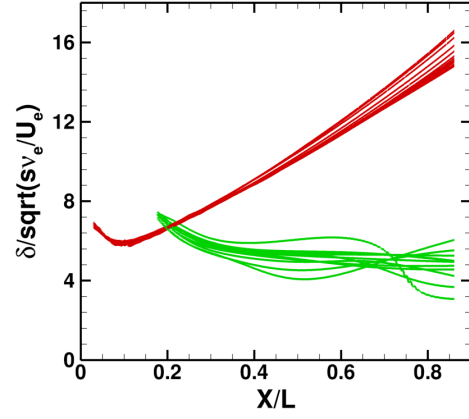


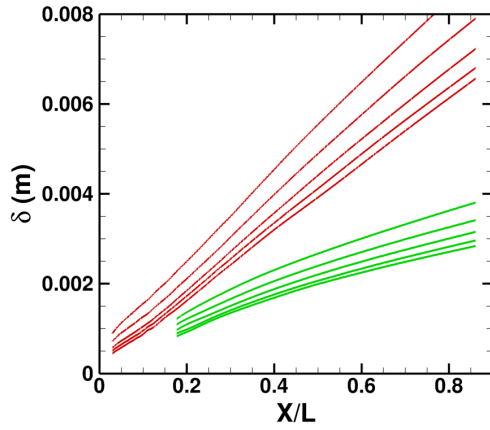
Figure 4. Crossplanes of streamwise velocity contours for $M_\infty = 5.9$ and $Re_\infty = 20.25 \times 10^6/\text{m}$.



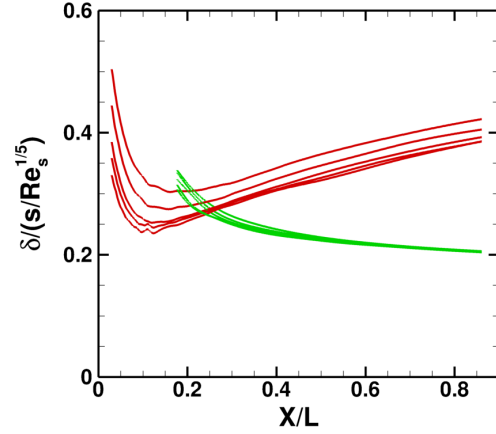
(a) $Re_\infty = 20.25 \times 10^6/\text{m}$, laminar



(b) $Re_\infty = 20.25 \times 10^6/\text{m}$, laminar



(c) $Re_\infty = 20.25 \times 10^6/\text{m}$, turbulent



(d) $Re_\infty = 20.25 \times 10^6/\text{m}$, scaled, turbulent

Figure 5. Boundary-layer thickness, $M_\infty = 5.9$.

A number of mean-flow parameters have been used to correlate both incipient and effective transition behind an isolated trip. In general, the trip height is the primary determinant of the movement in the transition location and the planform size tends to have a secondary effect. Thus, the term “incipient transition” refers to the smallest trip height producing a significant upstream movement in transition onset compared to a smooth surface and “effective transition” refers to the case where the transition occurs within a short distance behind the trip and a further increase in trip height leads to relatively small changes in that transition location. Schneider [11] provides a review of the various correlations that have been proposed, including a simple correlation based on the scaled trip height with respect to the local displacement thickness of the unperturbed boundary layer, i.e., k/δ^* [26] and other parameters suggested in the literature [27, 28].

Trip sizing during the HIFiRE-1 flight experiment was based on the simpler k/δ^* parameter, calibrated on the basis of extensive experimental measurements [29], where it was estimated that the incipient transition behavior correlated with $\frac{k}{\delta^*} = 1.2$ and effective transition with $\frac{k}{\delta^*} = 3.2$. The available instrumentation on the secondary side of the BOLT-II flight model is expected to allow up to two discrete trips, placed sufficiently apart from each other. A candidate streamwise location corresponds to $X = 0.083$ m on the scaled model, which is just downstream of the material discontinuity in the flight article and where one would likely encounter a local step in the surface height. The spanwise variation of the relevant boundary-layer parameters at $X = 0.083$ m is shown in Figs. 6(a) and 6(b) for two different Reynolds numbers. Based on the HIFiRE-1 correlations, trip heights of 2.2 mm and 5.8 mm are likely to

produce incipient and effective transition, respectively, along the centerline at $Re = 2.5 \times 10^6/m$. The corresponding estimates at the higher Reynolds number of $Re = 20.25 \times 10^6/m$ are approximately 1.1 mm and 2.9 mm, respectively.

King et al. [30] recommended the following two correlations for incipient transition over the shuttle Orbiter, i.e., for data indicating the first evidence of laminar-to-turbulent transition on the windward surface of the Orbiter.

$$\frac{Re_\theta}{M_e} \frac{k}{\delta} \left(\frac{h_{0,e}}{h_{0,w}} \right)^{0.30} = C_{orbiter,5}, \quad (1)$$

and

$$(Re_k)^{0.30} \left[Re_\theta \left(\frac{\mu_e}{\mu_k} \right) \right]^{0.4} = C_{orbiter,7}. \quad (2)$$

For protuberance-induced transition in a flight environment, the best-fit value of $C_{orbiter,5}$ was 61.3, with a 95-percent confidence interval of (35.3, 106.4). For transition in conventional ground facilities, these values changed to 42.8 and (25.3, 72.5), respectively. Analogously, $C_{orbiter,7} = 396.8$, along with a $\pm 2\sigma$ intervals of (220.7, 713.4) for inflight transition, and $C_{orbiter,7} = 217.6$ with a confidence interval of (118.0, 401.3) for ground facility data. Based on their best correlation (Eq. 1), the predicted trip height for incipient transition at $Re_\infty = 2.5 \times 10^6/m$ is $k = 1.16$ mm, with a 95-percent confidence interval from 0.48 mm to 1.37 mm.

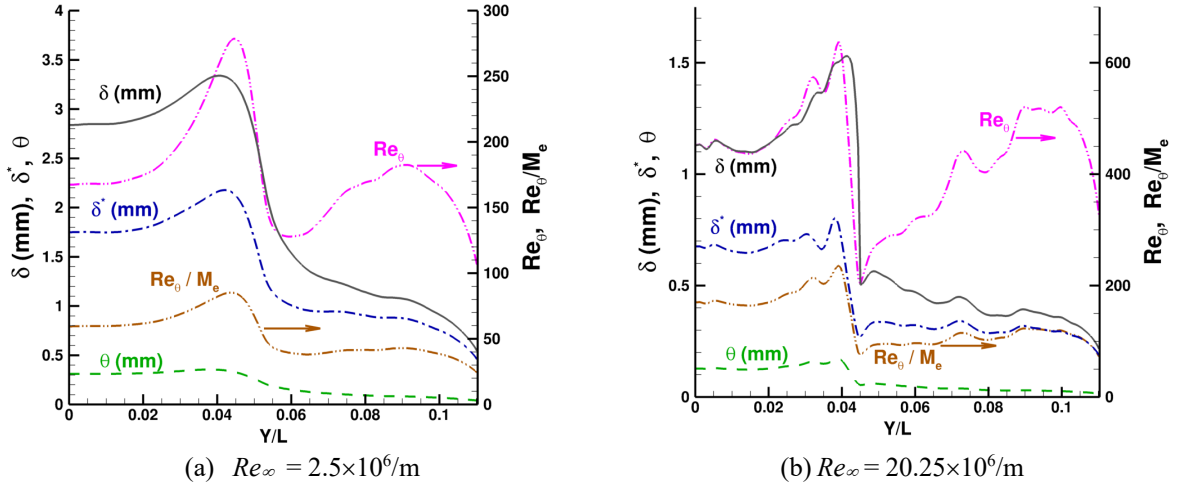


Figure 6. Spanwise variation in boundary layer parameters at $X = 0.083$ m, $M_\infty = 5.9$.

