

Hypersonic Boundary-Layer Instabilities over Cone-Flare Models

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Outline

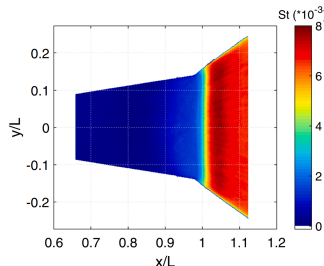
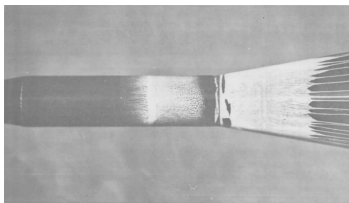
- 1 Motivations
- 2 Computational Analysis
 - Laminar basic state solution
 - Global instabilities
- 3 Summary and Concluding Remarks
- 4 Backup slides

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Streamwise streaks on cone-flare geometries

- Cone-flare geometries exhibit a shock-wave/boundary-layer interaction with high surface heating in the reattachment region
- Streamwise streaks past reattachment on axisymmetrical conical geometries¹
- Heat transfer on cone-flare geometries shows presence of streamwise streaks²



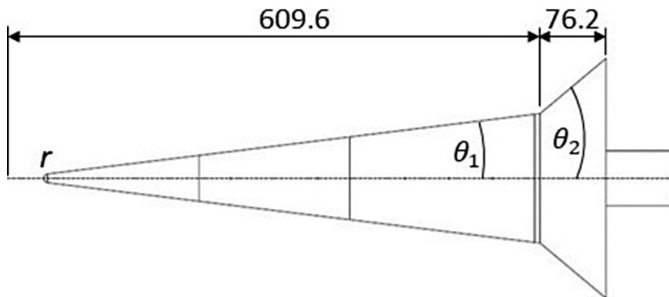
- **Objective:** Investigate global instability of the laminar, axisymmetric separation bubble as a potential contributor to the observed heat flux streaks

¹J. D. Gray. Investigation of the effect of flare and ramp angle on the upstream influence of laminar and transitional reattaching flows from Mach 3 to 7. AEDC-TR-66-190. Von Karman Gas Dynamics AEDC, TN, 1967.

²C. Running et al. "Hypersonic shock-wave/boundary-layer interactions on a cone/flare". In: *Exp. Therm. Fluid Sci.* 109 (2019).

Configurations

- Cone-flare experiments³
 - ▶ Mach-6 Ludwig Tube wind tunnel at Air Force Research Laboratory (AFRL)
 - ▶ $AoA = 0^\circ$, blunt 7° half-angle cone, $34^\circ - 43^\circ$ half-angle flare
 - ▶ $r_n = 0.1, 0.5, 5.1, 10.2$ mm
- Present study focuses on effects of bluntness and flare half-angle on global instability onset
 - ▶ Begin with lower flare half-angles ($14^\circ - 18^\circ$) to capture the onset of global instability



³C. Running et al. "Characterization of post-shock thermal striations on a cone/flare". In: *AIAA Journal* 58.5 (2020), pp. 2352–2358.

Outline

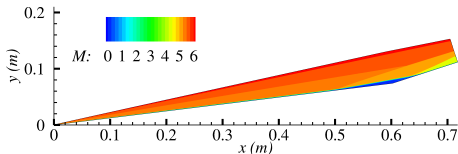
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Computational Analysis

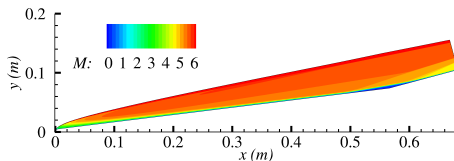
Laminar basic state solution

Laminar basic state solution

- VULCAN-CFD: shock-capturing, 2nd-order finite-volume NS solver
- $Re = 7.576 \times 10^6 \text{ m}^{-1}$, $P_0 = 0.92 \times 10^6 \text{ Pa}$, $T_0 = 490 \text{ K}$, $T_w = 300 \text{ K}$
- $r_n = \mathbf{0.1, 0.5, 1.0, 2.0, 5.1, 10.2 \text{ mm}}$; $14^\circ, 15^\circ, 16^\circ, 17^\circ$, and 18° half-angle flare
- Shock-adapted grid with 2401×801 grid points
- $r_n = 0.1 \text{ mm}, 18^\circ$ half-angle flare



