

A Computational Analysis of Boundary Layer Instability over the BOLT Configuration

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The complex boundary layer flow over the BOLT flight configuration is known to exhibit multiple and potentially interacting instability mechanisms. This paper represents a continuation of our numerical investigation of the flow instabilities over the main test surface of the BOLT configuration by using state-of-the-art tools in multidimensional instability analysis. Specifically, the paper extends our previous computations by considering the separate effects of a nonzero angle-of-attack and a nonzero yaw on the modal instability characteristics of the boundary layer streaks adjacent to the minor-axis symmetry plane. At a selected condition from the ascent part of the anticipated flight trajectory, either type of departure from the design condition is shown to have a considerable impact on the structure of the laminar basic state and, hence, also on the amplification characteristics of the instability waves. A broader set of computations, including N-factor predictions for the relevant instabilities, will be presented in the final paper.

Nomenclature

c_{ph}	=	phase velocity along boundary layer edge streamline at the center plane [m/s]
f	=	frequency of instability waves [kHz]
h	=	specific enthalpy [J/kg]
L	=	axial body length [m]
M	=	Mach number (nondimensional)
M_∞	=	freestream Mach number (nondimensional)
M_e	=	Mach number at the edge of the boundary layer (nondimensional)
P_∞	=	freestream pressure [Pa]
Pr	=	Prandtl number (nondimensional)
$\dot{q}$	=	surface heat flux [W/m ²]
Re_L	=	Reynolds number based on body length (nondimensional)
Re_∞	=	freestream unit Reynolds number [m ⁻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 given location (nondimensional)
U_∞	=	freestream velocity [m/s]
X	=	axial coordinate [m]
Y	=	coordinate along major axis of model cross section [m]
Z	=	coordinate along minor axis of model cross section [m]
α	=	angle of attack [deg]

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β = yaw angle [deg]
 $\delta_{0.995}$ = boundary layer thickness based on $h_0/h_{0\infty} = 0.995$
 ρ = fluid density [kg/m³]

Subscripts

0 = stagnation condition
 e = edge of the boundary layer based on $h_0/h_{0\infty} = 0.995$
 w = wall
 ∞ = freestream

Abbreviations

BOLT = boundary layer transition
 DNS = direct numerical simulations
 HIFiRE = hypersonic international flight research experimentation
 PNP = partially nonparallel
 PSE = parabolized stability equations
 WENO = weighted essentially nonoscillatory

I. Introduction

Variability in the transition onset location can account for a major part of the overall uncertainty in the predicted heat loads on the surface of a hypersonic flight vehicle. Therefore, accurate estimates of laminar-turbulent boundary layer transition is an important aspect of the aerothermodynamic modeling of these vehicles. Wind tunnel experiments have played a crucial role in guiding the development of transition prediction models for low-speed flows. However, the transition process in conventional supersonic and hypersonic facilities tends to be dominated by the high levels of freestream disturbances associated with the acoustic radiation from the turbulent boundary layers along the wind tunnel walls. While low-disturbance facilities, i.e., the so called quiet wind tunnels can better mimic the inflight transition process, the existing ground facilities of this type are often limited to subscale models. Thus, flight measurements of boundary layer transition are particularly important for the development of reliable models for boundary layer transition over high-speed vehicles.

Transition over high-speed vehicles is often dominated by the effects of unavoidable surface roughness. However, transition prediction for smooth surfaces provides a valuable reference to gauge the effects of the roughness. Earlier flight experiments involving canonical body shapes with nominally smooth surfaces provided transition data for circular cones at supersonic [1] and hypersonic flight speeds [2–4]. Other notable examples of high-speed transition experiments include the Pegasus flight experiment that provided crossflow transition measurements over a specially designed wing glove and the Hyper-X (X-43) flight data [5] that was likely dominated by Mack mode transition over the upper surface of the vehicle [6]. The subsequent flight experiments involving circular cone (HIFiRE-1) and elliptic cone (HIFiRE-5) configurations have provided more detailed measurements toward the calibration of stability-based models for the transition mechanisms related to the Mack mode and crossflow instabilities, respectively [7–10]. The HIFiRE-5b configuration also exhibited an additional, complex flow feature in the form of a centerline streak near the minor-axis symmetry plane that is likely to have transitioned via shear layer instabilities that are concentrated within one or more localized regions of high shear within the streak [11–13]. Building upon the success of the HIFiRE-1 and HIFiRE-5b flight campaigns, the BOLT flight experiment [14] will focus on a more complex geometric configuration. The BOLT configuration (Fig. 1) shares certain geometric and flowfield features with the HIFiRE-5b elliptic cone but also exhibits a few key differences in the model geometry that result in a more complex basic state than HIFiRE-5b. For overviews of the BOLT flight campaign, the reader is referred to the papers by Wheaton et al. [14, 15].

The BOLT geometry includes a 2D nose tip with four swept leading edges curving around from the spanwise ends of the tip. These four leading edges are joined by four laterally concave surfaces, each of which has a single plane of symmetry. 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. The strongly concave gutter regions on the lateral sides were designed to isolate the flows on sides A and B, respectively. As part of the preflight investigations, Berridge et al. [16] conducted experiments on subscale BOLT models in the Boeing/AFOSR Mach 6 Quiet Tunnel (BAM6QT) at Purdue University and a full scale model in the LENS II facility at CUBRC. The surface pressure measurements obtained during both of these tests revealed the presence of narrow band, high-frequency spectral peaks that were indicative of

an instability mechanism of some type. However, the nature of these instabilities could not be determined. Additional measurements in both quiet and conventional wind tunnels at the Texas A & M University [17, 18] also indicated the presence of a spectral hump in the surface pressure measurements near the center plane of the test surface, i.e., near the minor-axis plane of symmetry of the BOLT configuration. Additional measurements based on hot wire anemometry were used to provide extra information about the crossplane distribution of the velocity fluctuations within a limited part of the model cross section. Additional spectral peaks in other areas of the test surface were measured in the BAMQT by Berridge et al. [13], including a peak that was attributed to a travelling crossflow instability and another peak along the outboard edge of the thick vortical region near the center plane.