III. Centerline Trip on Wind Tunnel Model

Having examined the boundary layer flow over the wind tunnel model with a nominally smooth surface, i.e., without any trip, we next examine the effects of a diamond-planform (or “pizza-box”) trip on the baseline flow as well as the characteristics of disturbance amplification within the wake of this trip. The trip is located at $X = 0.0847$ m, corresponding to the targeted location of $X = 0.254$ m on the flight configuration. As mentioned at the end of the Introduction, the trip location and trip height for the flight case are based on preliminary information that was under consideration by the flight project. The height of the trip for the scaled configuration is taken to be $k = 0.875$ mm, whereas the length b of each side of the diamond-shaped planform of the trip is chosen to satisfy $b/k = 3.0$. For a unit Reynolds number of $Re_\infty = 20.25 \times 10^6/m$, we find that the trip height to boundary-layer thickness ratio is equal to $k/\delta \approx 0.75$, which is close to $k/d \approx 0.70$ for the design condition that was being considered for the flight experiment (Section IV). The freestream conditions for the wind tunnel case correspond to $M_\infty = 5.9$, $T_\infty = 60.28$ K, $U_\infty = 918.35$ m/s, and $p_\infty = 1648.9$ Pa, respectively.

Given the limited upstream influence of the trip, the basic state computation is simplified by using a computational domain that begins at $X = 0.063$ m, i.e., well downstream of the nose region, but sufficiently upstream of the trip location. Again, using the spanwise symmetry of both the basic state and the pizza-box trip geometry, only one

quadrant of the model cross-section is included within the computational domain. The computational grid includes a tight clustering within the nearfield of the trip as illustrated by the schematic of the surface mesh in Fig. 7. The streamwise length of the trip (i.e., the diagonal of the diamond planform) is resolved with 467 points, whereas there are 187 points along each edge of the diamond-shaped planform and a total of 163 points along the height of the roughness element. The initial phase of the computations reported in this paper did not allow for a detailed grid-convergence study for the basic-state computation. However, the results presented in the following section will demonstrate that the wake flow from the VULCAN-CFD computation agrees quite well with that obtained by using a 7th-order accurate WENO solution.

A. Basic State

A perspective view of the 3D vortex structures induced by the pizza-box trip is shown in Fig. 8, whereas contours of the crossplane distribution of the streamwise velocity at selected streamwise stations ($X/L = 0.275, 0.300, 0.350$, and 0.600) are shown in Figs. 9(a) through 9(d), respectively. Note that we have shifted the origin of the coordinate system in Fig. 9 to the wall at the symmetry line ($Y = 0$) for easy assessment of the extent of the vortex structures in the wall-normal direction. The trip is centered at $X = 0.0847$ m, which corresponds to $X/L = 0.254$ when normalized with respect to the model length scaled from the longer, BOLT-II configuration. Previous work with sufficiently large roughness elements (i.e., trip height approaching or exceeding the boundary-layer thickness) [20, 21, 31] has shown that the larger roughness elements induce a strong enough region of recirculating flow in front of the trip, and also lead to the formation of a prominent system of streamwise elongated vorticity structures within the wake region. These vortices interact with each other as well as the underlying three-dimensional flow, causing both the wall-normal and the spanwise locations of the trailing vortex structures to evolve along the length of the wake region. As shown in Figs. 8 and 9, the innermost system of vortex structures identified with the Q-criterion surrounds a centerline streak with a local bulge in the boundary-layer thickness. There also exist additional, necklace vortices wrapped around the trip. The outermost among these are clearly visible in the region close to the trip, but they become weaker fairly soon and are not observed in the downstream portion of Fig. 8.

The streamwise velocity contours at $X/L = 0.275$ (Fig. 9(a)) reveal a strong mushroom-shaped structure centered on the symmetry plane ($Y/L = 0$), an additional pair of mushroom structures near $Y/L = \pm 0.009$, and a pair of bell-shaped structures near $Y/L = \pm 0.013$. As X/L increases across Figs. 9(a) through 9(d), the interactions among the various vortices, the underlying flow, and the model surface result in a continued lift-up of the centerline mushroom structure, such that it is well above the fluid associated with the original boundary layer flow. The above lift-up of the centerline structure is accompanied by a gradual inward migration of the adjacent pair of mushroom structures (denoted herein as N1, i.e., the first structure associated with the outer, necklace vortex system) and it appears to have nearly displaced the centerline structure from its original position within the height of the unperturbed boundary layer. The apparent ejection of the centerline structure for suitable combinations of trip height and aspect ratio had been noted in the previous literature (see, e.g., Fig. 5(a) from Ref. [18]). However, the results of the wake instability analysis to be presented subsequently in this paper demonstrate that the boundary layer is likely to transition to turbulence before the centerline vorticity structure becomes separated from the rest of the boundary layer. Thus, this particular aspect of the wake development is not likely to have any significance in practice.

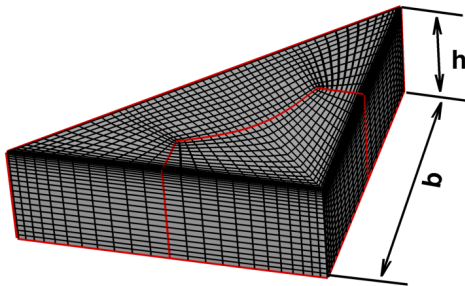


Figure 7. Schematic of grid over the trip surface (every 8th grid point shown).

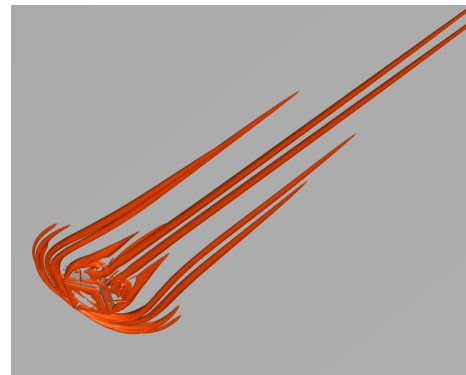


Figure 8. Vortex structures near the trip, plotted as an isosurface of $Q = 1.e-7$ (X increases from bottom left to top right).