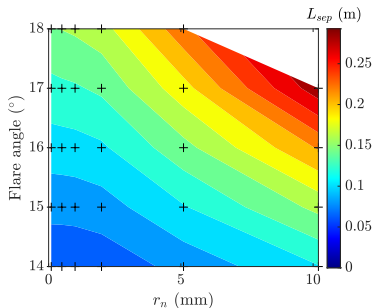
- $r_n = 5.1 \text{ mm}, 15^\circ$ half-angle flare



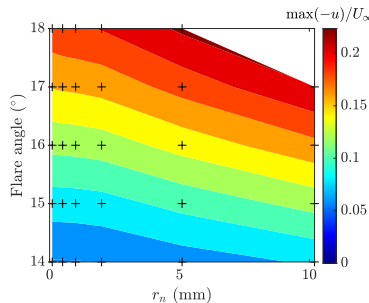
Laminar basic state solution

- Effect of nosetip radius and flare angle on separation characteristics

- Separation length, L_{sep}



- Maximum reverse velocity, $\max(-u)/U_\infty$



- Both separation length and maximum reverse velocity increase with increasing bluntness and/or increasing flare angle

Computational Analysis

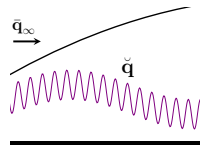
Global instabilities

Global linear stability analysis

- Global stability analysis (GSA): Frequency domain form of linearized N-S equations

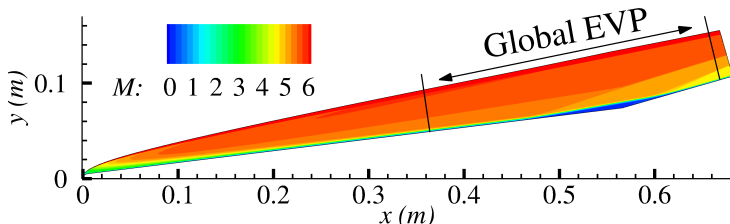
$$\mathbf{q}(\xi, \eta, \zeta, t) = \bar{\mathbf{q}}(\xi, \eta) + \tilde{\mathbf{q}}(\xi, \eta, \zeta, t)$$

$$\tilde{\mathbf{q}}(\xi, \eta, \zeta, t) = \check{\mathbf{q}}(\xi, \eta) \exp[i(m\zeta - \omega t)]$$



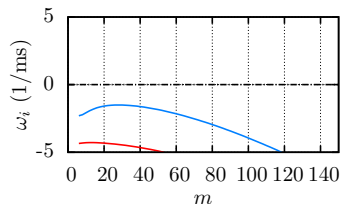
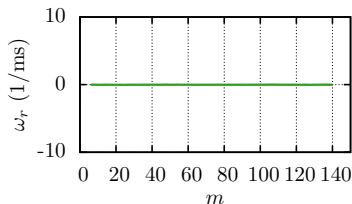
- PDE-based generalized EVP solved for each azimuthal wavenumber m :

$$\mathbf{A}\check{\mathbf{q}} = \omega \mathbf{B}\check{\mathbf{q}}, \quad f = \omega_r / (2\pi), \quad \sigma = \omega_i \Rightarrow \begin{cases} \sigma < 0 : \text{stable} \\ \sigma > 0 : \text{unstable} \end{cases}$$

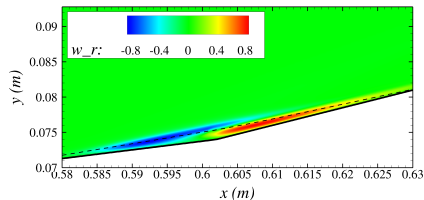
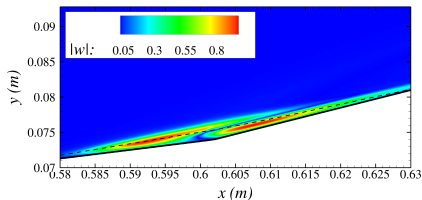


Global mode analysis of cone-flare models

- $R_n = 0.1$ mm, 14° half-angle flare, $m(\sigma_{\max}) = 28$

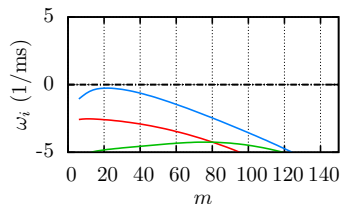
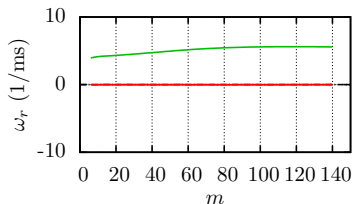