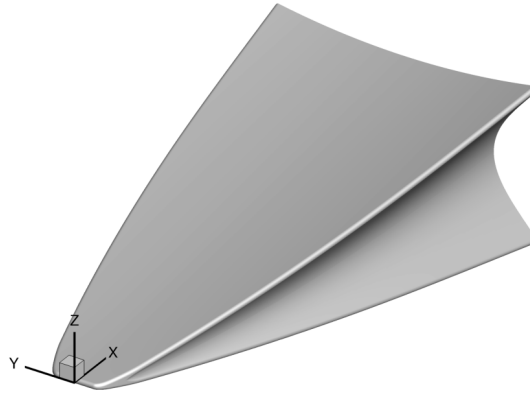


Figure 1. Schematic of the BOLT geometry. Side A corresponds to the top surface and Side B is the bottom surface that is hidden in this figure.

Thermographic measurements of a subscale BOLT configuration in the NASA Langley 20-Inch Mach 6 Air Tunnel by Berry et al. [20] revealed a prominent two-lobed transition pattern within the crossflow dominated region closer to the attachment lines along with transition along the center plane that was less obvious from the heat transfer imaging. The onset of transition was sensitive to the flow Reynolds number, but only weakly dependent on the angle of attack. On the other hand, a nonzero yaw resulted in a strongly asymmetric transition pattern on the test surface.

Direct numerical simulations (DNS) of the BOLT flight configuration at the University of Minnesota [21–23] revealed the presence of prominent, streamwise elongated vorticity structures along the test surface. The DNS methodology was extended to account for the effects of conjugate heat transfer in Ref. [24]. The thermal footprint of the computed vorticity structures was in good agreement with the measurements in the quiet flow experiments [21, 22]. The DNS also indicated the presence of four different types of nonstationary disturbances amplifying within the boundary layer flow, namely, those concentrated within the streaks along the outboard portions of the thickened boundary layer adjacent to the center plane, traveling crossflow disturbances inboard of the attachment line, a Mack mode instability that amplified in two different azimuthally localized regions, and the so-called mixed modes with a broad range of frequencies within the midspan region. Moyes et al. [25] analyzed the stability characteristics of the BOLT boundary layer and found significantly large N-factor values for the Mack mode instabilities in the region of adverse pressure gradient near the leading edge, as well as a strong amplification of crossflow instability modes within a wedge-shaped region on either side of the center plane. Even though some of the stationary streaks included in the DNS solutions from Refs. [22, 23] were not captured in the basic state computations with a second-order accurate, upwind-biased CFD scheme, Moyes et al. [26] showed that the streak evolution within the DNS solution could also be captured in the computations based on the nonlinear parabolized stability equations (PSE) by suitably tuning the initial disturbance amplitudes.

Berridge et al. [19] highlighted the lack of understanding of the transition mechanisms in the vicinity of the centerline as an important need. A recent analysis by Li et al. [27] showed that the streak instabilities adjacent to the BOLT center plane are analogous to those on the HIFIRE-5 elliptic cone, but that there are also important differences between the two because the streaks over the BOLT always remain at a finite distance from the center plane. There was encouraging agreement between the predicted frequency range of the streak instabilities and those measured in the experiments at TAMU. The computations also confirmed the strong effects of the flow Reynolds number on the amplification factors of streak instabilities, in agreement with the experimental observations by Berry et al. [20]. The investigation by Li et al. [27] also indicated the effects of a nonzero angle of attack and a nonzero yaw on the streak

patterns within the boundary layer. However, no detailed analysis of either the basic state structures or the instabilities thereof was carried out. The present work denotes the continuation of that study. In particular, an illustrative set of results pertaining to the basic state characteristics at $\alpha = 4$ deg and $\beta = 4$ deg are described in this extended abstract, along with the dominant types of modal instabilities in the former case. A broader set of computations of the boundary layer instability over the BOLT configuration, including N-factor curves for the relevant modes of instability, will be included in the final paper. A description of the flow configuration and the computational methodology is given in Section II. The laminar basic states at the flow conditions of interest are described in Section III, and the results of the instability analysis are presented in Section IV. Conclusions are presented in Section V.

II. Flow Configuration and Numerical Methodology

As mentioned in the Introduction, the flow configuration of interest corresponds to the BOLT configuration from Fig. 1. The flight article is 0.866 meters long, with a base width and base height of 0.438 meters and 0.256 meters, respectively. The BOLT geometry is symmetric about two mutually orthogonal planes and we denote the normal directions to these planes as the Y and Z axes of a Cartesian coordinate system, with the X axis along the axis of the model. The BOLT configuration differs from the HIFiRE-5 elliptic cone by virtue of its 2D nose tip with a twice as large nose radius (5 mm versus 2.5 mm for the HIFiRE-5 model) and a cross-section with concave transverse curvature on all four sides. However, the centerline geometry ($Y = 0$) of both configurations corresponds to a planar wedge inclined at 7 degrees with respect to the major-axis plane of symmetry (i.e., $Z = 0$).

As described by Li et al. [27], the basic state computations employ a two-step strategy, starting with a precursor computation based on the second-order, shock capturing code VULCAN (Viscous Upwind ALgorithm for Complex flow ANalysis) [28]. The VULCAN solution provides the boundary conditions for a higher-order DNS code focused on the flow downstream of the nose region and underneath the bow shock. 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 Sutherlands's law and the coefficient of thermal conductivity is computed by assuming a constant Prandtl number ($Pr = 0.72$).

The VULCAN code solves the unsteady, conservation equations appropriate for a laminar or turbulent flow of calorically or thermally perfect gases with a spatially second-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 [29] and the Low Dissipation Flux Split Scheme (LDFSS) of Edwards [30]. 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 second-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 [31] with a constant CFL number of 20. Due care was taken to ensure that the grid was aligned with the shock surface so as to avoid the generation of spurious flow features, especially within the nose region.

The basic states used for instability analysis were obtained by using higher-order computations based on the DNS-WENO code that derive the inflow and freestream boundary conditions from the VULCAN solutions. A detailed description of the governing equations and the numerical algorithms used in the DNS-WENO code is given by Wu and Martin [32]. For brevity, this code is henceforth referred to as simply the DNS code. The inviscid fluxes from the governing equations are computed using a seventh-order weighted essentially nonoscillatory (WENO) finite-difference as introduced by Jiang and Shu [33], and the DNS-WENO code also includes an optimized scheme that reduces the numerical dissipation by means of limiters [34]. Both an absolute limiter on the WENO smoothness measurement and a relative limiter on the total variation are employed simultaneously during the simulation. The viscous fluxes are discretized by using a fourth-order central difference scheme and the time integration is based on a third-order low-storage Runge-Kutta scheme [35]. The DNS code has also been used in the study of centerline transition on the HIFiRE-5b model and the evolution of the streak instabilities based on the DNS was in excellent agreement with the predictions of the plane marching PSE [11].

