Stability Analysis of Streaks Induced by Optimized Vortex Generators

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Outline

Motivation

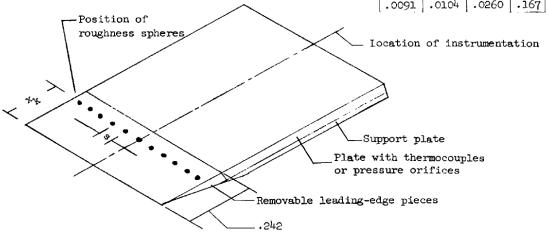
Can streaks delay transition in compressible BLs?[1]

- Holloway and Sterrett[7] studied the effect of Discrete Roughness Elements (DREs) on compressible BLs
- Wind tunnel: Langley 20-inch Mach 6 tunnel and Mach 6.2 blowdown tunnel
- Sketch of model assembly

Characteristics of spheres

k	d	s	x_k
0	0	0	
.0018	.0026	.0167	.167
.0030	.0039	.0167	.167
.0044	.0053	.0167	.167
.0054	.0065	.0260	.167
.0067	.0078	.0260	.167
.0091	.0104	.0260	.167

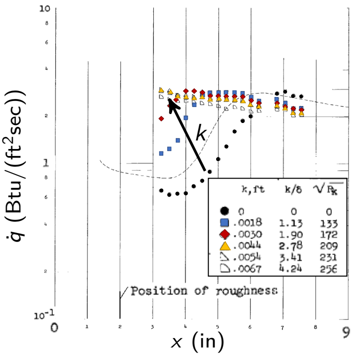
(lengths in ft)

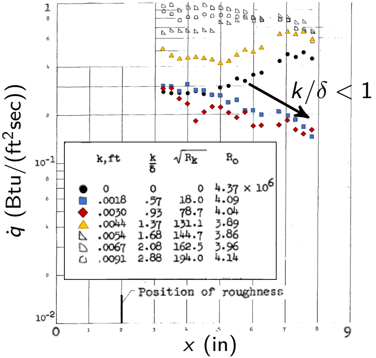


[1] P.F. Holloway and J.R. Sterrett. *Effect of controlled surface roughness on boundary-layer transition and heat transfer at Mach number of 4.8 and 6.0*. NASA TR-D-2054. 1964.

Can streaks delay transition in compressible BLs?[2]

- Heating-rate, $\dot{q}$, evolution for selected roughness heights, k
  - $M = 4.8$, $Re' \approx 9.8 \times 10^6/\mathrm{ft}$
  - $M = 6$, $Re' \approx 4 \times 10^6/\mathrm{ft}$





- Transition onset moves downstream only for $M = 6$ and $k < \delta$

[2] P.F. Holloway and J.R. Sterrett. *Effect of controlled surface roughness on boundary-layer transition and heat transfer at Mach number of 4.8 and 6.0.* NASA TR-D-2054. 1964.

Present study

Objective

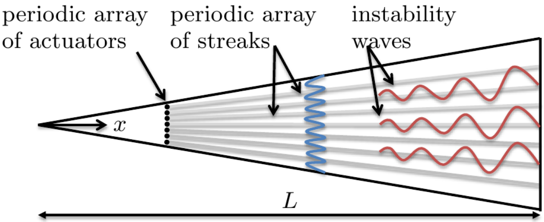
- Study the effects of realizable streaks on hypersonic boundary layer instabilities for axisymmetric hypersonic configurations
  - Use optimized wall-mounted vortex generators (VGs) to induce the streaks

Assumptions

- Transition location is based on the same N-factor value for both perturbed and unperturbed flows
- Scattering of upstream perturbations by the VGs does not play an important role in overall transition process

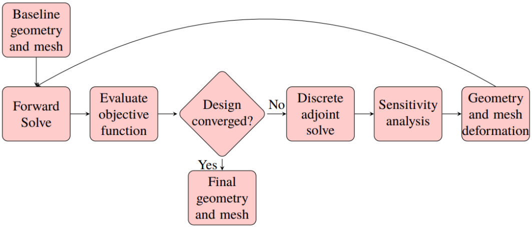
Present study

- Flow problem: Hypersonic boundary-layer flow over a 7° half-angle cone
- Stability analysis of unperturbed flow
- Full Navier-Stokes solution of perturbed flow with wall-mounted VGs
- Stability analysis of perturbed boundary-layer flow



Vortex Generator Shape Optimization[4]

- SU2:[3] open-source suite for multiphysics simulation and design
- SU2 adjoint VG shape optimization algorithm developed by Ref. [4]



- Objective function J defined as the integral of the streak amplitude A:

$$J = \int_{\xi_1}^{\xi_2} A(\xi) d\xi, \quad A(\xi) = \frac{1}{2u_\infty} \max_{\eta}(\max_{\zeta}(u) - \min_{\zeta}(u))$$

- A constraint is imposed to keep the $\max(A)$ below an specified value

[3] https://su2code.github.io/

[4] C. Pederson et al. *Shape optimization of vortex generators to control Mack mode amplification*. AIAA Paper 2020-2963. 2020.

