

Effects of Optimized Vortex Generators on Mack Mode-Dominated Boundary Layer Transition

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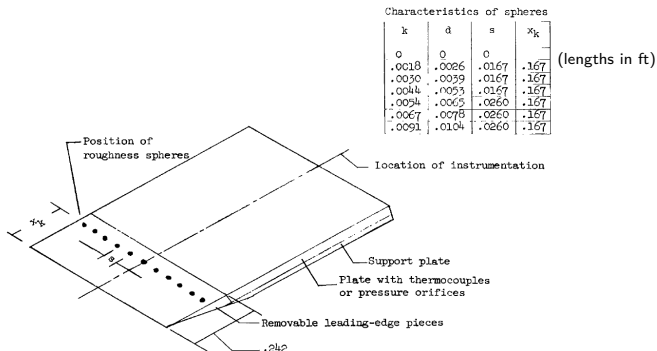
Outline

- 1 Motivation
- 2 Theory
- 3 Results
- 4 Summary and Conclusions

Motivation

Can streaks delay transition in compressible BLs?¹

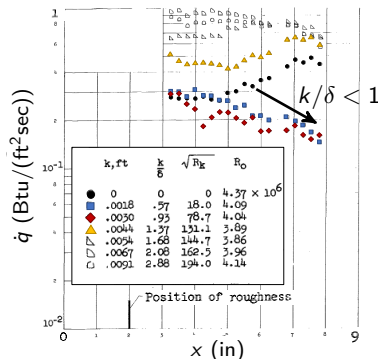
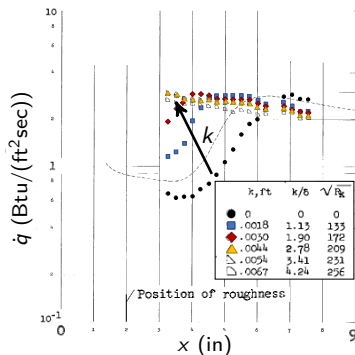
- Holloway and Sterrett⁷ studied the effect of Discrete Roughness Elements (DREs) on compressible BLs
- Wind tunnel: Langley 20-inch Mach 6 tunnel and Mach 6.2 blowdown tunnel
- Sketch of model assembly



¹P.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
- $M = 4.8$, $Re' \approx 9.8 \times 10^6/\text{ft}$
- $M = 6$, $Re' \approx 4 \times 10^6/\text{ft}$



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

²P.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

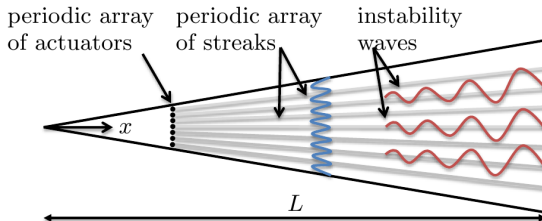
- Study the effects of realizable streaks on hypersonic boundary layer instabilities for axisymmetric hypersonic configurations
 - ▶ Use optimized wall-mounted vortex generators (VGs) to induce the streaks

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

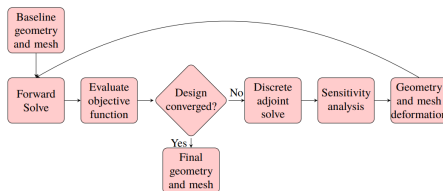
Present study

- 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 Optimization⁴

- SU2:³ open-source suite for multiphysics simulation and design
- SU2 adjoint shape optimization algorithm



- 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/>

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

Linear Plane-Marching PSE⁵

- Decomposition of flow variables

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

- Linear plane-marching PSE

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

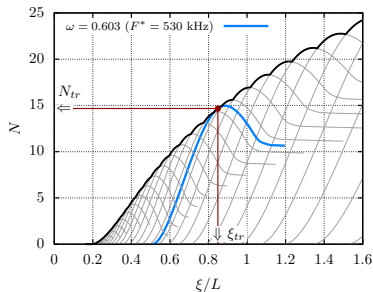
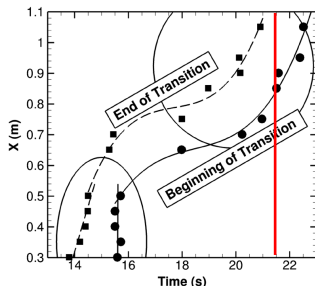
- Transition onset estimated by using an N -factor criterion:

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

⁵P. 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
 - ▶ $M_\infty = 5.3$, $Re_\infty = 13.42 \times 10^6 \text{ m}^{-1}$, $T_{wall}/T_{ad} \approx 0.35$
- Solution computed with VULCAN-CFD
- Stability analysis confirmed that transition is driven by planar Mack modes⁷
- Transition location
- N -factor curves



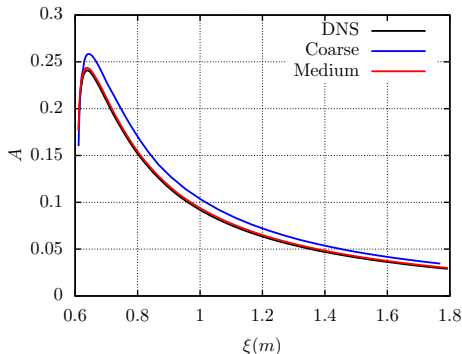
- Measured transition location at $t = 21.5$ s is $\xi_{tr}/L = 0.85$: $N_{tr} = 14.7$

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

⁷F. 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 7th-order WENO solver⁸
- 3 grids over original unmodified VGs: coarse (245×49×25), medium (491×97×128), and fine (938×129×257)

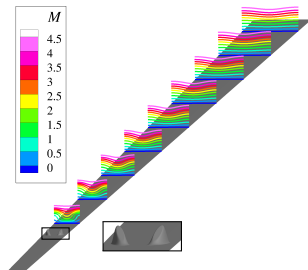


- Coarse and medium grid streak amplitudes showed 7.26% and 1.09% maximum difference from DNS respectively
- Coarse mesh used to 'tune' solver with anticipation for medium-mesh optimization

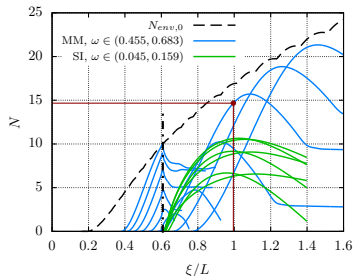
⁸M. Wu and M.P. Martin. "Direct numerical simulation of supersonic boundary layer over a compression ramp". In: *AIAA J.* 45.4 (2007), pp. 879–889.

Array of Vortex Generators⁹

- 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

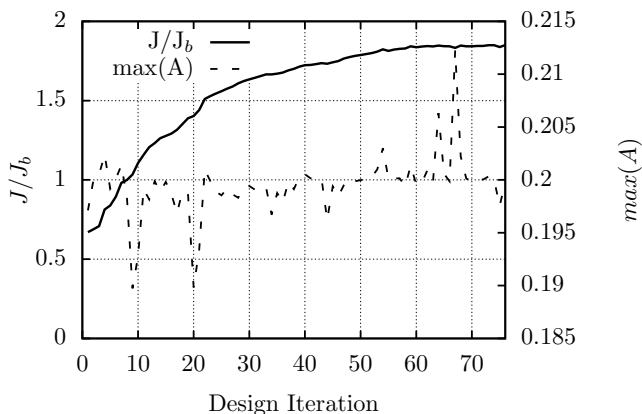


- Single VG array leads to 17% transition delay
 - ▶ Could the VG design be optimized to yield high efficient streaks for BLT control?

⁹P. 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

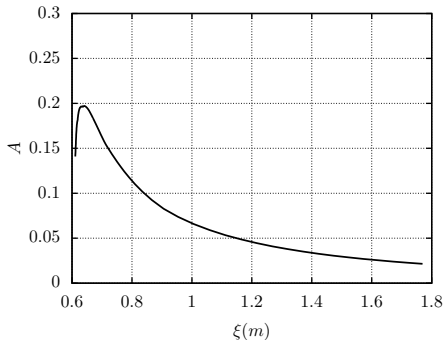
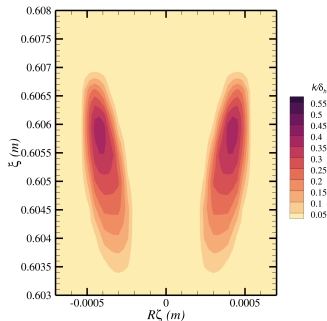
- Objective function evaluation tends towards a clear limit