The specific cases investigated thus far are outlined in Table 1, and the sizes of the computational grids used in each case are listed in Tables 2 and 3 for the VULCAN and the DNS computations, respectively. We use the same case designation as that of Li et al. [27], who used the identifier FAL (i.e., Flight-Ascent-Low Reynolds number) to denote the two cases of interest in this extended abstract. The subscript 'b' in the mesh designation refers to the baseline mesh resolution. Exploiting the symmetry of the BOLT geometry, only the appropriate half of the model

was used for each the two cases corresponding to a nonzero α and nonzero β , respectively. The lack of grid sensitivity of the basic state computation on the grids used herein was confirmed in Ref. [27] for the $\alpha = \beta = 0$ case.

Table 1 Flow configurations and associated freestream conditions.

<i>Case Designation</i>	<i>BOLT configuration</i>	α (deg)	β (deg)	M_∞	Re_∞ (m ⁻¹)	Re_L	U_∞ (m/s)	P_∞ (Pa)	T_∞ (K)	T_w (K)
FAL $_\alpha$	Ascent ($t = 28.8767$ s)	4	0	5.53	4.25M	3.68M	1650.9	2380.2	222.0	400.00
FAL $_\beta$		0	4							

Table 2 Mesh parameters for VULCAN computations.

<i>Case Number</i>	<i>Mesh</i>	<i>Leading Edge Block</i>	<i>Main Part of BOLT Model</i>
FAL $_\alpha$	V-FAL $_{2Z,b}$	289×257×301	1121×833×301
FAL $_\beta$	V-FAL $_{2Y,b}$	577×129×301	1121×833×301

Table 3 Mesh parameters for DNS-WENO computations.

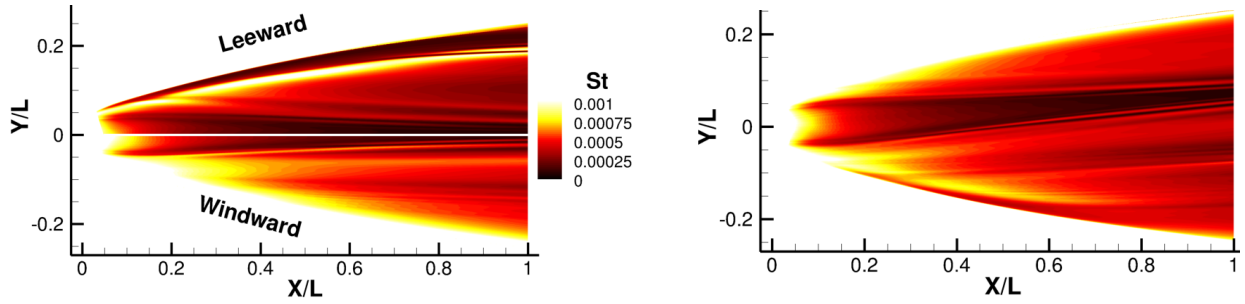
<i>Case Number</i>	<i>Mesh</i>	<i>Leading Edge Block</i>	<i>Main Part of BOLT Model</i>
FAL $_\alpha$	FAL $_{2Z,b}$	N/A	526×1138×246
FAL $_\beta$	FAL $_{2Y,b}$	N/A	526×1217×246

The stability of the basic states computed in this manner is investigated by using a combination of local, multidimensional eigenvalue analysis and plane marching parabolized stability equation (PSE) implementation [36]. The analysis of instability modes within the boundary layer streaks must account for the enhanced azimuthal gradients associated with the streaks within the region of interest, which correspond to relatively compact azimuthal regions (relative to the overall width of the body) on either side of the inviscid streamline from the center of the nose tip (i.e., $X = Y = 0$). As seen later in Section III, this region corresponds to a narrow subset of the test surface in the vicinity of the center plane (i.e., $Y = 0$) for all cases with a zero yaw angle. For a nonzero yaw angle, the above region is inclined with respect to the $Y = 0$ plane at approximately the same angle as the yaw direction. For $\beta = 0$ degrees, the basic state is symmetric about the center plane, and hence, it is more convenient to restrict the stability analysis to the $Y > 0$ side, with the flow disturbances assumed to be either symmetric or antisymmetric with respect to the $Y = 0$ plane [11, 27]. The symmetric modes 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 are associated with homogeneous Dirichlet boundary conditions in those quantities.

A typical grid size for the eigenvalue computations corresponds to 121 to 161 points in the wall-normal direction and between 151 to 251 points in the azimuthal direction. The azimuthal domain is truncated a short distance beyond the region of strong streaks adjacent to the center plane.

III. Basic States

Computational results pertaining to basic state computations for the two flow configurations of interest are presented in this section. The surface distributions of the Stanton number for the FAL $_\alpha$, and FAL $_\beta$ are plotted in Figs. 2(a) and 2(b), respectively. Both the angle of attack and the yaw produce a clearly visible effect on the number of prominent thermal streaks, their locations, and strengths. Significant differences are seen between the streak patterns along the windward and leeward segments of the test surface in both Figs. 2(a) and 2(b). In particular, a prominent set of hot and cold streaks is observed in close proximity to the attachment line along the leeward surface for case FAL $_\alpha$. The FAL $_\beta$ case also shows a prominently asymmetric streak pattern over the test surface, with multiple strong roll-ups on the windward side.



(a) Case FAL_α (Note that the leeward and windward sides are not physically contiguous and have been shown as mirror images of each other purely for convenience of illustration.)

(b) Case FAL_β

Fig. 2. Stanton number contours for Cases FAL_α (mesh $FAL_{2Z,b}$) and FAL_β (mesh $FAL_{2Y,b}$).

Cross-plane contours of the Mach number distributions at selected axial stations for the FAL_α case are shown in Figs. 3 and 4 for the leeward and windward sides, respectively. These figures indicate a qualitatively different streak evolution on the two sides. While the Mach number contours on both sides indicate two prominent rolled-up structures resembling inclined mushrooms over the aft portion of the model, there are significant differences between the two structures on the windward side. Specifically, the inboard structure (i.e., the one closer to the center plane) rolls up earlier and is appreciably greater in size in comparison with the outboard structure. On the other hand, the two structures on the leeward side are very comparable in both size and the respective roll-up locations. As shown in the following section, these differences in streak structures lead to large differences in the amplification characteristics on the windward and the leeward sides. Although not shown, the angle of attack also modifies the flow behavior in the vicinity of the leading edges, leading to the formation of rollup structures adjacent to the leading edge on the leeward side, and also on the gutter side of the windward leading edge. The instability characteristics of the former structures on the instability of the boundary layer flow over the test surface will be examined in the full paper.