Linear Plane-Marching PSE[5]

- Decomposition of flow variables

$$\begin{aligned}\mathbf{q}(\xi,\eta,\zeta,t) &= \bar{\mathbf{q}}(\xi,\eta,\zeta)+\tilde{\mathbf{q}}(\xi,\eta,\zeta,t)\\ \tilde{\mathbf{q}}(\xi,\eta,\zeta,t) &= \hat{\mathbf{q}}(\xi,\eta,\zeta)\exp\left[\mathrm{i}\left(\int_\xi \alpha(\xi')d\xi'-\omega t\right)\right]\end{aligned}$$

- Linear plane-marching PSE

$$\begin{aligned}\left(\mathbf{L}+\mathbf{M}\frac{\partial}{\partial\xi}\right)\hat{\mathbf{q}}(\xi,\eta,\zeta) &= 0\\ \int_\Omega \hat{\mathbf{q}}^*\frac{\partial\hat{\mathbf{q}}}{\partial\xi}\,\mathrm{d}\Omega &= 0\end{aligned}$$

- Transition onset estimated by using an N-factor criterion:

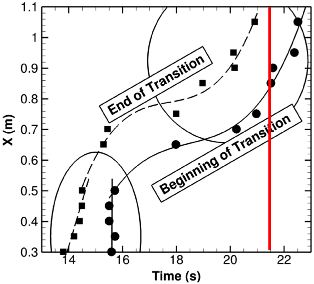
$$N(\xi)=\int_{\xi_0}^{\xi}\sigma_E(\xi')\,\mathrm{d}\xi';\;\; \sigma_E(\xi)=-\alpha_i(\xi)+1/2\frac{\mathrm{d}}{\mathrm{d}x}log(\hat{E}(\xi));\;\; \sigma_E(\xi_0)=0$$

[5] P. Paredes. "Advances in global instability computations: from incompressible to hypersonic flow". PhD thesis. Universidad Politécnica de Madrid, 2014.

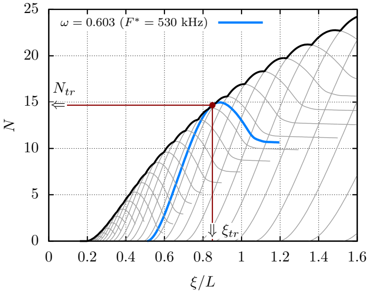
HIFiRE-1 Flight Experiment

- HIFiRE-1 flight experiment at $t = 21.5$ s during ascent phase:[6]
  - $7°$ half-angle cone, nose radius $r_n = 2.5$ mm, cone length $L_c = 2.0$ m
  - $M_\infty = 5.3$, $Re_\infty = 13.42 \times 10^6$ m^{-1}, $T_{wall}/T_{ad} \approx 0.35$
- Solution computed with VULCAN-CFD
- Stability analysis confirmed that transition is driven by planar Mack modes[7]

- Transition location



- N-factor curves



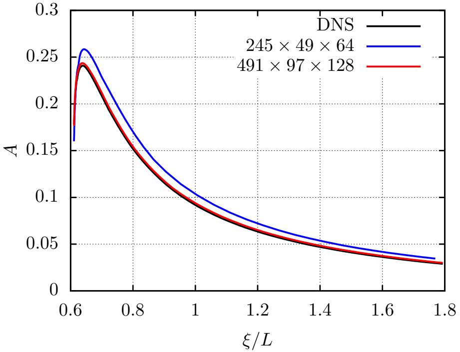
- Measured transition location at $t = 21.5$ s is $\xi_{tr}/L = 0.85$: $N_{tr} = 14.7$

[6] R. Kimmel et al. "HIFiRE-1 ascent-phase boundary-layer transition". In: *J. Spacecraft Rockets* 52.1 (2015), pp. 217–230.

[7] F. Li et al. "Transition analysis for the ascent phase of HIFiRE-1 flight experiment". In: *J. Spacecraft Rockets* 52.5 (2015), pp. 1283–1293.