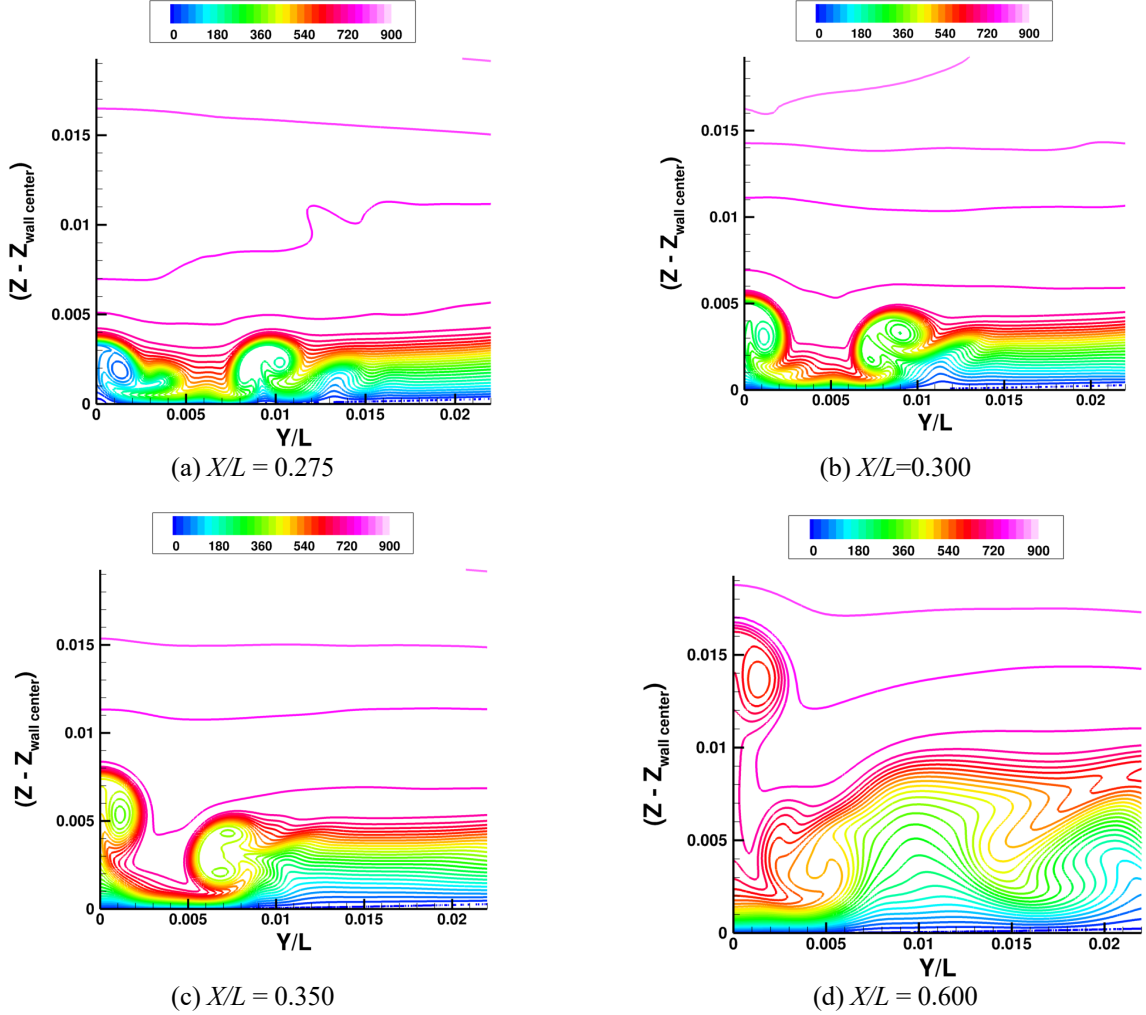


Figure 9. Streamwise velocity contours of the laminar basic state at selected streamwise locations (the crossplane coordinates are normalized with respect to $L = 0.333$ m, the scaled length of the BOLT-II configuration).

B. Trip-Wake Instability

The analysis of instability modes within the trip-wake region must account for the enhanced azimuthal gradients associated with the streaks. Accordingly, the stability of the basic state described in the previous subsection was investigated by using a combination of local, multidimensional eigenvalue analysis and plane-marching parabolized stability equations (PSE). The procedure used for the instability analysis follows that used for analysis of streak instabilities in the vicinity of the HIFiRE-5b centerplane [32] and those behind a 3D roughness patch [33] and the reader is directed to Refs. [32] and [33] for the relevant details, along with Ref. [34] for a description of the plane-marching PSE. In particular, because the basic state is symmetric about the center plane, the stability analysis is confined to the $Y > 0$ side, with the flow disturbances assumed to be either symmetric or antisymmetric with respect to the $Y = 0$ plane [33]. The symmetric modes (denoted by the letter “S”) have zero azimuthal gradient in the axial-velocity fluctuation component u' (as well as in the fluctuations in the surface-normal velocity and all thermodynamic variables) at $Y = 0$, whereas the antisymmetric modes (denoted by the letter “A”) are associated with homogeneous Dirichlet boundary conditions in those quantities.

The inflow disturbance for the plane-marching PSE corresponds to the eigenfunctions based on a partially nonparallel (PNP) eigenvalue analysis that retains the axial gradients of the basic state, while assumes locally parallel mode eigenfunctions and eigenvalues. Of course, the solutions to the plane-marching PSE include all of the important nonparallel effects on the disturbance evolution. The results of both the PNP analysis and the PSE can have noticeable variations depending on the path of the axial grid lines. For the results described here, the computational grid is designed to follow the primary streaks of interest. A similar approach was used in Ref. [32], where excellent agreement was found between disturbance-growth predictions based on the plane-marching PSE and direct numerical simulations. A typical crossplane grid used for the eigenvalue computations and the plane-marching PSE has 201 points in both the wall-normal and the azimuthal directions. The azimuthal domain is truncated a short distance beyond the azimuthal location of the rapid change in the thickness of the boundary layer over the baseline BOLT configuration (i.e., in the absence of the trip). As such, the computations can reveal the potential presence of sufficiently unstable instability modes in that region as well as the instability modes within the roughness wake.

The growth-rate spectra for selected families of unstable modes obtained via the PNP eigenvalue analysis of the basic state in the vicinity of the center plane at $X/L = 0.300, 0.350, 0.400$, and 0.600 are shown in Figs. 10(a) through 10(d), respectively. For the purpose of illustration, the results for only symmetric modes are included here. Although we have not shown the results for the antisymmetric modes here, the growth-rate spectra for the A-type modes are very analogous to those of the S-type modes in Fig. 10, both in terms of their overall frequency range and the approximate range of peak growth rates. An in-depth analysis of the stability computations is still in progress and this paper reports only a partial set of computations performed so far.