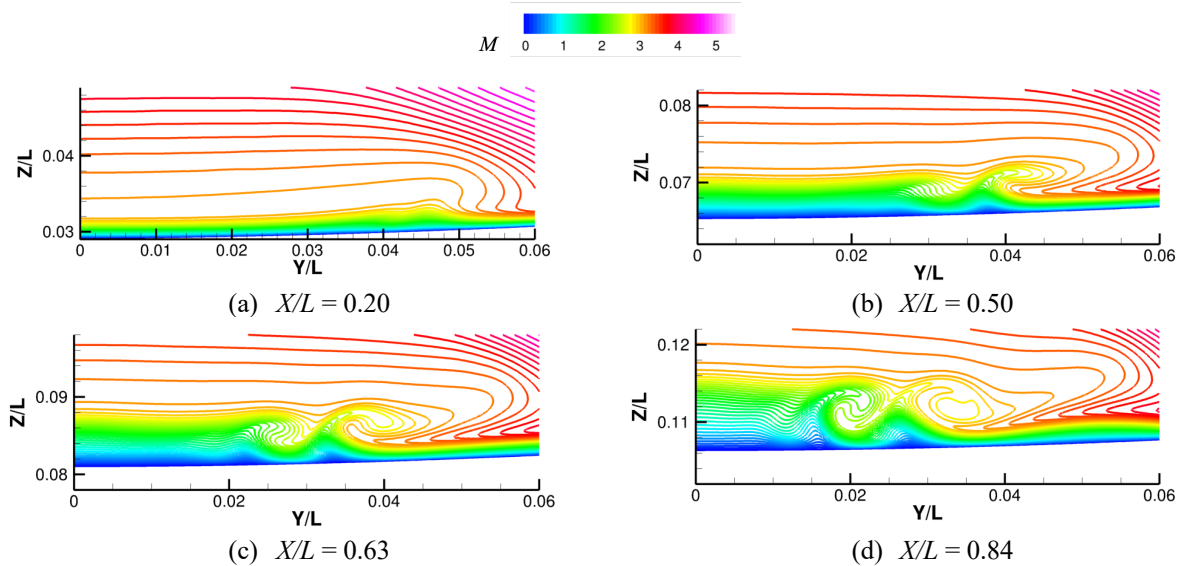


Fig. 3. Mach number contours of the basic state near the leeward symmetry plane for Case FAL_α (mesh $FAL_{2Z,b}$). Contour values range from 0 to 5, in increments of 0.1.

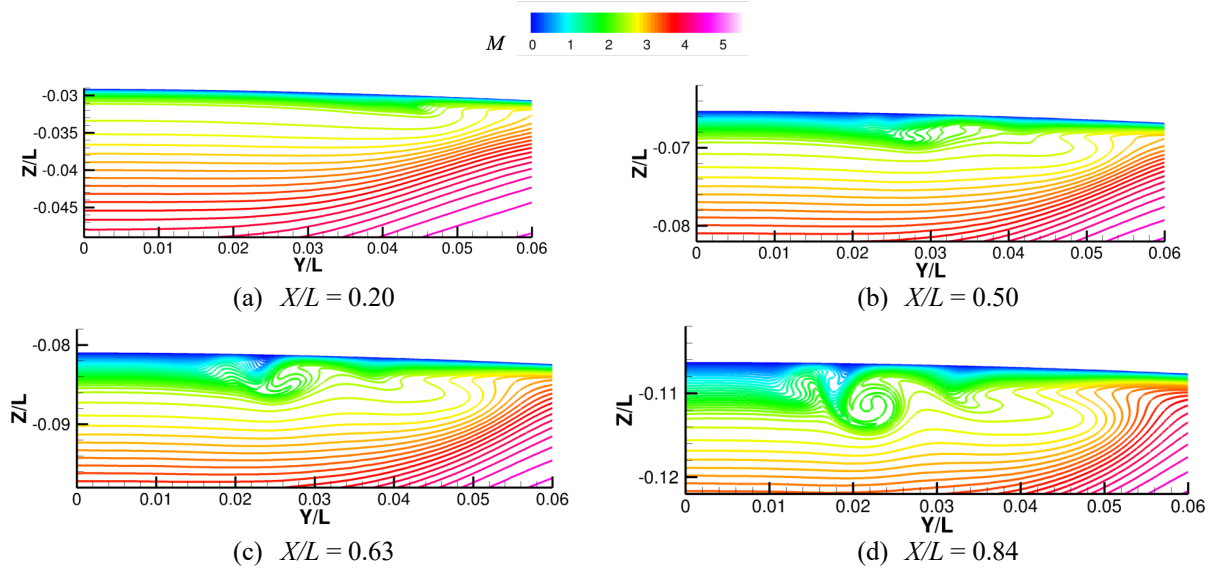


Fig. 4. Mach number contours of the basic state near the windward symmetry plane for Case FAL_α (mesh $FAL_{2z,b}$). Contour values range from 0 to 5, in increments of 0.1.

Mach number contours at the same set of locations for the FAL_β case are displayed in Fig. 5. Due to the nonzero angle of yaw, the region of thickened boundary layer behind the 2D nose tip is now shifted to the right. Indeed, at $X/L = 0.63$ and $X/L = 0.84$, both sets of rolled-up structures appear to the right of the geometric symmetry plane ($Y/L = 0$) of the model. Similar to the previously discussed evolution for the FAL_α case, one observes a prominent asymmetry between the rollup of the Mach number contours on either side of the azimuthal region of thickened boundary layer. As a result, the relative strengths of the multiple rolled-up structures indicate significant variations between the two sides.

