

Hypersonic Boundary-Layer Instabilities over Ogive-Cylinder Models

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Outline

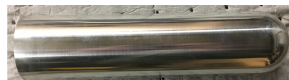
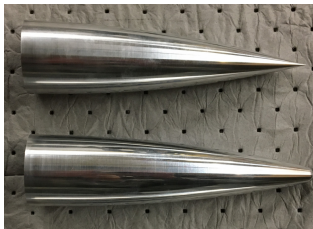
- 1 Motivations
- 2 Computational Analysis
 - Laminar Basic State Solution
 - Modal Analysis
 - Nonmodal Analysis
- 3 Summary and Concluding Remarks

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Previous Experiments

- Ogive forebodies improve aerothermodynamic performance
- Low-enthalpy Air Force Research Laboratory Mach-6 Ludwig Tube by Hill¹
- $AoA = 0^\circ$, ogive tips followed by cylinder with base radius $R=31.1$ mm, $L = 1$ m
- Half-angle: **14**, **28**, 56° ; Nosetip bluntness $r_n^* = \mathbf{0.1}$ mm, $\mathbf{1/4 R}$, $\mathbf{1/2 R}$, $\mathbf{R}$
- PCBs, Kulites, schlieren, and focused laser differential interferometry (FLDI)
- Sharp 4 caliber (14°) and blunt ($1/4R$)
- Sharp 2 caliber (28°) and blunt ($1/4R$)
- Hemisphere ($1/2$ caliber)

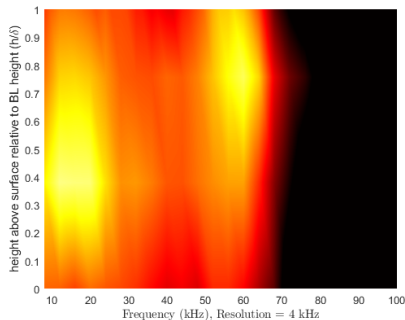


¹J.L. Hill et al. *Experimental measurements of hypersonic instabilities over ogive-cylinder at Mach 6*. AIAA Paper 2021-0153. 2021.

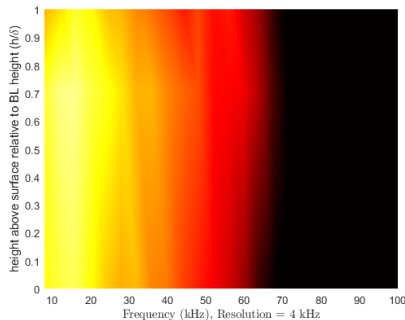
Power Spectral Density from FLDI

- Measurements at $x = 0.5$ m

- Sharp 4C (14°)



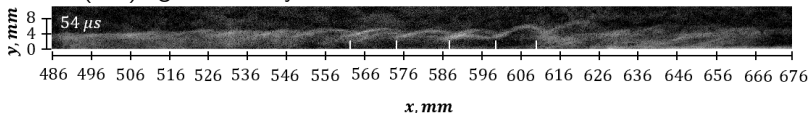
- Sharp 2C (28°)



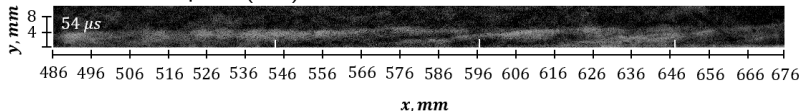
- Low frequency (5-25 kHz) $\rightarrow$ elongated structure
- High frequency (60 kHz) $\rightarrow$ rope-like structure, second Mack mode instability
- FLDI for sharp 1C (56°) only measures $f < 30$ kHz

Disturbances Observed on Ogive-Cylinder Geometries

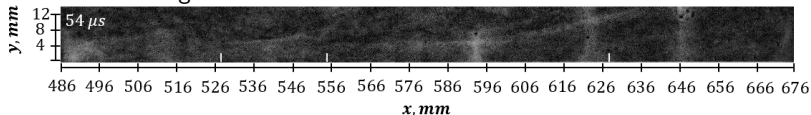
- Rope-like: planar Mack's second mode within boundary layer for sharp 4C (14°) and 2C (28°) ogive forebody