Grid Refinement Study

- Reference DNS solution computed using a 7^{th}-order WENO solver[8]
- 2 grids over original unmodified VGs: 245x49x25 and 491x97x128

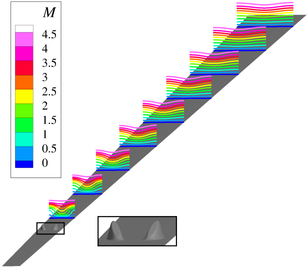


- 245x49x25 streak amplitude showed larger differences from DNS than 491x97x128
- 491x97x128 mesh used for optimization

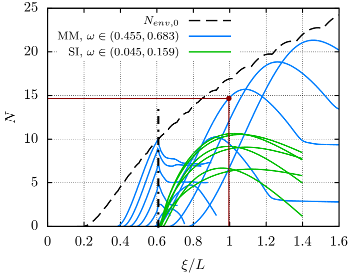
[8] M. Wu and M.P. Martin. "Direct numerical simulation of supersonic boundary layer over a compression ramp". In: *AIAA J.* 45.4 (2007), pp. 879–889.

Array of Vortex Generators[9]

- VGs designed on the basis of optimal growth theory
- Single array of VGs at $\xi_{VG}/L = 0.61$
  - Mach number contours



  - *N*-factor curves

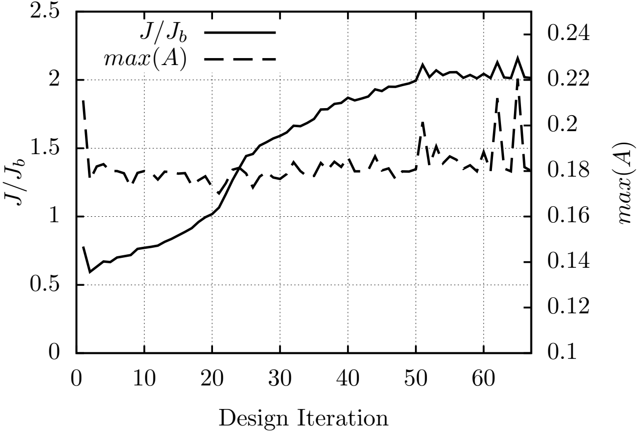


- Single VG array leads to 17% transition delay
- Induces streak instabilities (SI) which could lead to transition
- **Could the VG design be optimized to yield high-efficiency streaks for BLT control?**

[9] P. Paredes, M. Choudhari, and F. Li. *Transition delay via vortex generators in a hypersonic boundary layer at flight conditions*. AIAA Paper 2018-3217. 2018.

Adjoint Convergence

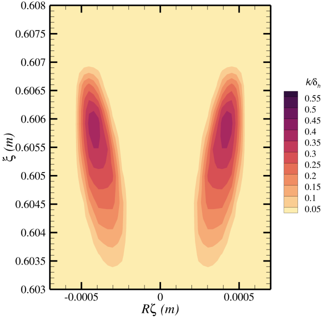
- Objective function evaluation plateaus and does not increase further



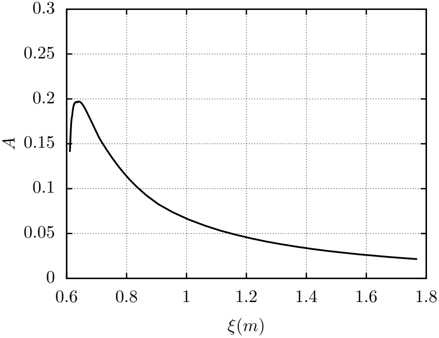
- Adjoint density residual reduced to 10^{-8}, solution density residual reduced to 10^{-13}
- Objective function was improved $> 100\%$ compared to baseline design

Shape Optimization of Vortex Generators

- Objective function: Integral of streak amplitude with constraint $max(A) \leq 0.18$.
  - Original top-down VG shape

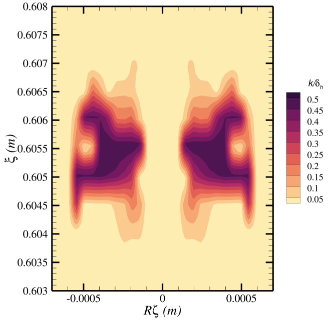


- Original streak amplitude

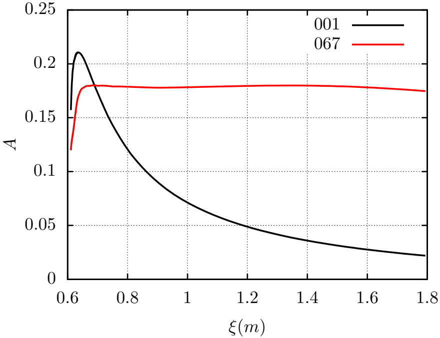


Shape Optimization of Vortex Generators

- Objective function: Integral of streak amplitude with constraint $max(A) \leq 0.18$.
  - Final optimized VG shape