- Adjoint density residual reduced to 10^{-8} , solution density residual reduced to 10^{-13}
- Objective function was improved $> 117\%$

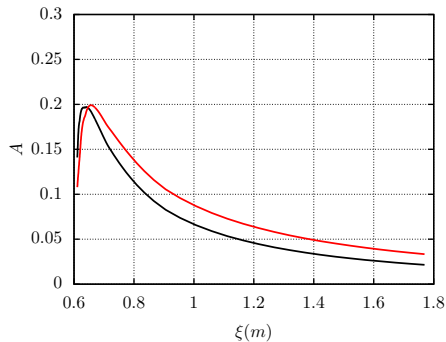
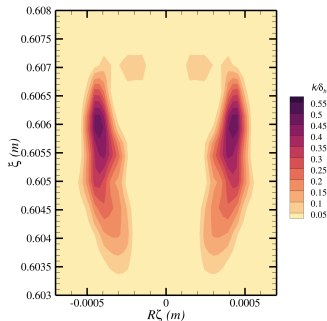
Shape Optimization of Vortex Generators

- Objective function: Integral of streak amplitude with constraint $\max(A) \leq 0.2$.
- Shape optimization
- Streak amplitude evolution



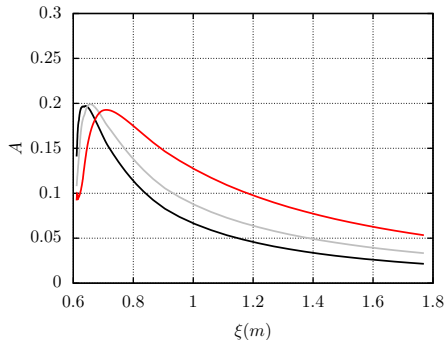
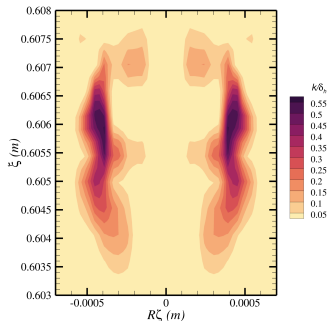
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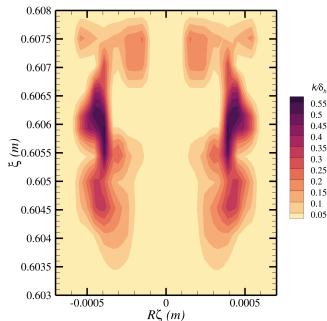
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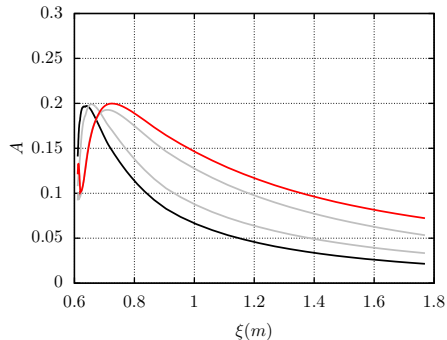


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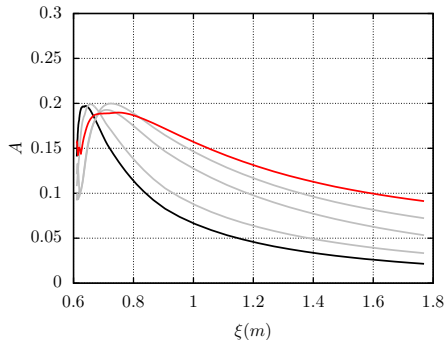
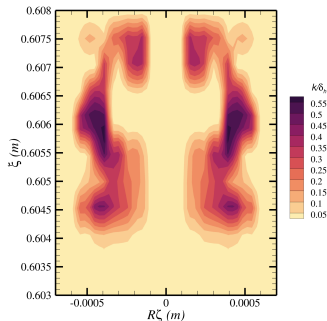