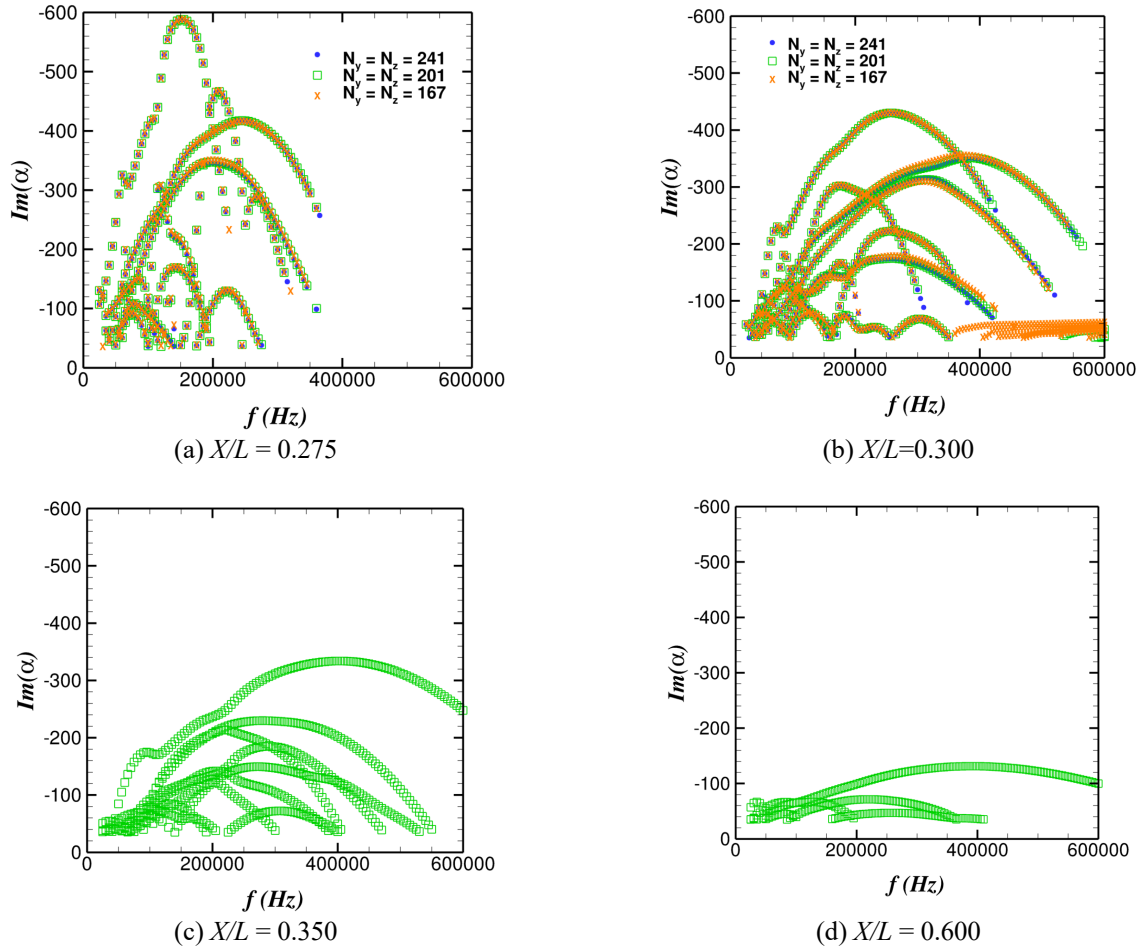


Figure 10. Growth rates as functions of frequency for the relevant instability modes at selected X/L locations. For brevity, only the modes with u' fluctuations that are symmetric with respect to the center plane (i.e., S-type) are shown here.

The baseline grid used for the PNP computations in Figs. 10(a)–(d) includes 201 points each along both Y and Z directions that are clustered near the regions of high gradients in either direction. The results obtained on this grid are indicated with green open squares in these figures. The results shown in Figs. 10(a) and 10(b) also include additional predictions based on a finer grid with 241 points in each direction (indicated by blue filled circles) as well as a coarser grid with 167 points each (displayed as orange crosses). In general, the growth rate spectra at each station correspond to a complex topology that is comprised of a large number of families of unstable modes. For ease of referencing, these mode families will be numbered according to the peak growth at the reference station of $X/L = 0.300$. It should be noted, however, that the highest local growth rate at any given station does not necessarily translate into the highest overall amplification factors, even within a given family of modes. Although not shown, all of these modes are concentrated within the high shear regions associated with one or more streaks associated with either the centerline mushroom structure or the dominant vorticity structures associated with the necklace vortices.

The results in Fig. 10 show that the highest disturbance growth rates are observed at the most upstream station with $X/L = 0.275$, i.e., within the near-wake region and the peak growth rate decreases monotonically by a factor of nearly four as one moves downstream from Fig. 10(a) to Fig. 10(d). Concomitantly, however, the overall frequency bandwidth of the wake instabilities is found to increase somewhat along the downstream direction.

As previously mentioned, the PNP eigenvalue computations were used to initiate plane-marching PSE computations over a range of frequencies for each mode family that were deemed as potentially significant. Close to ten mode families of the S-type and a similar number for the A-type disturbances were included in the PSE marching computations. Without any loss of significant information, we only present the results corresponding to the envelope of the N-factor curves for each mode family of interest. These results are shown in Fig. 11 below. The N-factor values are based on the surface integral of Mack's energy norm over the cross-section of the computational domain at any given axial station [34]. The mode-shape designation included in the legend indicates the symmetry of the mode shape, whether the peak fluctuations associated with the mode occur within the centerline (CL) streak or within the first (N1) or second (N2) necklace vortices and the ranking of this mode in terms of the peak local growth rate at $X/L = 0.275$.

Figure 11 shows that disturbance modes concentrated within the first necklace vortex (N1) amplify more rapidly than the remaining modes and represent the most amplified group of wake instabilities throughout the length of the wake shown in the figure. Both S- and A-type modes reach $N = 10$ near $X/L = 0.34$ and a N-factor of 15 just upstream of $X/L = 0.40$.

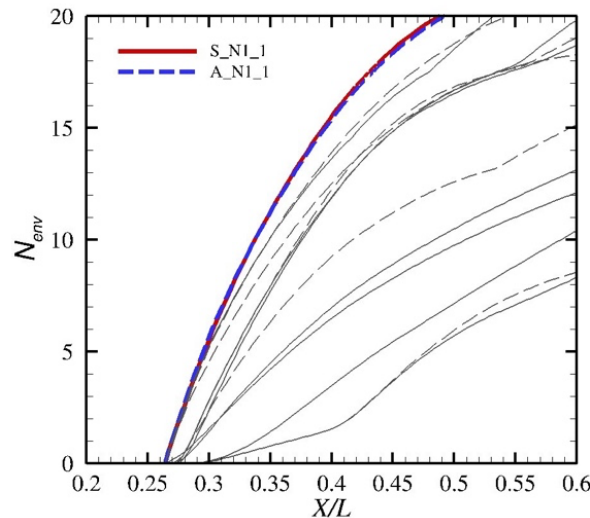


Figure 11. N-factor envelopes for the dominant families of unstable modes. The solid and dashed lines denote symmetric (S) and antisymmetric (A) modes, respectively.

Mode-shape evolution for the most amplified frequencies from the leading mode families of the S-type and A-type instabilities is shown in Fig. 12. As remarked earlier, the disturbances concentrated within the N1 and N2 vortex structures are sufficiently further away from the symmetry plane that they are not really influenced by the nature of

spanwise symmetry condition and may be regarded as effectively the same family. Thus, it is not surprising that the mode-shape evolution for the two modes in Fig. 12(a) and 12(b) is initially nearly the same up to $X/L > 0.4$, where the disturbance peak approaches the symmetry plane.