- Magnitude and real component of azimuthal velocity perturbation

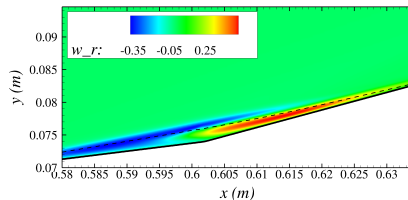
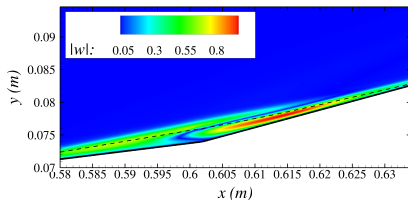


Global mode analysis of cone-flare models

- $R_n = 0.1$ mm, 15° half-angle flare, $m(\sigma_{\max}) = 22$

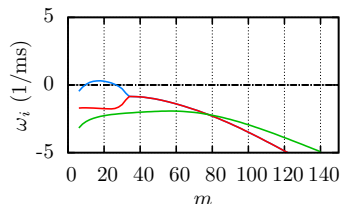
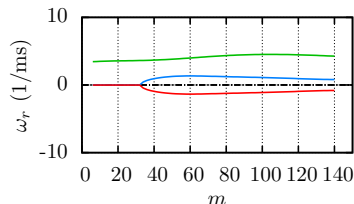


- Magnitude and real component of azimuthal velocity perturbation

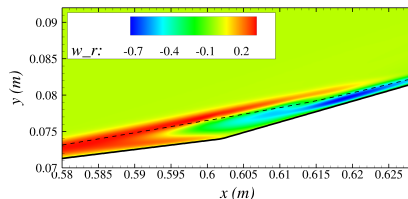
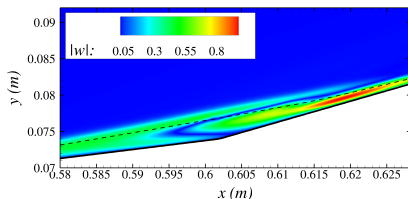


Global mode analysis of cone-flare models

- $R_n = 0.1$ mm, 16° half-angle flare, $m(\sigma_{\max}) = 18$



- Magnitude and real component of azimuthal velocity perturbation

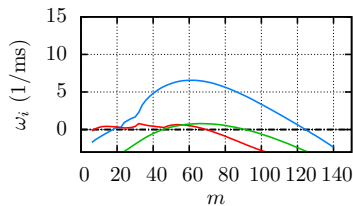
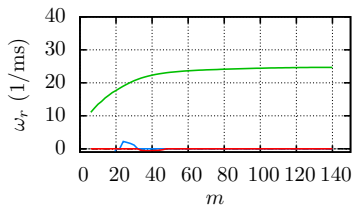


- Critical mode also found in Mach 5 flow over sharp, slender double wedge⁴

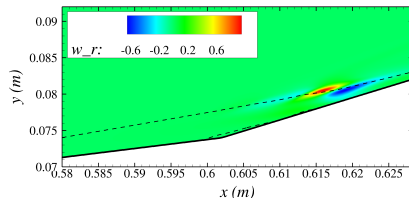
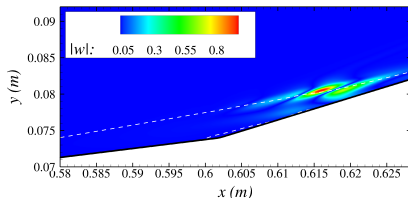
⁴S. GS et al. "Onset of three-dimensionality in supersonic flow over a slender double wedge". In: *Physical Review Fluids* 3.093901 (2018), pp. 1–29. DOI: 10.1103/PhysRevFluids.3.093901.