- Elongated: co-exist with rope-like, more dominant in sharp 2C (28°) and the only one visible for sharp 1C (56°)



- Wisp-like: above boundary-layer edge, no specific wavelength or frequency, only visible for blunt ogival forebodies



- **Objective:** Perform linear modal and nonmodal analysis to understand the measured disturbances and effect on transition

Outline

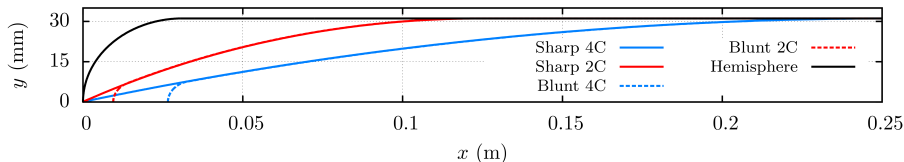
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Computational Analysis

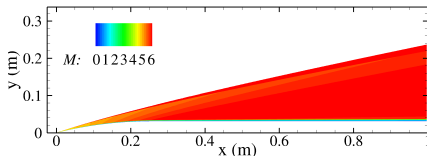
Laminar Basic State Solution

Laminar Basic State Solution

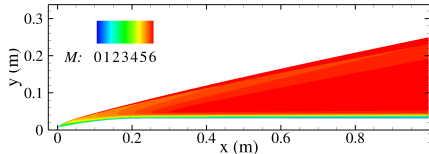
- VULCAN-CFD: shock-capturing, 2nd-order finite-volume NS solver
- $Re = 7.01 \times 10^6 \text{ m}^{-1}$, $P_0 = 896.3 \text{ kPa}$, $T_0 = 490 \text{ K}$, $T_w = 300 \text{ K}$, Keyes law
- Shock-adapted grid with 1000×600 grid points
- Cylinder base $R^* = 31.1 \text{ mm}$



- Mach contour sharp 4 caliber

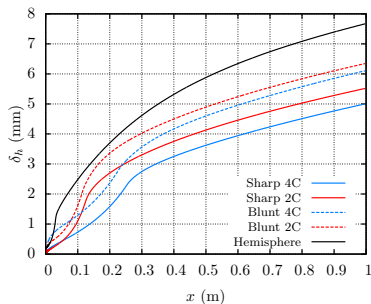


- Mach contour blunt 4 caliber

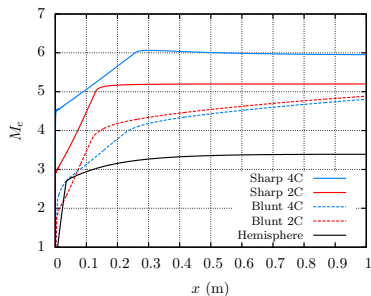


Axial Evolution

- Effect of nosetip bluntness and ogive half-angle
- Boundary-layer thickness



- Edge Mach number



- Increasing bluntness increases δ_h and decreases M_e along the cylinder
- Decreasing caliber (i.e. increasing ogive half-angle) increases δ_h along the cylinder
 - ▶ Sharp ogive: decrease M_e
 - ▶ Blunt ogive: increase M_e

Wall-Normal Profiles

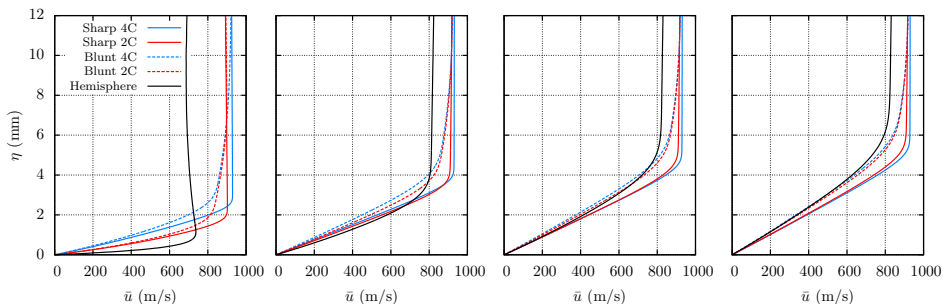
- Streamwise velocity
- Ogive-cylinder junction at x_j