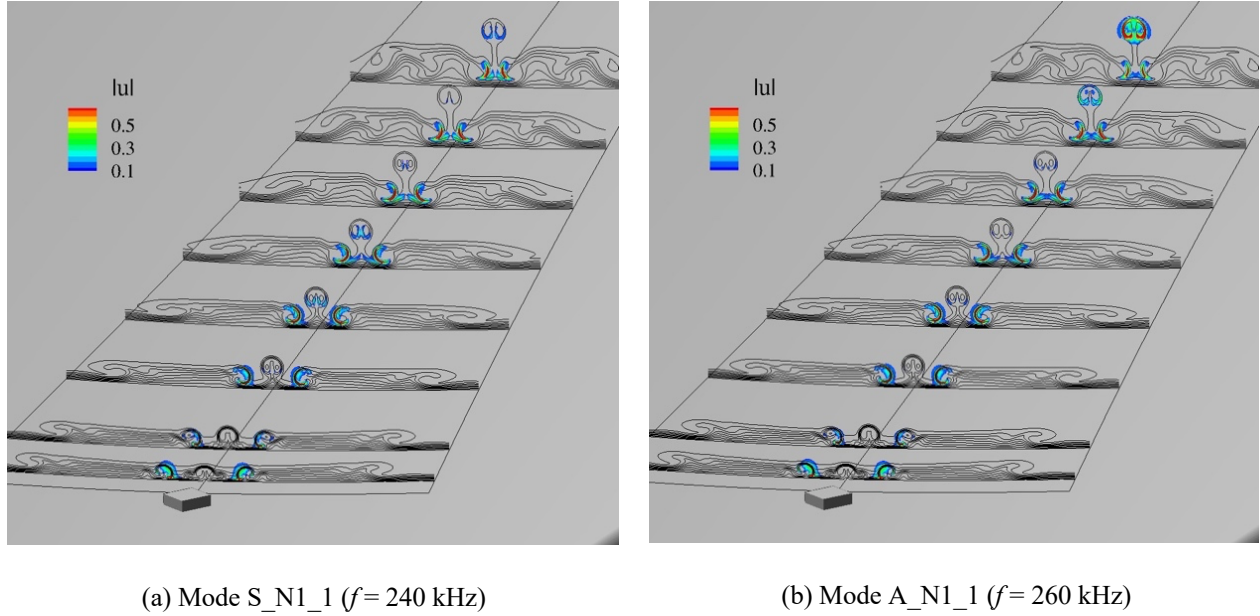


Figure 12. Mode-shape evolution for the most amplified disturbances from selected families of unstable modes. The iso-contours of streamwise-velocity perturbation, as well as the isolines of basic-state streamwise velocity ($u/U_\infty = 0:0.1:0.8$) are shown at the streamwise locations $X/L = 0.275, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55$, and 0.6 .

IV. Centerline Trip on Flight Configuration

A similar analysis of the centerline trip as that described in the previous section for the 1/3 scale model at wind tunnel conditions was also performed for the flight configuration at freestream conditions corresponding to a selected condition from the anticipated flight trajectory. The freestream conditions for this case are listed in Table 2. For the initial computations reported in this paper, the model temperature for the flight configuration is approximated as uniform throughout the surface, equal to $T_w = 400$ K. The same choice was also made in the case of the stability analysis for the primary side of the BOLT flight article in Ref. [10]. Based on preliminary information under consideration by the flight project, the centerline trip is located at $X = 0.254$ m, corresponding to $X/L = 0.254$ similar to the wind-tunnel configuration. The height of the trip is three times larger than that in the wind-tunnel case, i.e., $k = 2.625$ mm, planform side length, b , is again given by $b/k = 3.0$. For the targeted unit Reynolds number of $Re = 2.5 \times 10^6/\text{m}$ (which was, again, based on preliminary information under consideration by the flight project), we find that the trip height to boundary-layer thickness ratio is equal to $k/\delta \approx 0.70$, which is slightly smaller than the value of $k/d \approx 0.75$ in the wind-tunnel case from Section III. A comparison of the boundary-layer parameters at the trip location between the two cases is shown in Table 3. The correlation parameters $\frac{Re_\theta}{Me} \frac{k}{\delta} \left(\frac{h_{0,e}}{h_{0,w}} \right)^{0.30}$ and $(Re_k)^{0.30} \left[Re_\theta \left(\frac{\mu_e}{\mu_k} \right) \right]^{0.4}$ correspond, respectively, to the two best correlations from Ref. [30] as derived from flight and ground-facility data related to the shuttle Orbiter. The values of both correlation parameters for the present two trip configurations are significantly larger in comparison with the best fit values (namely, $Corbiter,5$ and $Corbiter,7$) as well as the corresponding bands of ± 2 standard deviations as given in Ref. [30]. Then it follows that the heights of both the wind-tunnel trip from Section III and the flight-case trip studied in the present section are well beyond the incipient transition criteria based on the shuttle Orbiter data. For the wind-tunnel case, this prediction based on either of the two empirical criteria from Eqs. (1) and (2) is consistent with the upper bound on transition location predicted via the higher fidelity wake

instability analysis in Section III. The comparison between the flight case predictions based on the empirical criteria and the linear-stability-based, semiempirical criterion will be investigated in the present section. We also note that the values of k/θ and Re_θ/M_e for the flight case in Table 3 are slightly higher in comparison with the TAMU predictions that were used to size the trip (S. C. Berry, private communication). Since the present results are relatively insensitive to the grid resolution, in follow-on work, the underlying basic-state flow profiles from the two solutions will be compared with each other to ascertain the reason behind this discrepancy.

Table 2. Freestream conditions for the flight configuration.

M_∞	Re_∞ ($10^6/\text{m}$)	Re_t (10^6)	U_∞ (m/s)	P_∞ (Pa)	T_∞ (K)
5.44	2.49	2.49	1637.63	1637.69	225.50

Table 3. Boundary layer parameters at the trip location ($X/L = 0.254$)

Flow Configuration	Re_∞ ($10^6/\text{m}$)	Re_t (10^6)	k (mm)	$\frac{h_{0,e}}{h_{0,w}}$	k/δ	k/δ^*	k/θ	Re_θ/M_e	Re_k	Re_{kk}	$\frac{Re_\theta k}{M_e \delta} \cdot \left(\frac{h_{0,e}}{h_{0,w}}\right)^{0.30}$	$(Re_k)^{0.30} \cdot \left[Re_\theta \left(\frac{\mu_e}{\mu_k}\right)\right]^{0.4}$
Wind Tunnel	20.25	6.75	0.875	1.60	0.75	1.69	7.11	164	1672	2392	141.82	1304.40
Flight	2.49	2.49	2.625	3.90	0.70	3.27	5.60	133	1647	1438	138.69	976.45

A. Basic State

The computational strategy for the trip configuration in flight is very similar to that of the wind-tunnel configuration from Section III and the grid used for the basic-state computation via VULCAN-CFD is actually a scaled version of the grid described in the context of Fig. 7. Figure 13 displays the vortex structures identified by applying the Q criterion to the solution for the flight configuration. Despite the difference in the Reynolds number from the wind-tunnel configuration, the vortex structures in Fig. 13 are seen to be very similar to those in Fig. 8 for the scaled version of this trip over the wind-tunnel configuration. Again, one observes a prominent pair of structures immediately adjacent to the centerplane and an outer pair of closely spaced structures associated with the system of necklace vortices.

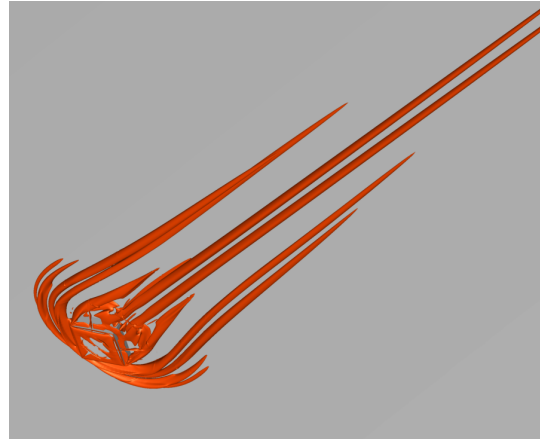


Figure 13. Vortex structures near the trip, plotted as an isosurface of $Q = 1.e-7$ (X increases from bottom left to top right).