- Streak amplitude evolution



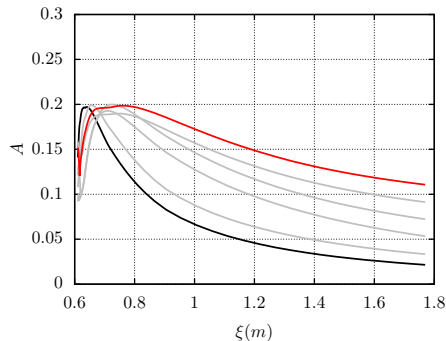
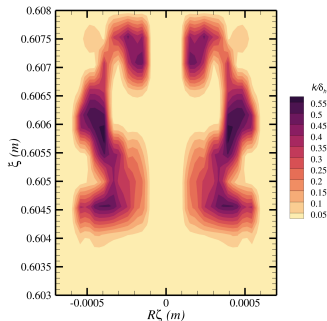
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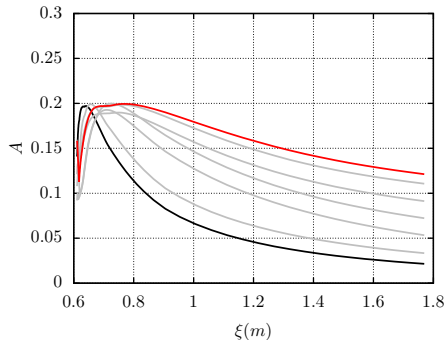
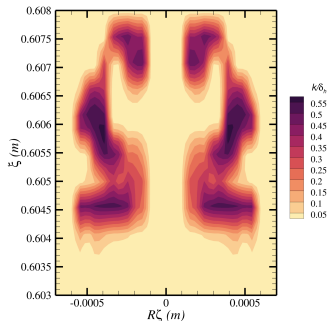
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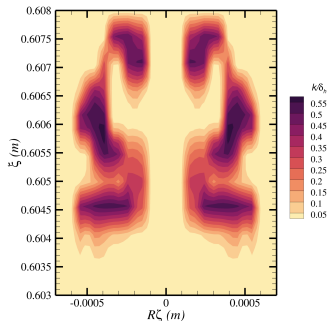
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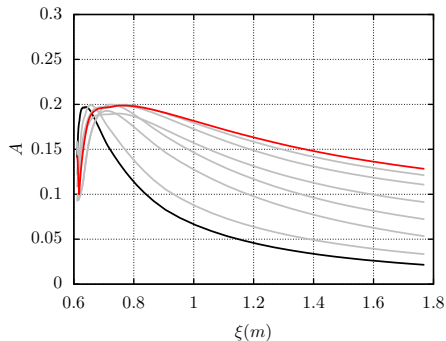


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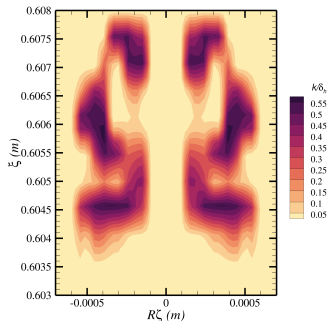


- Streak amplitude evolution

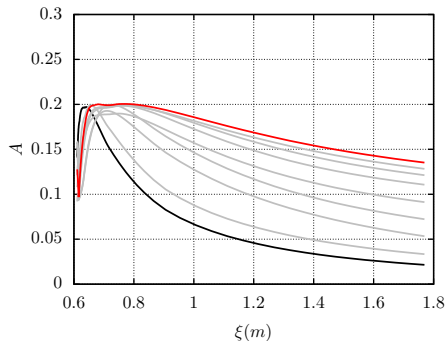


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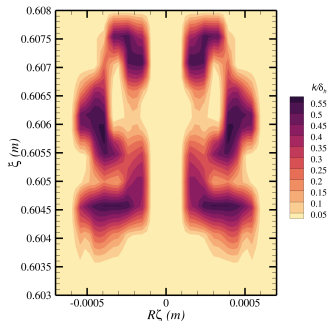


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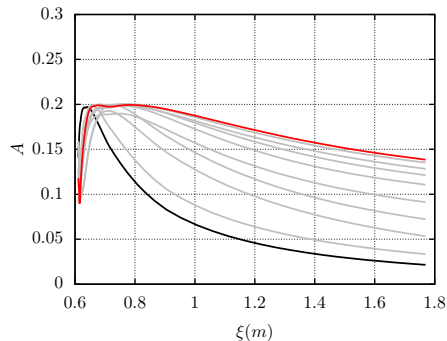


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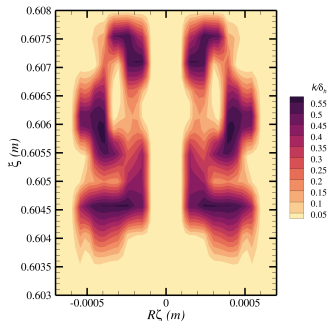