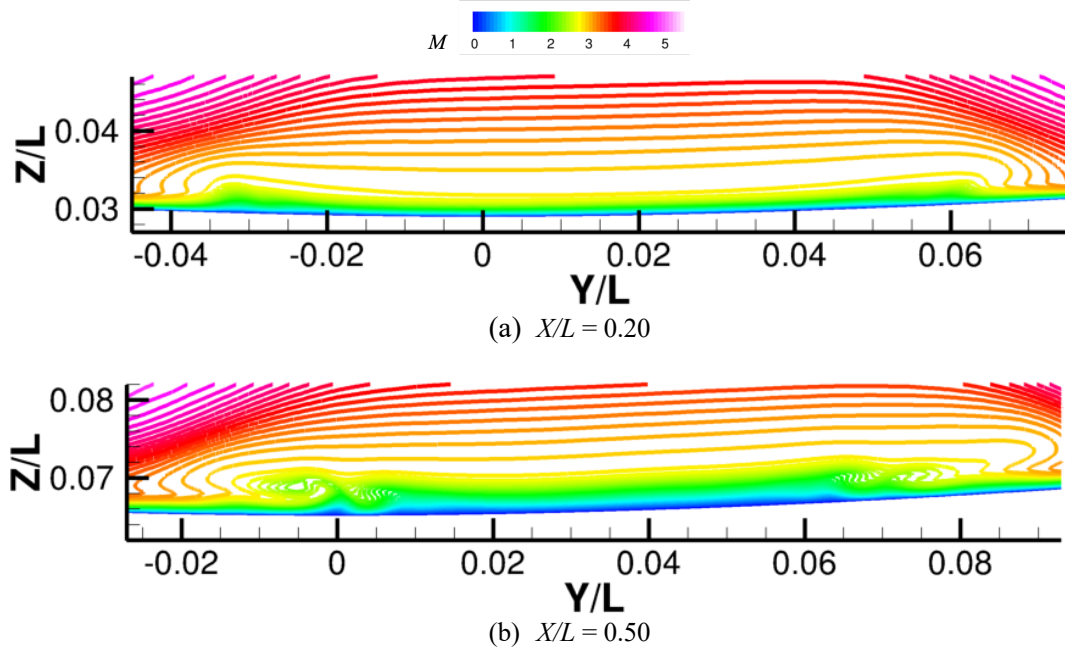


Fig. 5. Mach number contours of the basic state near the symmetry plane for Case FAL_β (mesh $FAL_{2Y,b}$). Contour values range from 0 to 5, in increments of 0.1 (continued on the following page).

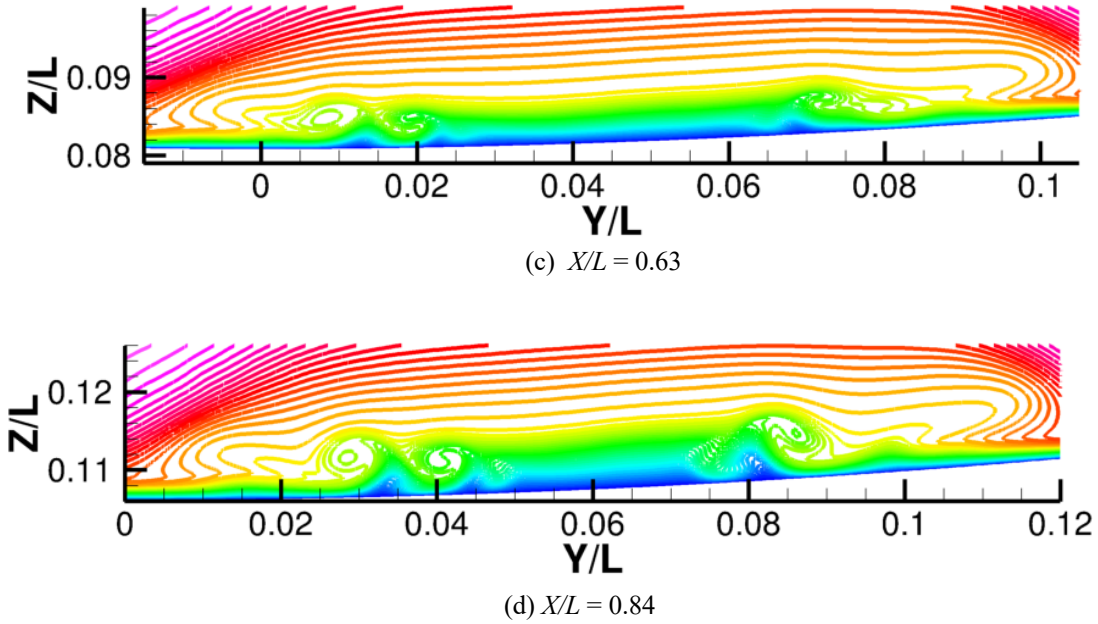


Fig. 5. Continued from the previous page.

IV. Streak Instability Characteristics

Computational findings based on the stability analyses of the basic state for the Case FAL_α are outlined in this section. A more complete set of results for each case of interest will be described in the final paper.

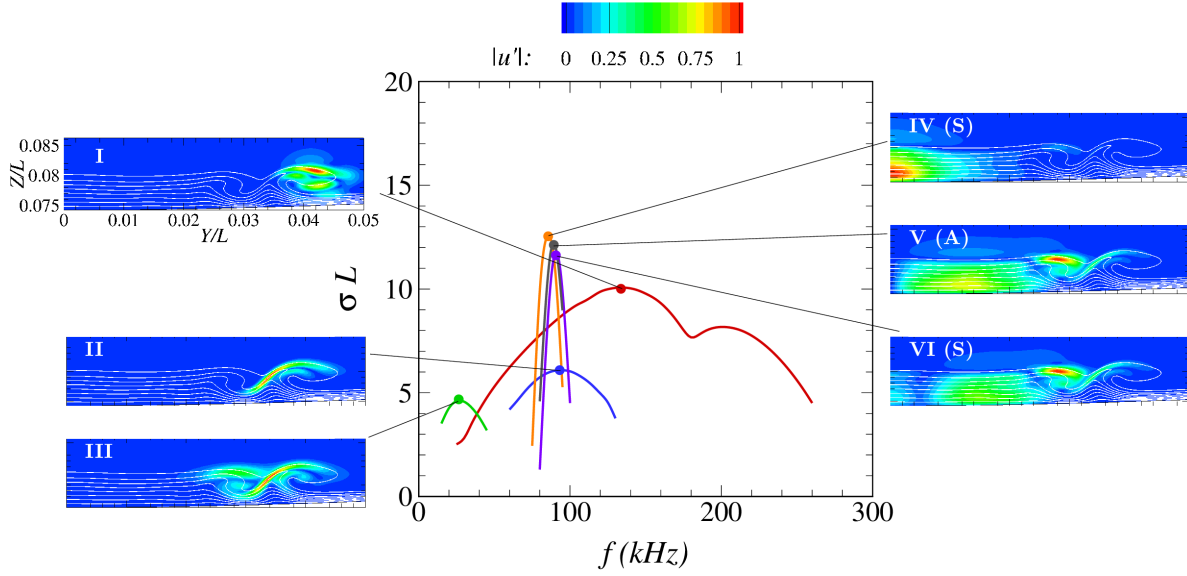
The growth rate spectra for selected families of unstable modes obtained via the partially nonparallel (PNP) eigenvalue analysis [27] of the basic state in the vicinity of the center plane on the leeward side at $X/L = 0.515$ are shown in Fig. 6(a), along with the mode shapes of the $|u'|$ velocity perturbation for the disturbance frequencies that approximately correspond to the most unstable mode from each family. The white lines in the mode shape plots represent the streamwise velocity contours of the base flow, and the colored contours indicate the magnitude of the axial velocity fluctuations. The associated phase speeds of the modes is plotted in Fig. 6(b). Analogous results for the windward side are shown in Figs. 7(a) and 7(b), respectively.