The basic state within the trip-wake region was also computed with a 7th-order accurate algorithm in a DNS code [35], which will be referred to herein as the DNS computation of the basic state. The VULCAN-CFD solution immediately behind the trip was used as the inflow for the DNS computation. The algorithmic details of the high-order accurate solution are very similar to those in Ref. [10] and, therefore, are not repeated herein. It is sufficient to say that the DNS grid includes approximately 98 million grid points and is azimuthally clustered in the vicinity of the trip in order to resolve the spanwise gradients within the wake region. A comparison of the streamwise velocity

contours based on the VULCAN-CFD and DNS solutions at $X/L = 0.300$ is shown in Fig. 14(a), whereas a similar comparison at $X/L = 0.350$ is shown in Figure 14(b). In general, the DNS solution appears to provide a somewhat crisper definition of the vortex structures and the differences between the two solutions become more noticeable at the downstream station. Besides these differences, however, the two solutions are quite close to each other and essentially depict the same vortex structures in nearly identical positions. Nevertheless, a majority of the results presented in this section will use the basic state computed with the DNS instead of the VULCAN-CFD solution.

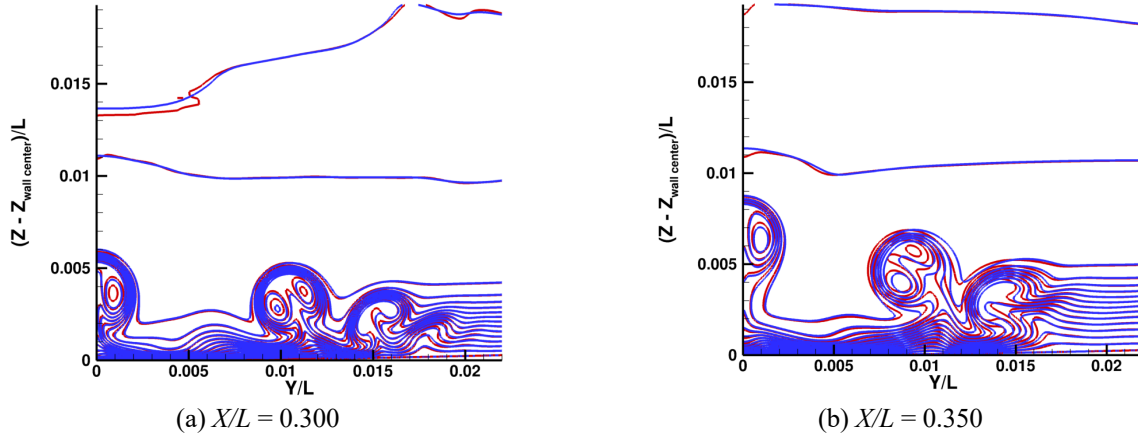


Figure 14. Comparison of VULCAN-CFD (blue) and DNS (red) solutions: Streamwise velocity contours of the laminar basic state at selected X locations.

Streamwise velocity contours based on the DNS solution at the farther downstream stations of $X/L = 0.400$ and $X/L = 0.600$ are shown in Figs. 15(a) and 15(b), respectively. The most significant difference between the crossplane contours in the wind tunnel and flight cases is that the flight case shows a prominent second necklace vortex structure (referenced herein as N2) near $Y/L = 0.013$ at both $X/L = 0.350$ in Fig. 14(b) and $X/L = 0.400$ in Fig. 15(a). In contrast, the crossplane contours for $X/L = 0.350$ in the wind-tunnel case reveal the vortex structure N1 as the only prominent feature besides the centerline streak (Fig. 9(c)).

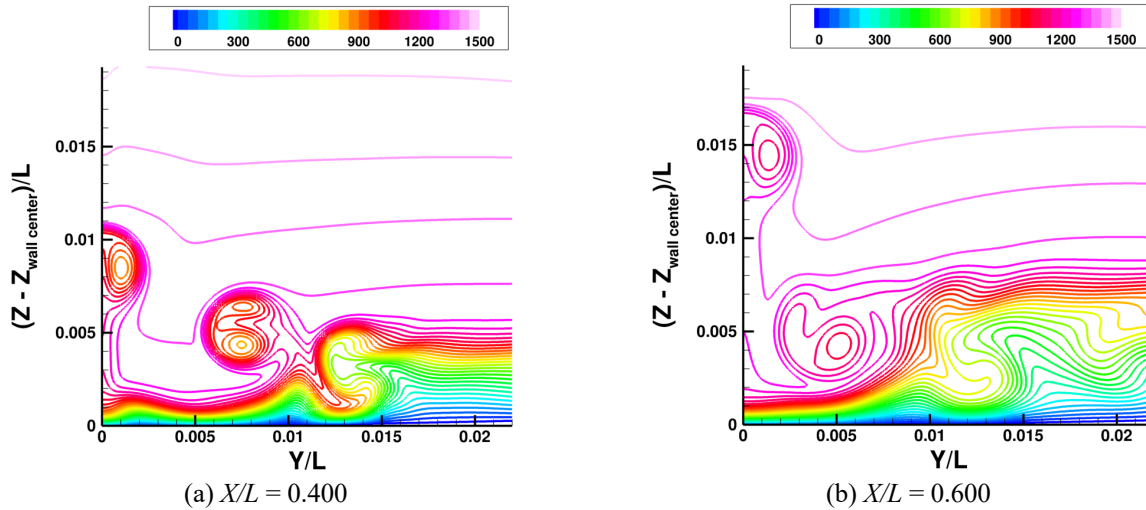


Figure 15. Downstream evolution of streamwise velocity contours in the DNS solution for the trip wake.

B. Trip-Wake Instability

The local growth rate spectra obtained from the PNP eigenvalue computations based on the DNS solution for the trip configuration in the flight case are plotted in Figs. 16(a) through 16(d) below. Only the results for the symmetric modes on the baseline grid are shown here. We also mention that the growth rate spectra based on the VULCAN-CFD solution indicated similar sets of modes, but the peak growth rate values were slightly lower in comparison to those based on the DNS basic state, presumably because of the higher resolution in the high-order solution.