• $x = x_j$

• $x = x_j + 0.2 \text{ m}$

• $x = x_j + 0.4 \text{ m}$

• $x = x_j + 0.6 \text{ m}$



- Weaker gradients for higher bluntness due to entropy layer
- Streamwise velocity reduced within entropy layer induced by blunter ogival forebody

Wall-Normal Profiles

- Temperature

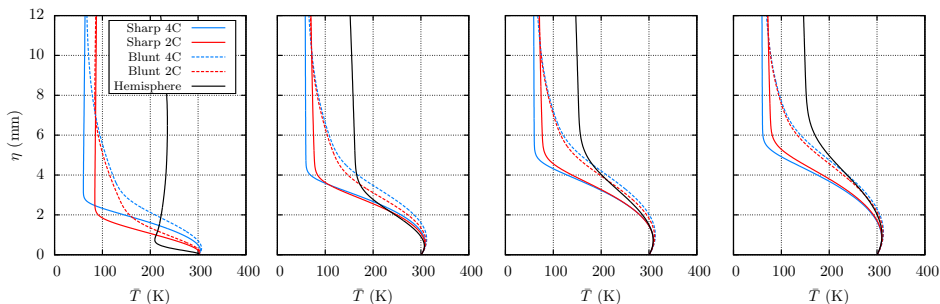
- Ogive-cylinder junction at x_j

- $x = x_j$

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- $x = x_j + 0.6 \text{ m}$



- Weaker gradients for higher bluntness due to entropy layer

- Temperature increased within entropy layer induced by blunter ogival forebody

Computational Analysis

Modal Analysis

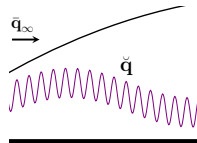
Linear Modal Analysis²

- Decomposition of flow variables:

$$\mathbf{q}(\xi, \eta, \zeta, t) = \bar{\mathbf{q}}(\xi, \eta) + \epsilon \tilde{\mathbf{q}}(\xi, \eta, \zeta, t); \quad \bar{\mathbf{q}} = \mathcal{O}(1); \quad \epsilon \ll 1$$

- Harmonic Linearized Navier-Stokes Equations (HLNSE):
 - exploit basic state independence w.r.t. time and azimuthal direction
 - solution of a 2D linear system of equations

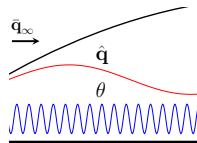
$$\tilde{\mathbf{q}}(\xi, \eta, \zeta, t) = \check{\mathbf{q}}(\xi, \eta) \exp[i(m\zeta - \omega t)]$$



- Parabolized Stability Equations (PSE):**

- exploit slow variations in streamwise direction via separation of scales
- parabolic integration in ξ coupled with normalization condition

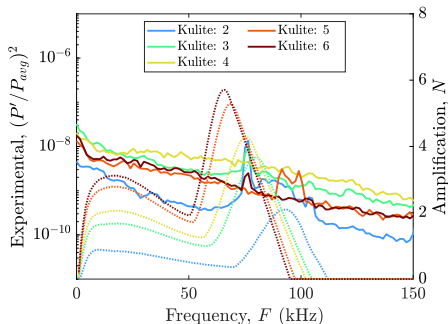
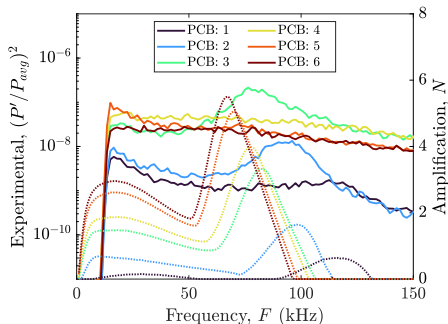
$$\check{\mathbf{q}}(\xi, \eta) = \hat{\mathbf{q}}(\xi, \eta) \theta(\xi); \quad \theta(\xi) = \exp \left[i \int_{\xi_0}^{\xi} \alpha(\xi') d\xi' \right]$$