A total of six different families of unstable modes are plotted in Fig. 6 for the leeward side. For ease of referencing, these mode families are numbered as I through VI, respectively, but the ordering of the modes does not have any physical significance. There are additional unstable modes, but they were deemed to be unimportant either because of low overall amplification factors or because their peak fluctuations occur outboard of the prominent streak adjacent to the center plane. For example, disturbances resembling traveling crossflow instabilities can occur in the outboard region, but they are considered to be beyond the scope of the present analysis, which is focused on the streak instabilities near the center plane.

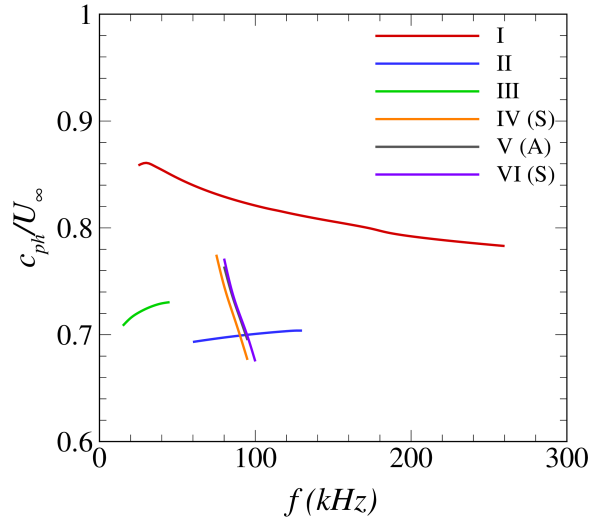
The line contours in white in the mode shape plots of Fig. 6(a) indicate the two vorticity structures or the streak regions of interest adjacent to the center plane, specifically, one just inboard of $Y/L = 0.03$ and the other near the outboard edge of the thickened boundary layer in the vicinity of $Y/L = 0.04$. Modes I through III denote the shear layer modes that are concentrated in the regions of high basic state shear within the two vorticity structures. Mode I, which has the highest amplification rates among these shear layer modes, is concentrated near the top of the outboard streak, whereas Modes II and III have their peak velocity fluctuations concentrated within the inclined portion of the shear layer along the inboard side of the outer streak. The peak growth rate of Mode I is nearly twice as large as the peak growth rate associated with Mode II. On the other hand, the wall-normal distribution of the velocity fluctuations associated with Mode IV resembles the typical structure of Mack mode instabilities. While the wall-normal distribution of Modes V and VI within the inboard region resembles that of Mode IV, the peak $|u'|$ values associated with these two modes are observed within the shear layers farther outboard. Furthermore, consistent with the known

behavior of the Mack mode instabilities, the frequency bandwidth of Modes IV through VI is substantially lower than that of the dominant shear layer Mode (Mode I). On the other hand, each of the Mack mode like disturbances have higher peak growth rates than that of the Mode I.

The axial phase speeds of Mode Families IV through VI are very close to each other at any given frequency. On the other hand, the phase speeds of Modes II and III are significantly lower than those of the Mode I disturbances, consistent with the fact that Modes II and III are concentrated in the inclined shear layer as against the top of the streaks.

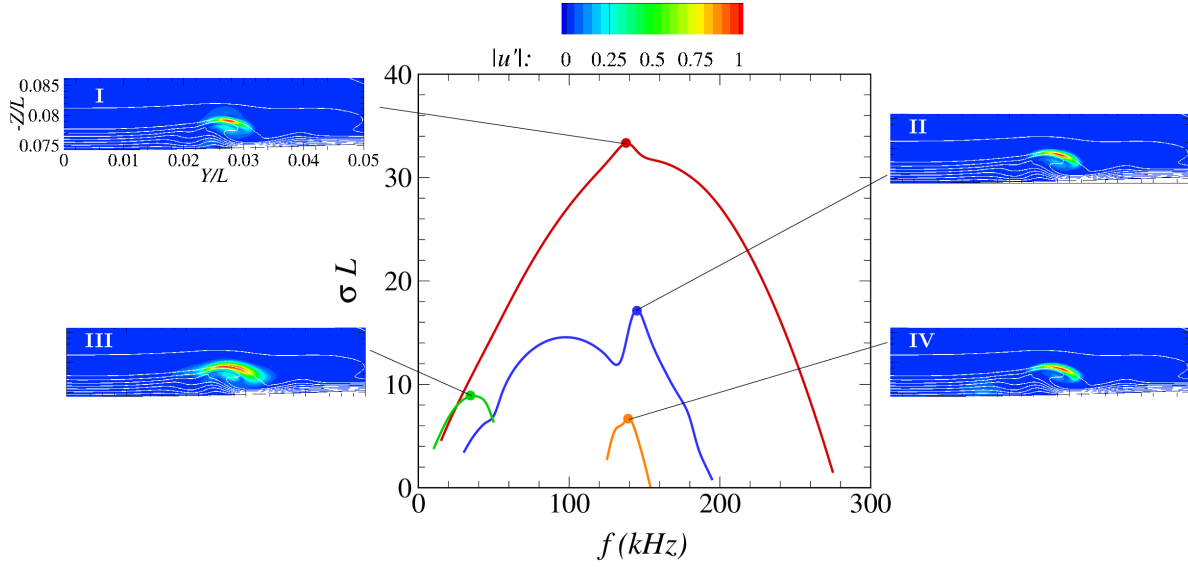


(a) Growth rate spectra and associated mode shapes

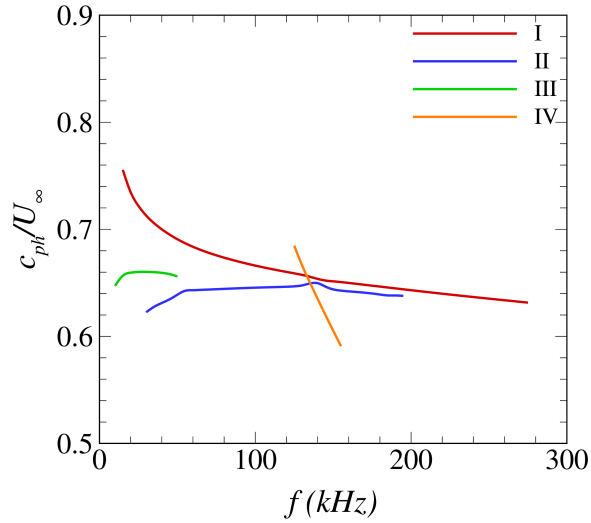


(b) Phase speed spectra (line colors identical to mode families indicated in part (a))