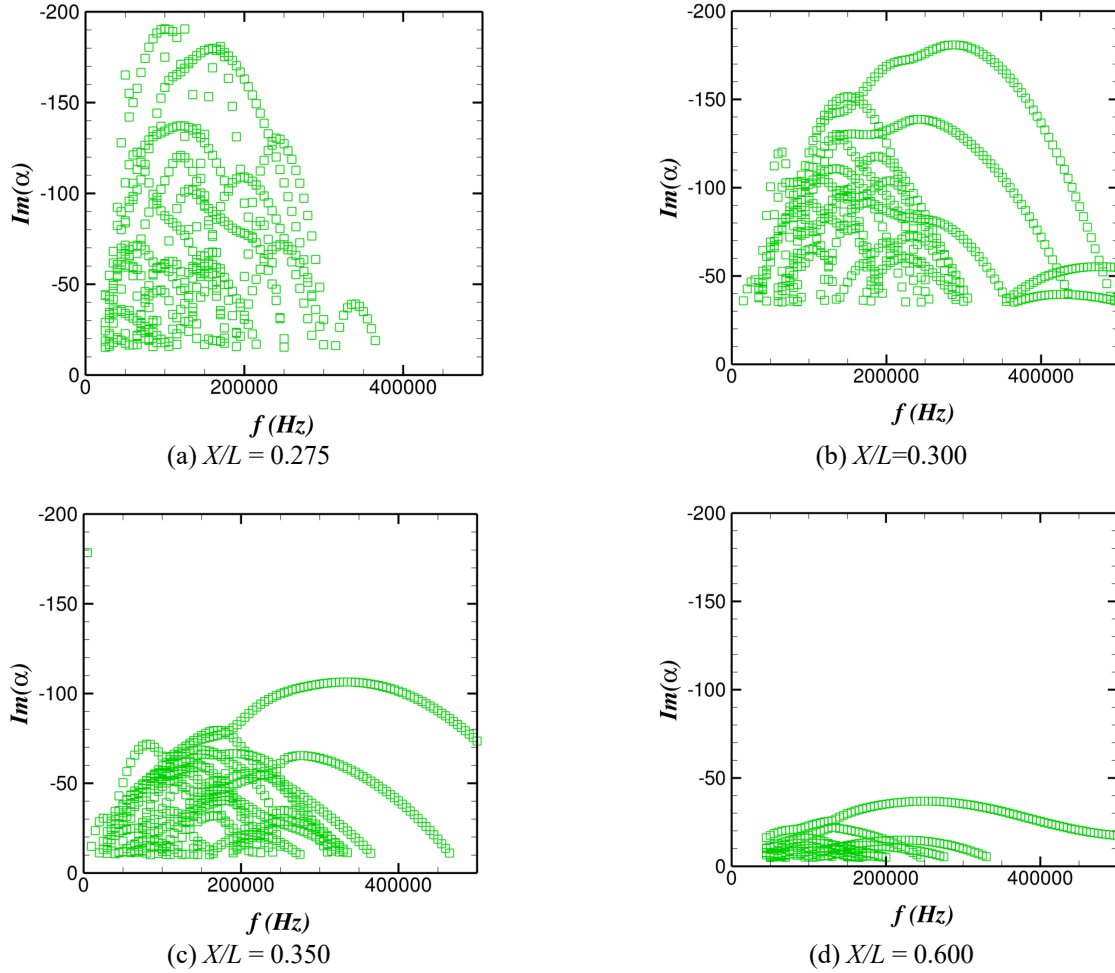


Figure 16. Growth rates as functions of frequency for the relevant instability modes at selected X/L locations. For brevity, only the modes with u' fluctuations that are symmetric with respect to the center plane (i.e., S-type) are shown here.

The trends in the growth rate spectra for the flight case are very similar to those observed in Fig. 10 for the wind tunnel configuration. Again, the highest growth rates are observed in the near wake and the frequency bandwidth at the downstream stations corresponding to the intermediate- and far-wake stations is higher than that for the $X/L = 0.275$ station in Fig. 16(a). The absolute values of the peak overall growth rate at each station are substantially lower than those at the corresponding stations from the wind-tunnel case; however, the decrease in peak growth rates is approximately consistent with the differences in the model (and trip) length scales. Thus, the change in freestream conditions and the surface temperature ratio between the two cases does not appear to have a strong influence on the peak local growth rates. This finding suggests that, at least in this particular case, the geometric similarity, combined with very close values of the k/δ parameter, leads to similar (overall) disturbance growth characteristics for the two

configurations. Therefore, it may be reasonable to expect the predicted transition locations (normalized by the respective reference length scales) would also be similar between the two configurations. This conjecture will be evaluated when we discuss the results for the overall amplification factors for the wake instabilities over the flight configuration.

The evolution of PSE-based N-factors for the shear-layer modes for the flight case is shown in Fig. 17. Again, both symmetric and antisymmetric disturbances concentrated within the N1 vortex structure are the first to achieve an N-factor of $N = 15$ and, in fact, represent the most amplified disturbances at any axial station; however, disturbances that are initially concentrated within the outer, N2 vortex also reach $N = 10$ at nearly the same location as the leading modes within N1. The disturbances within the centerline streak also achieve high N-factor values, albeit slightly downstream of the modes that originate from the instability within the N1 vortex. Overall, instability modes within the frequency range of 80 kHz – 280 kHz are estimated to achieve $N = 15$ or greater.

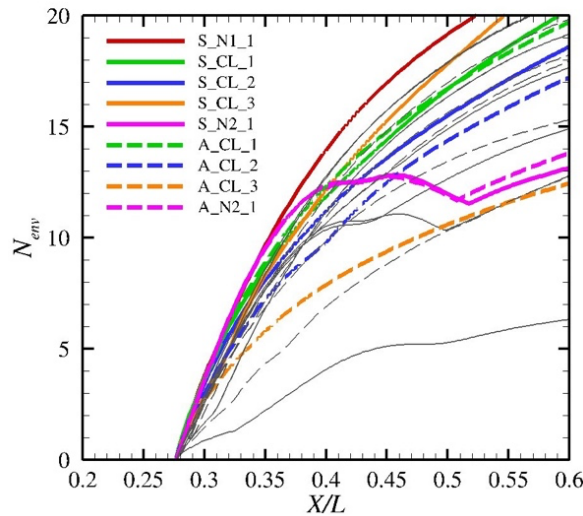
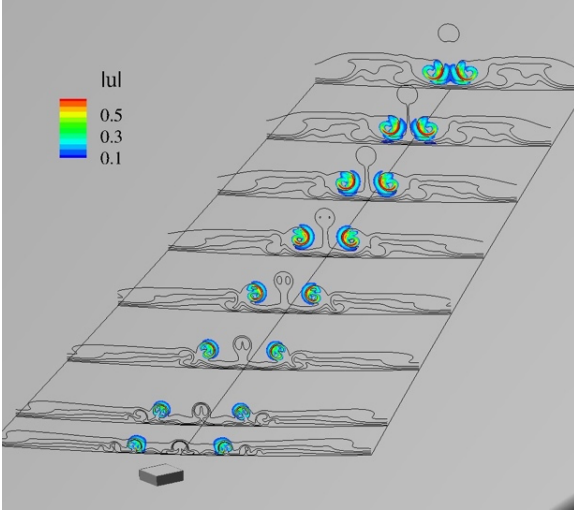
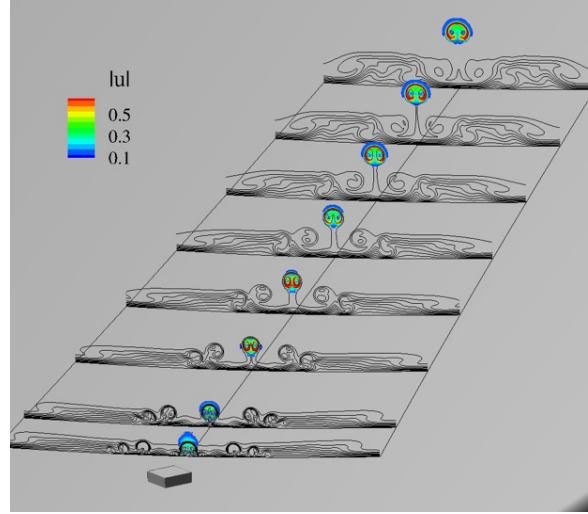


Figure 17. N-factor envelopes for the dominant families of unstable modes. The solid and dashed lines denote symmetric (S) and antisymmetric (A) modes, respectively.