²P. Paredes et al. "Nose tip bluntness effects on transition at hypersonic speeds: experimental and numerical analysis". In: *Journal of Spacecraft Rockets* 56.2 (2019).

Linear Modal Analysis vs Experimental Data

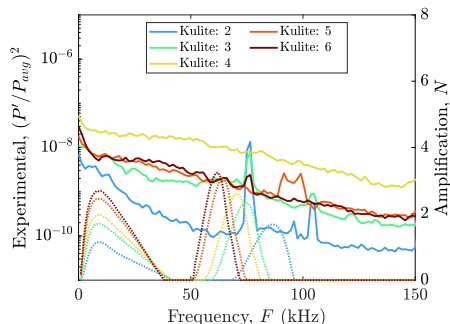
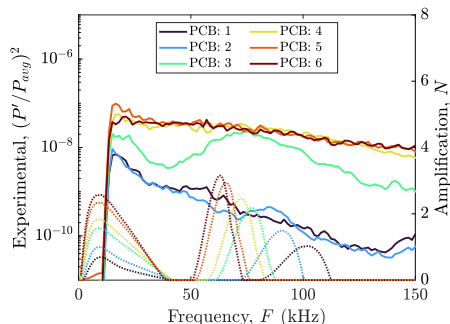
- Sharp 4C
- PCB data high-pass filtered at 12 kHz by design



- Low and high frequency disturbances
- Downstream amplification increases and frequency decreases due to increase in boundary-layer thickness
- High frequency disturbance peaks between 60 and 130 kHz, matching PCBs 1, 2, 3 and Kulites 2, 3 from experiments

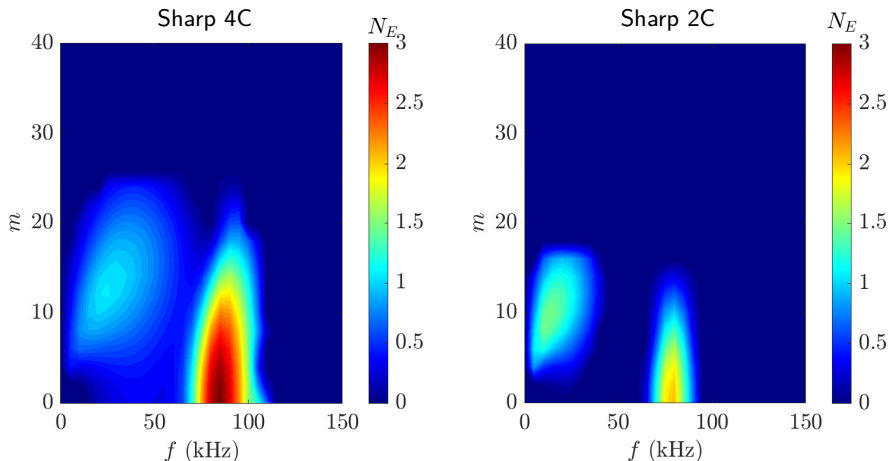
Linear Modal Analysis vs Experimental Data

- Sharp 2C
- PCB data high-pass filtered at 12 kHz by design



- Lower amplification than sharp 4C
- Second disturbance peaks agree with PCBs 2, 3 and Kulites 2, 3
- Kulites 2 and 3 seem to measure low frequency disturbances correlating with oblique first mode (same frequencies measured by FLDI)