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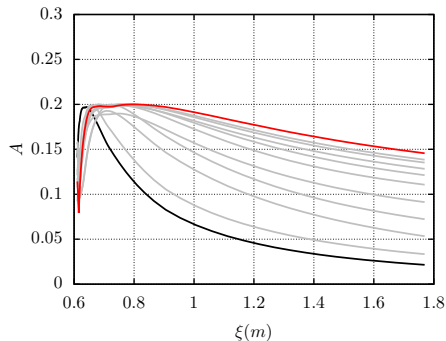


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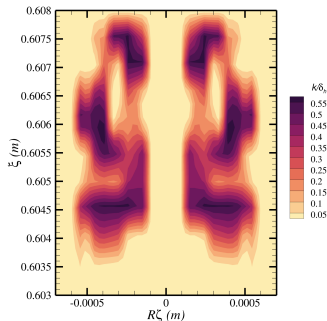


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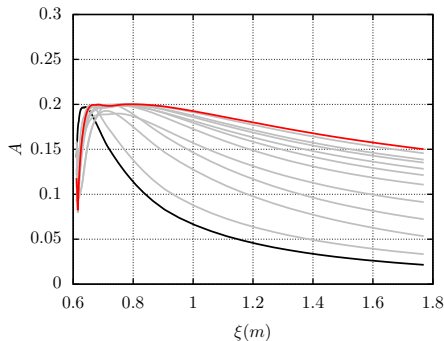


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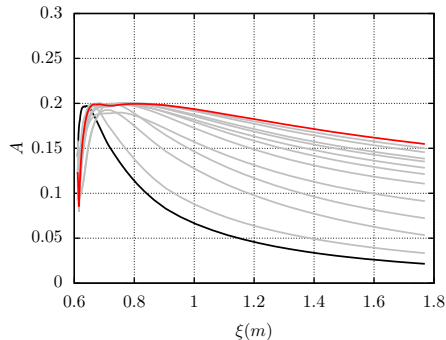
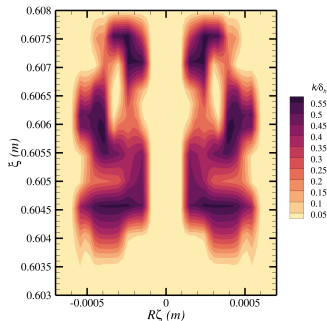


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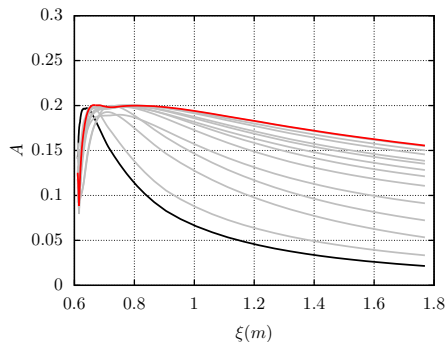
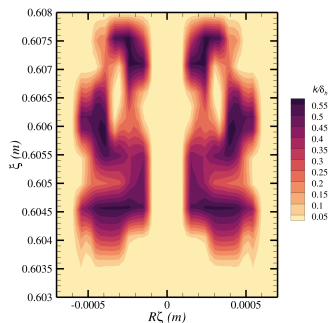
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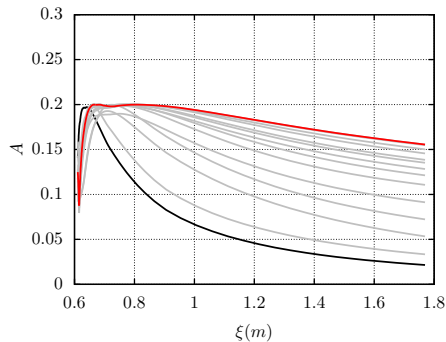
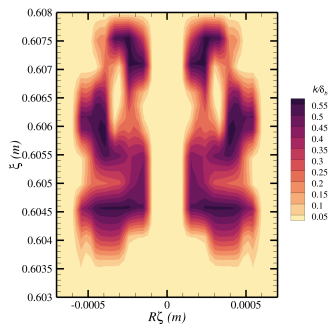
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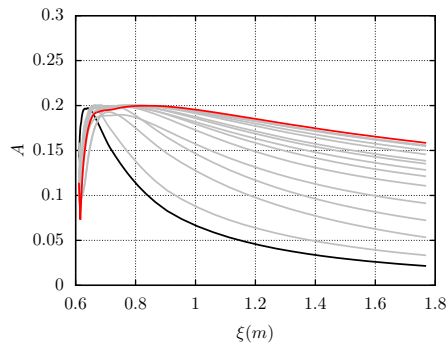
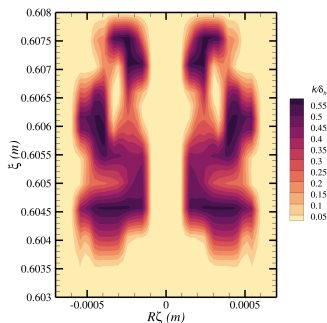
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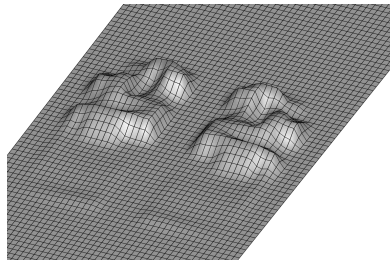
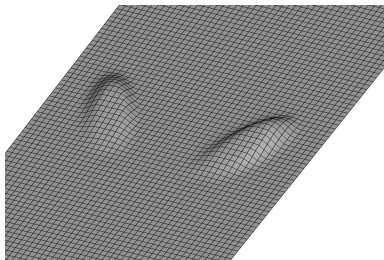
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Vortex Generator Evolution