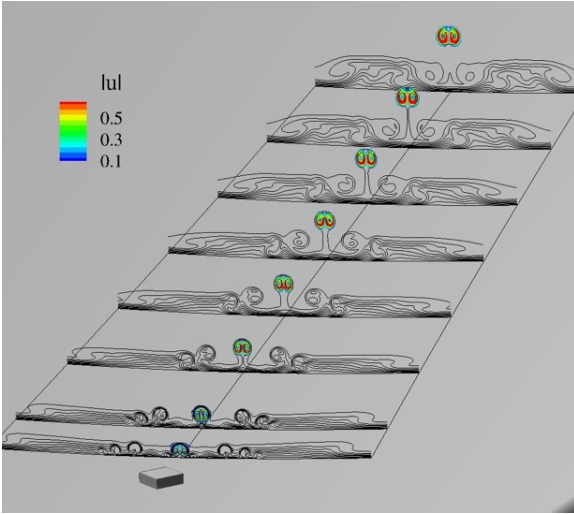
Figures 18(a,b) and 18(c,d) display the mode-shape evolution for the most amplified disturbances from the dominant groups of symmetric (S) and antisymmetric (A) mode families, respectively. The mode families selected for these plots are representative of the disturbances that originate from the instabilities of the centerline (CL) streak, the N1 vortex, as well as the N2 vortex. The disturbance mode shapes plotted in Figs. 18(a) through 18(c) appear to remain localized within the same structure throughout their evolution. On the other hand, the disturbance of mode type A_N2_1 is initially concentrated within the vortex structure N2, but switches over to the N1 vortex at the last two stations, namely, at $X/L = 0.55$ and 0.60 , respectively. We also note that because the peak amplitudes of the dominant instability modes of the centerline streak occur relatively farther from the wall, the breakdown induced by those instabilities would likely require a longer streamwise distance to propagate to the wall so that the cycle of self-sustained turbulent events can begin. Thus, even if those centerline modes were to reach the transition N-factor at about the same distance as the instabilities that are concentrated within the necklace vortices, the latter would be expected to induce an earlier onset of turbulence within the boundary layer.



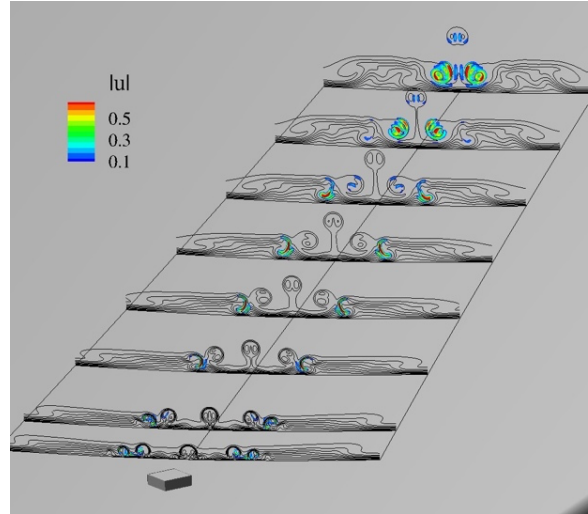
(a) Mode S_N1_1 ($f = 225$ kHz)



(b) Mode S_CL_1 ($f = 160$ kHz)



(c) Mode A_CL_1 ($f = 140$ kHz)



(d) Mode A_N2_1 ($f = 130$ kHz)

Figure 18. Mode-shape evolution for most amplified disturbances from selected families of unstable modes. The isocontours of streamwise velocity perturbation, as well as the isolines of basic state streamwise velocity ($u/U_\infty = 0:0.1:0.8$) are shown at streamwise locations $X/L = 0.275, 0.3, 0.35, 0.4, 0.45, 0.5, 0.55$, and 0.6 .

V. Summary and Concluding Remarks

Fundamental research during recent years has led to a considerably enhanced understanding of the physical mechanisms related to boundary-layer transition due to discrete trips. The NASA led secondary side experiment during the BOLT-II flight campaign should provide valuable data to augment the sparse set of flight measurements related to discrete, protuberance trips at hypersonic speeds, as well as extending the previous work related to mechanism-based transition prediction [12] to include the effects of a strong entropy layer and a nonzero crossflow component in the approaching boundary layer. In the present work, computations were performed to delineate the distortion of the boundary layer flow due to a pizza-box trip ($k/\delta \approx 0.70$, $b/k = 3.0$) along the centerline of the BOLT-II configuration as well as the effects of this distortion on the amplification of modal instabilities within the trip wake.

Results were presented for the flight configuration and freestream parameters corresponding to the design point ($M_\infty = 5.44$ and $Re_\infty = 2.5 \times 10^6/\text{m}$) from the descent portion of the planned flight trajectory as well as for a 1:3 scale model at flow conditions relevant to wind tunnel experiments. Trip location and dimensions for the flight case were based on preliminary information that was under consideration by the BOLT-II flight project. For the wind tunnel configuration, the trip size selected for the computations was scaled by the geometric scale factor of the overall model and the unit Reynolds number ($Re_\infty = 20.25 \times 10^6/\text{m}$) was chosen to maintain a similar ratio of roughness height to boundary-layer thickness ($k/\delta \approx 0.75$). In both cases, the trip was shown to induce a strong distortion of the unperturbed boundary layer in the vicinity of the trip, manifested in the form of multiple streamwise elongated vorticity structures within the wake of the trip. Analogous to the previous computations of relatively large roughness elements [20, 21, 31], these structures include a prominent centerline streak and additional streaks on either side that are associated with the system of necklace vortices formed in front of the trip.

The wake instability theory [17] was used in conjunction with computations based on the plane-marching PSE [34] to predict the modal amplification of traveling disturbances along in the wake region. Multiple types of instability modes were predicted to undergo strong amplification within the wake of the trip, and several different families of instability modes within the frequency range of approximately 80 kHz – 280 kHz were estimated to achieve a logarithmic amplification factor of $N = 15$ or greater. The fastest amplifying mode is concentrated within the necklace vortex N1, has a frequency of approximately 225 kHz and is predicted to reach $N = 15$ as early as $X/L = 0.42$. There also exist other mode types that amplify nearly equally rapidly and could also dominate the transition process depending on their receptivity characteristics. Regardless of which one or more of these modes dominate the transition process, the rapid amplification of the wake instabilities implies that the trip geometry analyzed herein is likely to induce laminar-turbulent transition over the BOLT-II secondary surface well before the design condition is reached, i.e., at lower unit Reynolds numbers than $Re_\infty = 2.5 \times 10^6/\text{m}$ during the descent part of the BOLT-II trajectory. Our follow-on work will focus on basic state computations on finer grids to allow a fuller assessment of the grid sensitivity of the stability results. Because prior computations for $k/\delta > 1$ [20, 21] have indicated the possibility of self-sustained unsteadiness just ahead of the trip, we also plan to investigate if a similar, global instability may arise at the lower values of k/δ considered for the BOLT-II flight experiment. Additional computations will investigate the effects of the downstream trip closer to the leading edge.

The basic-state computations without a trip were used to assess the roughness heights that may result in incipient transition according to the mean-flow correlation parameters used to predict the onset of transition in practical applications. For the centerline trip in flight, the present trip height of 2.625 mm was found to be well beyond the trip heights for incipient transition as predicted using the mean-flow parameters related to the boundary-layer edge and wall properties that had provided the best overall correlation metrics for the shuttle-orbiter specific transition data under the BLT Tool V. 2 for the shuttle-orbiter specific transition data [30]. Thus, the results of empirical correlations for protuberance induced transition are approximately consistent with those based on the wake instability paradigm, in that they both predict a significantly post-critical trip at $Re_\infty = 2.5 \times 10^6/\text{m}$. When the data from the USAFA experiment are fully postprocessed, the correlations based on the HIFiRE-1 and shuttle orbiter work will be further evaluated and tuned, if necessary, to enable more accurate predictions of protuberance induced transition for BOLT-like configurations.

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