Planar and Oblique Modal Disturbances at PCB 3



- Planar second mode more amplified than oblique first mode
- Weaker amplifications for the sharp 2C ogive forebody
- Modal analysis for blunt tips does not predict disturbance amplification due to the entropy layer stabilizing effect

Computational Analysis

Nonmodal Analysis

Linear Nonmodal Analysis^{3,4}

- Initial location selected close to the nosetip ($\xi_0 = 0.1$ m)
- Final location selected near PCB 3 ($\xi_1 = 0.55$ m)
- Optimal initial disturbance, $\tilde{\mathbf{q}}_0$: initial condition at ξ_0 that maximizes J :

► Outlet energy gain: $J = G_E^{out} = \frac{E(\xi_1)}{E(\xi_0)}$

- Energy norm: $E(\xi) = \int_{\eta} \tilde{\mathbf{q}}(\xi)^* \mathbf{M}(\xi) \tilde{\mathbf{q}}(\xi) h_{\xi} h_{\zeta} d\eta$

$$\mathbf{M}(\xi) = \text{diag} \left[\frac{\bar{T}(\xi)}{\gamma \bar{\rho}(\xi) M^2}, \bar{\rho}(\xi), \bar{\rho}(\xi), \bar{\rho}(\xi), \frac{\bar{\rho}(\xi)}{\gamma(\gamma - 1) \bar{T}(\xi) M^2} \right]$$

- Variational formulation using direct and adjoint **HLNSE**

$$\mathcal{L}(\tilde{\mathbf{q}}, \tilde{\mathbf{q}}^{\dagger}) = J(\tilde{\mathbf{q}}) - \langle \tilde{\mathbf{q}}^{\dagger}, \mathbf{L} \tilde{\mathbf{q}} \rangle$$

- Parametric analysis w.r.t. wavenumber (m) & frequency (f)

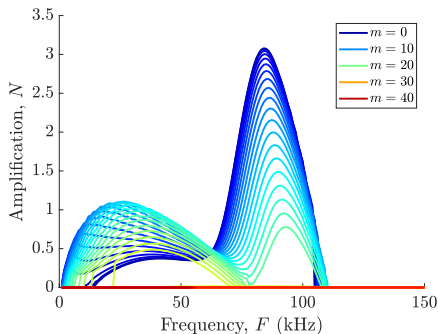
³P. Paredes et al. "Optimal growth in hypersonic boundary layers". In: *AIAA Journal* 54.10 (2016), pp. 3050–3061.

⁴P. Paredes et al. "Nose tip bluntness effects on transition at hypersonic speeds: experimental and numerical analysis". In: *Journal of Spacecraft Rockets* 56.2 (2019).

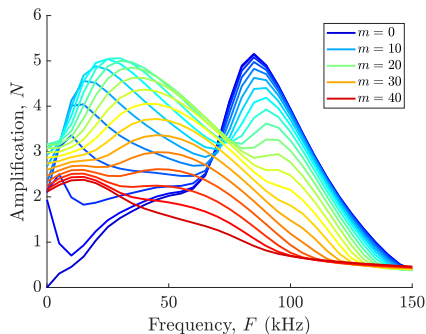
Modal vs Nonmodal at PCB 3

- Sharp 4C

Modal



Nonmodal

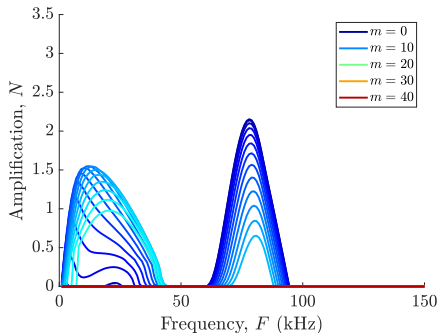


- Higher nonmodal amplification for both modes
- Comparable oblique first and planar second Mack mode nonmodal amplification