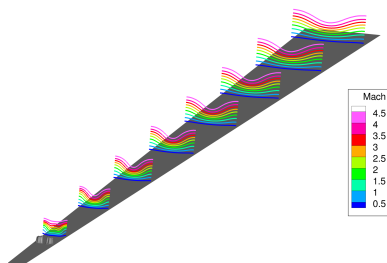
- Zoom of initial and final VG shapes (x -to- z axis ratio 0.2)
 - Original vortex generator
 - Optimized vortex generator



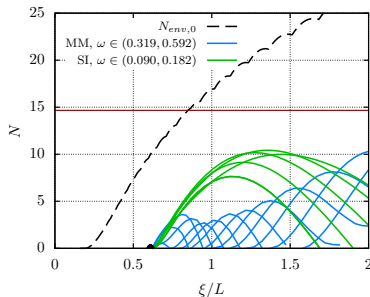
- Original ovular ramp shape evolves to a final, more complex 'S' shape

Wake Stability Analysis

- Optimized VGs with $\max(A) < 0.2$
- Mach number contours



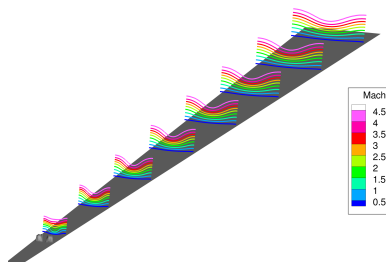
- Optimized N -factor curves



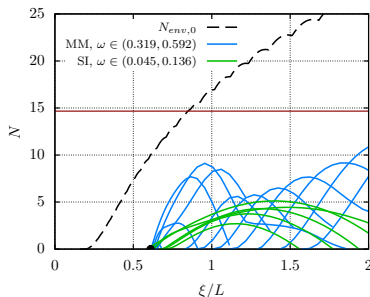
- Amplification of second-mode instabilities well below their critical value along the length of the vehicle
- Streak instabilities do not grow enough to induce transition

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
- Maximum N -factor of streak instabilities reduced by factor of 2 with respect to $\max(A) < 0.2$

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 can significantly delay boundary layer transition
- While a maximum of 17% transition delay is achieved with the baseline VG design, a 130% delay (total length) is achieved with optimized VGs
- Current investigations underway towards finer-mesh optimization as well as allowing positive and negative wall deformations for optimized VGs
- In the future, begin investigating physical mechanisms behind induced streak amplitude decay

Acknowledgments

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 - ▶ the NASA Hypersonic Technology Project (HTP) under the Aeronautics Research Mission Directorate (ARMD)
- Resources supporting this work are provided by
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 - ▶ NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center
 - ▶ NASA Midrange K cluster at the Langley Research Center