Fig. 6. Growth rate and phase speed as functions of frequency for the relevant instability modes on the leeward side at $X/L = 0.515$. The label within the parentheses next to the mode number indicates whether the mode corresponds to a symmetric (S) or an antisymmetric (A) mode. The representative mode shapes of each family indicate the $|u'|$ fluctuations associated with the locally most unstable disturbance frequency from that family. The $|u'|$ values are normalized to a peak value of unity.



(a) Growth rate spectra and associated mode shapes



(b) Phase speed spectra (line colors identical to mode families indicated in part (a))

Fig. 7. Growth rate and phase speed as functions of frequency for the relevant instability modes on the windward side at $X/L = 0.515$. The representative mode shapes of each family indicate the $|u'|$ fluctuations associated with the locally most unstable disturbance frequency from that family. The $|u'|$ values are normalized to a peak value of unity. To allow for easier visual comparison of the mode shapes with those on the leeward side, the direction of the Z axis is reversed in part (a).

On the other hand, the growth rate spectra in Fig. 7(a) demonstrate that, despite the weaker rollup of the basic state velocity contours on the windward side, the peak growth rates of the streak instabilities are significantly higher than either the shear layer modes or the Mack mode type disturbances on the leeward side. The peak growth rate for Mode I disturbances on the windward side is more than twice the peak growth rate of the various instabilities near the leeward center plane. Also, all four dominant modes on the windward side correspond to shear layer modes that are concentrated near the top of the rollup structure near the outboard edge of the thickened boundary layer. The rapid change in boundary layer thickness at this azimuthal location is associated with the change in entropy layer behavior due to the transition from the 2D nose tip to the highly swept leading edges of the BOLT configuration. We also note

that the frequency range of the dominant shear layer mode (Mode I) is very similar on both sides of the model; however, the phase speed of the Mode I disturbances on the windward side is significantly lower than that on the leeward side (Fig. 7(b)).

V. Summary and Concluding Remarks

This paper represents the continuation of the previous numerical studies pertaining to the streak instabilities within the region of boundary layer thickening near the center plane of nonaxisymmetric hypersonic configurations. Specifically, the analysis of streak instabilities on either side of the center plane of the BOLT flight configuration is extended to include the effects of a nonzero angle of attack and a nonzero yaw angle. Each of these attitude modifications is shown to have a prominent effect on the overall streak pattern over the model, including the streaks on either side of the region of boundary layer thickening. The resulting asymmetry of the streaks also leads to large differences in the amplification rates of the shear layer instabilities associated with the streaks. An expanded set of computations pertaining to the transition behavior over the test surface of the BOLT configuration would be presented in the final paper.

Acknowledgments

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References

1. Dougherty, N. S. and Fisher, D. F., "Boundary Layer Transition on a 10-degree Cone: Wind Tunnel/Flight Data Correlation," AIAA Paper 1980-0154, 1980.
2. Sherman, M. M., and Nakamura, T., "Flight Test Measurements of Boundary-Layer Transition on a Nonablating 22-Degree Cone," *Journal of Spacecraft and Rockets*, Vol. 7, No. 2, 1970, pp. 137–142.
3. Carter, H. S., Raper, J. L., Hinson, W. F., and Morris, W. D., "Basic Measurements from a Turbulent-Heating Flight Experiment on a 5° Half-Angle Cone at Mach 20 (Reentry F)," NASA TM X-2308, 1971.
4. Johnson, C. B., Stainback, P. C., Wicker, K. C., and Bony, L. R., "Boundary-Layer Edge Conditions and Transition Reynolds Number Data for a Flight Test at Mach 20 (Reentry F)," NASA TM X-2584, 1972.
5. Malik, M. R., Li, F., and Choudhari, M., "Analysis of Crossflow Transition Flight Experiment aboard the Pegasus Launch Vehicle," AIAA Paper 2007-4487, 2007.
6. Berry, S., Daryabeigi, K., Wurster, K., and Bittner, R., "Boundary-Layer Transition on X-43A," *Journal of Spacecraft and Rockets*, Vol. 47, No. 6, 2010, pp. 922–934. <https://doi.org/10.2514/1.45889>
7. Kimmel, R. L., Adamczak, D., Paull, A., Paull, R., Shannon, J., Pietsch, R., Frost, M., and Alesi, H., "HIFiRE-1 Ascent-Phase Boundary-Layer Transition," *Journal of Spacecraft and Rockets*, Vol. 52, No. 1, 2015, pp. 217–230. <https://doi.org/10.2514/1.A32851>
8. Li, F., Choudhari, M., Chang, C.-L., Kimmel, R., Adamczak, D., and Smith, M., "Transition Analysis for the Ascent Phase of HIFiRE-1 Flight Experiment," *Journal of Spacecraft and Rockets*, Vol. 52, No. 5, 2015, pp. 1283–1293. <https://doi.org/10.2514/1.A33258>
9. Kimmel, R. L., Adamczak, D. A., and DSTG AVD Brisbane Team, "HIFiRE-5b Flight Overview," AIAA Paper 2017-3131, June 2017. <https://doi.org/10.2514/6.2017-3131>
10. Tufts, M. P., Gosse, R., and Kimmel, R. L., "PSE Analysis of Crossflow Instability on HIFiRE 5b Flight Test," AIAA Paper 2017-0764, January 2017. <https://doi.org/10.2514/6.20178-0764>
11. Choudhari, M., Chang, C.-L., Li, F., Berger, K., Candler, G., and Kimmel, R., "Transition Analysis for the HIFiRE-5 Vehicle," AIAA Paper 2009-4056, 2009. <https://doi.org/10.2514/6.2009-4056>
12. Paredes, P., Gosse, R., Theofilis, V., and Kimmel, R. L., "Linear Modal Instabilities of Hypersonic Flow over an Elliptic Cone," *J. Fluid Mechanics*, Vol. 804, 2016, pp. 442–466. <https://doi.org/10.1017/jfm.2016.536>
13. Choudhari, M., Li, F., and Paredes, P., "Streak Instabilities on HIFiRE-5 Elliptic Cone," AIAA Paper 2020-0828, 2020. <https://doi.org/10.2514/6.2020-0828>
14. Wheaton, B., Berridge, C., Wolf, T., Stevens, R., and McGrath, B., "Boundary Layer Transition (BOLT) Flight Experiment Overview," AIAA Paper 2018-2892, 2018. <https://doi.org/10.2514/6.2018-2892>
15. Wheaton, B., Berridge, C., Wolf, T., Stevens, R., Araya, D., Stevens, R., McGrath, B., and Adamczak, D., "Final Design of the Boundary Layer Transition (BOLT) Flight Experiment," AIAA Paper 2020-1041, 2020. <https://doi.org/10.2514/6.2020-1041>
16. Berridge, D. C., McKiernan, G. R., Wheaton, B. M., Wolf, T. D. and Schneider, S. P., "Hypersonic Ground Tests In Support of the Boundary Layer Transition (BOLT) Flight Experiment," AIAA Paper 2018-2893, 2018. <https://doi.org/10.2514/6.2018-2893>