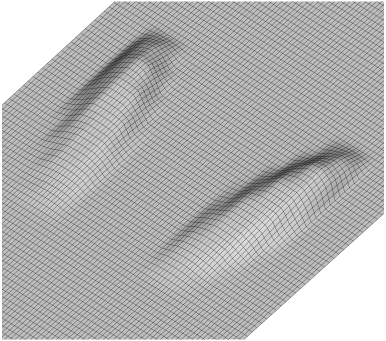
  - Final streak amplitude

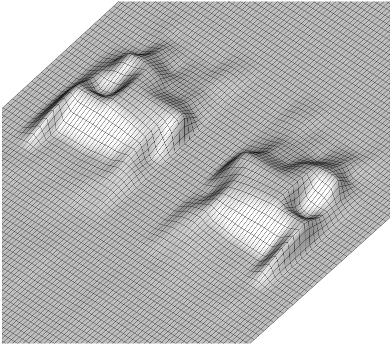


- Optimized streak amplitude remains nearly constant at $max(A)$

Vortex Generator Evolution

- Zoom of initial and final VG shapes (axes ratios altered for better perspective)
  - Original vortex generator
  - Optimized vortex generator

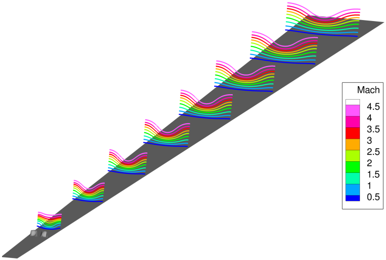




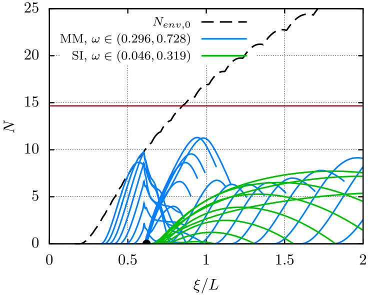
- Original ovular ramp shape evolves to a final more complex shape

Wake Stability Analysis

- Optimized VGs with $\max(A) < 0.18$
  - Mach number contours



- Optimized N-factor curves

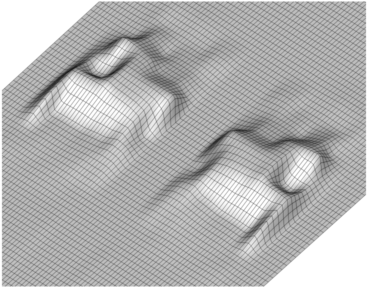


- Amplification of second-mode instabilities well below their critical value along the length of the vehicle
- Streak instabilities do not grow enough to induce transition

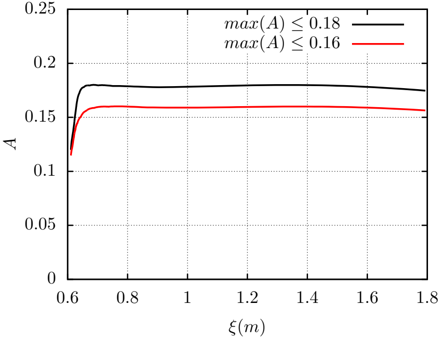
Shape Optimization of Vortex Generators

- $N_{SI,crit}$ cannot currently be calculated with high confidence
  - Reducing streak amplitude will subsequently reduce SI amplification
- Objective function: Integral of streak amplitude with constraint $max(A) \leq 0.16$.

- Shape optimization



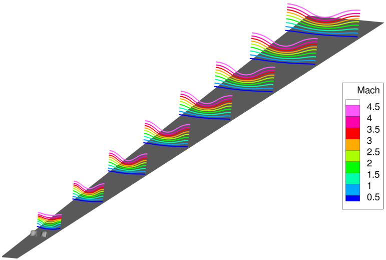
- Streak amplitude evolution



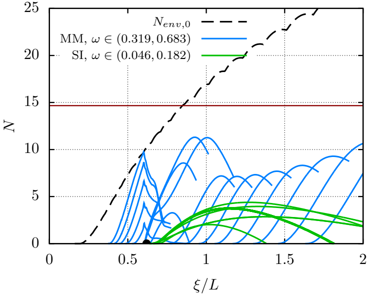
- Reduced $max(A)$ shows similar downstream streak evolution

Wake Stability Analysis

- Optimized VGs with $\max(A) < 0.16$
  - Mach number contours



- Optimized N-factor curves



- Amplification of second-mode instabilities well below their critical value along the length of the vehicle
- Maximum N-factor of streak instabilities reduced by an approximate factor of 2 with respect to $\max(A) < 0.18$

Summary and Conclusions

Summary and Conclusions

- The potential of realizable streaks to stabilize a hypersonic boundary-layer flow at flight conditions is investigated
- Optimized vortex generators have the potential to significantly delay boundary layer transition
- While a maximum of 17% transition delay is estimated with the baseline VG design, a 130% delay (total length) is likely with optimized VGs
- Range of $max(A)$ values shows potential for damping MM instabilities
- Potential for future work allowing positive and negative wall deformations for optimized VGs
- Looking into the physical mechanisms behind slow decay of induced streak amplitude

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