Global mode analysis of cone-flare models

- $R_n = 0.1$ mm, 17° half-angle flare, $m(\sigma_{\max}) = 62$



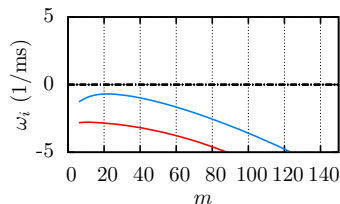
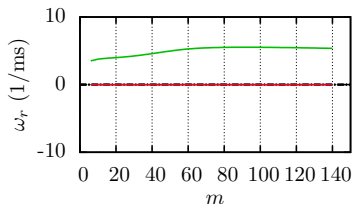
- Magnitude and real component of azimuthal velocity perturbation



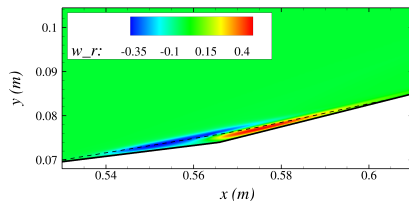
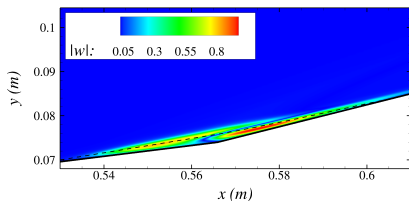
- Leading mode concentrates near reattachment
- Secondary separation emerges at the corner

Global mode analysis of cone-flare models

- $R_n = 5.1$ mm, 14° half-angle flare, $m(\sigma_{\max}) = 22$

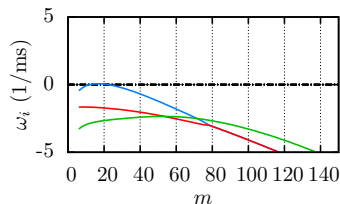
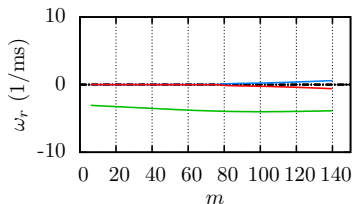


- Magnitude and real component of azimuthal velocity perturbation

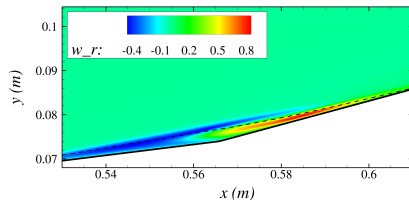
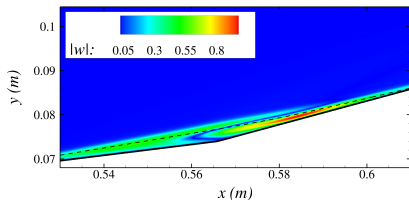


Global mode analysis of cone-flare models

- $R_n = 5.1$ mm, 15° half-angle flare, $m(\sigma_{\max}) = 16$

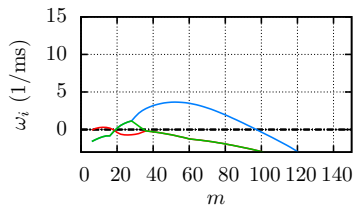
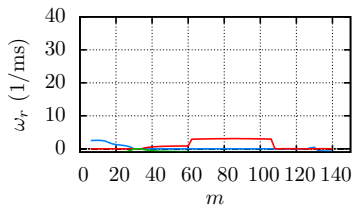


- Magnitude and real component of azimuthal velocity perturbation

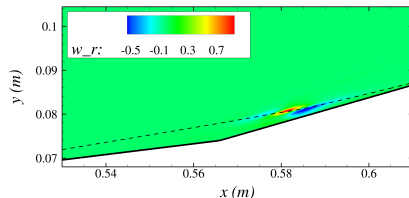
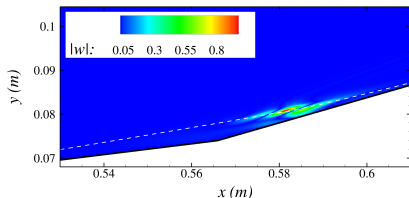


Global mode analysis of cone-flare models

- $R_n = 5.1$ mm, 16° half-angle flare, $m(\sigma_{\max}) = 52$



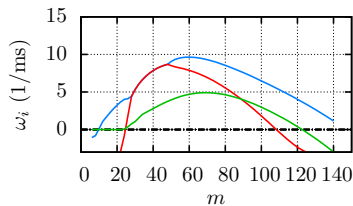
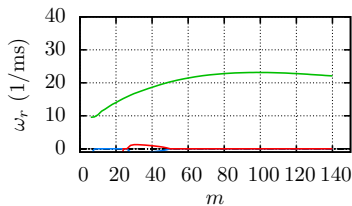
- Magnitude and real component of azimuthal velocity perturbation