17. Kostak, H. E., Bowersox, R. D. W., McKiernan, G., Thome, J., Candler, G., and King, R. A., "Freestream Disturbance Effects on Boundary Layer Instability and Transition on the AFOSR BOLT Geometry," AIAA Paper 2019-0088, 2019. <https://doi.org/10.2514/6.2019-0088>
18. Kostak, H. E. and Bowersox, R. D. W., "Hypersonic Boundary Layer Off-Body and Surface Measurements on the AFOSR BOLT Geometry," AIAA Paper 2020-1043, 2020. <https://doi.org/10.2514/6.2020-1043>
19. Berridge, D., Kostak, H., McKiernan, G., King, R., Wason, M., Wheaton, B., Wolf, T., and Schneider, S., "Hypersonic Ground Tests with High-frequency Instrumentation in Support of the Boundary Layer Transition (BOLT) Flight Experiment," AIAA Paper 2019-0090, 2019. <https://doi.org/10.2514/6.2019-0090>
20. Berry, S. A., Mason, M. L., Greene, F. A., King, R. A., Rieken, E. F., and Basore, K. D., "LaRC Aerothermodynamic Ground Tests in Support of BOLT Flight Experiment," AIAA Paper 2019-0091, 2019. <https://doi.org/10.2514/6.2019-0091>
21. Thome, J., Dwivedi, A., Nichols, J., and Candler, G., "Direct Numerical Simulation of BOLT Hypersonic Flight Vehicle," AIAA Paper 2018-2894, 2018. <https://doi.org/10.2514/6.2018-2894>
22. Knutson, A., Thome, J., and Candler, G., "Numerical Simulation of Instabilities in the Boundary-Layer Transition Experiment Flowfield," *Journal of Spacecraft and Rockets*, 2019. <https://doi.org/10.2514/1.A34599>
23. Thome, J., Knutson, A., and Candler, G., "Boundary Layer Instabilities on BOLT Subscale Geometry," AIAA Paper 2019-0092, 2019. <https://doi.org/10.2514/6.2019-0092>
24. Thome, J., Reinert, J. D. and Candler, G., "Effect of Steady Forcing on BOLT Flowfield for Flight Reynolds Numbers," AIAA Paper 2020-1042, 2020. <https://doi.org/10.2514/6.2020-1042>
25. Moyes, A. J., Kocian, T. S., Mullen, C. D., and Reed, H. L., "Preflight Boundary-Layer Stability Analysis of BOLT Geometry," AIAA 2018-2895, 2018. <https://doi.org/10.2514/6.2018-2895>
26. Moyes, A. J. and Reed, H. L., "Nonlinear Boundary-Layer Stability Analysis of BOLT and HIFiRE-5," AIAA 2019-2972, 2019. <https://doi.org/10.2514/6.2019-2972>
27. Li, F., Choudhari, M., and Paredes, P., "Streak Instability Analysis for BOLT Configuration," To be presented at the AIAA Aviation Forum, June 2020.
28. <http://vulcan-cfd.larc.nasa.gov/index.html> (April 17, 2020)
29. van Albada, G. D., van Leer, B. and Roberts, W. W., "A Comparative Study of Computational Methods in Cosmic Gas Dynamics," *Astronomy and Astrophysics*, Vol. 108, pp. 76-84, 1982. https://doi.org/10.1007/978-3-642-60543-7_6
30. Edwards, J. R., "A Low-Diffusion Flux-Splitting Scheme for Navier-Stokes Calculations," *Computer and Fluids*, Vol. 6, pp. 635-659, 1997. [https://doi.org/10.1016/S0045-7930\(97\)00014-5](https://doi.org/10.1016/S0045-7930(97)00014-5)
31. Litton, D., Edwards, J., and White, J., "Algorithmic Enhancements to the VULCAN Navier-Stokes Solver," AIAA Paper 2003-3979, 2003. <https://doi.org/10.1017/S0022112010005094>
32. Wu, M. and Martin, M. P., "Direct Numerical Simulation of Supersonic Boundary Layer over a Compression Ramp," *AIAA Journal*, Vol. 45, No. 4, 2007, pp. 879-889. <https://doi.org/10.2514/1.27021>
33. Jiang, G. S. and Shu, C. W., "Efficient Implementation of Weighted ENO Schemes," *J. Comp. Phys.*, Vol. 126, No. 1, 1996, pp. 202-228. <https://doi.org/10.1006/jcph.1996.0130>
34. Taylor, E. M., Wu, M., and Martin, M. P., "Optimization of Nonlinear Error Sources for Weighted Non-Oscillatory Methods in Direct Numerical Simulations of Compressible Turbulence," *J. Comp. Phys.*, Vol. 223, No. 1, 2006, pp. 384-397. <https://doi.org/10.1016/j.jcp.2006.09.010>
35. Williamson, J., "Low-Storage Runge-Kutta Schemes," *J. Comp. Phys.*, Vol. 35, No. 1, 1980, pp. 48-56. [https://doi.org/10.1016/0021-9991\(80\)90033-9](https://doi.org/10.1016/0021-9991(80)90033-9)
36. 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. 14C, 2015, pp. 35-44.