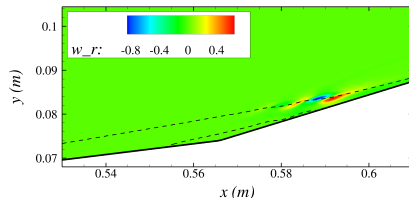
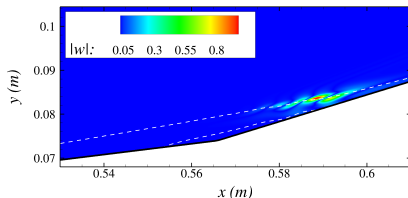
- Leading mode concentrates near reattachment
- Secondary separation emerges at the corner

Global mode analysis of cone-flare models

- $R_n = 5.1$ mm, 17° half-angle flare, $m(\sigma_{\max}) = 60$



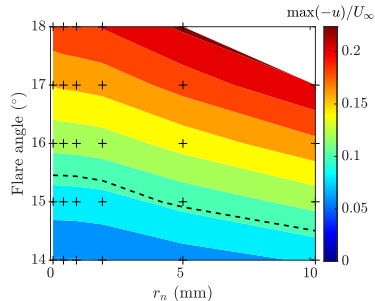
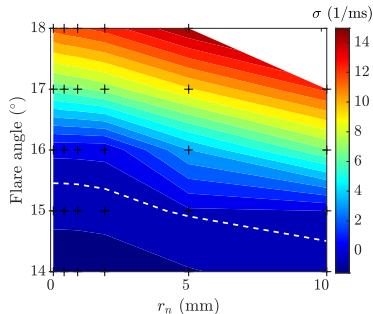
- Magnitude and real component of azimuthal velocity perturbation



- Leading mode concentrates near reattachment
- Secondary separation emerges at the corner

Global instabilities

- Effect of nosetip radius and flare angle on global instability of separated flow
 - Leading mode growth rate
 - Maximum reverse velocity



- Dashed line indicates global instability onset, $\sigma = 0$
- Nosetip bluntness destabilizes separated flow
 - ▶ Onset found for lower flare angles with increasing nosetip radius
 - ▶ Global instability onset found to correlate with a constant maximum reverse velocity ($\max(-u)/U_\infty|_{\sigma=0} \approx 0.105$)

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Concluding remarks

- Nosetip bluntness is shown to move the onset of global instability of the separated flow to lower flare angles
- Global instability onset correlates with $\max(-u)/U_\infty|_{\sigma=0} \approx 0.105$
- Leading mode suddenly concentrates near reattachment as half-angle flare increases and a secondary separation emerges at the corner

Thank you for your attention

- Acknowledgments

- ▶ This research was sponsored in part by the U. S. Office of Naval Research (ONR) under award number N00014-20-1-2261 with P.O. Eric Marineau and by the NASA Hypersonic Technology Project (HTP) under the Aeronautics Research Mission Directorate (ARMD).
- ▶ Resources supporting this work were provided by the DoD High Performance Computing Modernization Program, the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center and the NASA K-Midrange Cluster at Langley Research Center.
- ▶ We thank Mr. White and Dr. Baurle for their generous advice concerning the VULCAN-CFD computations.

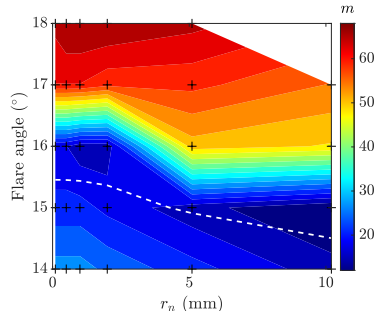
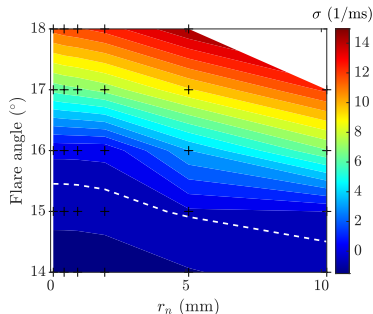


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Global instabilities

- Effect of nosetip radius and flare angle on global instability of separated flow
 - Leading mode growth rate
 - Associated azimuthal wavenumber



- Dashed line indicates global instability onset, $\sigma = 0$
- Nosetip bluntness destabilizes separated flow
 - ▶ Onset found for lower flare angles with increasing nosetip radius
 - ▶ Jump in m indicates switch from critical to reattachment mode