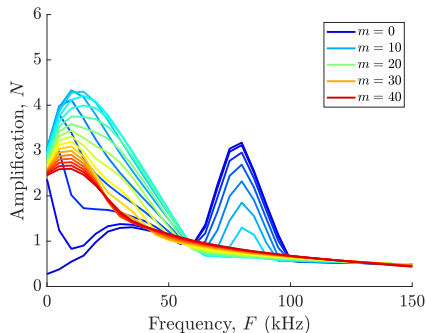
Modal vs Nonmodal at PCB 3

- Sharp 2C

Modal



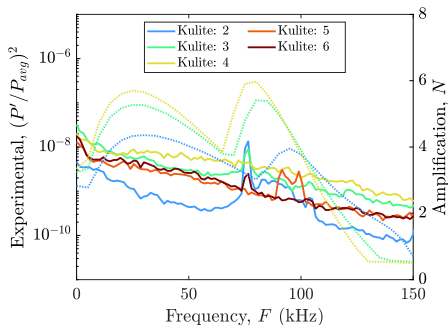
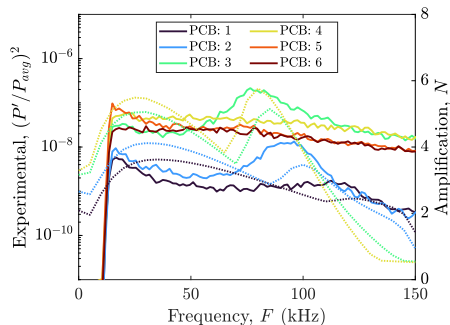
Nonmodal



- Peak modal amplitude starts to switch from planar second mode to oblique first mode
- First mode dominates nonmodal amplification

Linear Nonmodal Analysis vs Experimental Data

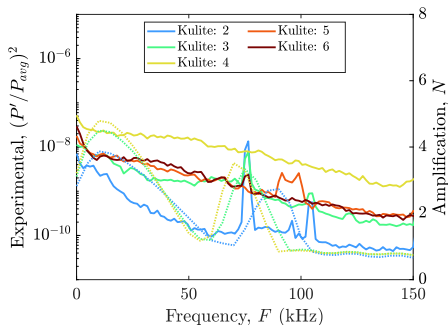
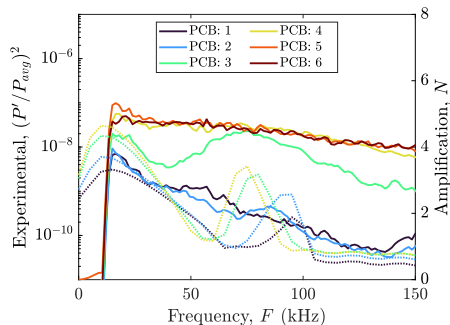
- Sharp 4C



- Second mode peaks matched to both PCB and Kulites

Linear Nonmodal Analysis vs Experimental Data

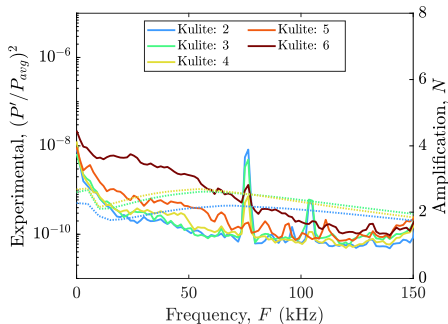
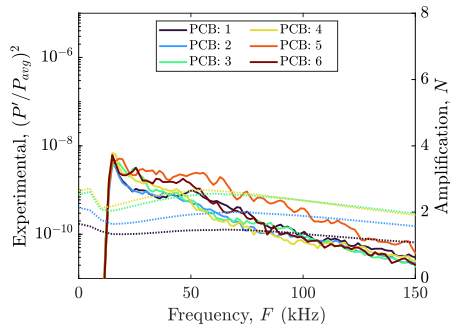
- Sharp 2C



- Lower amplification than sharp 4C ogive

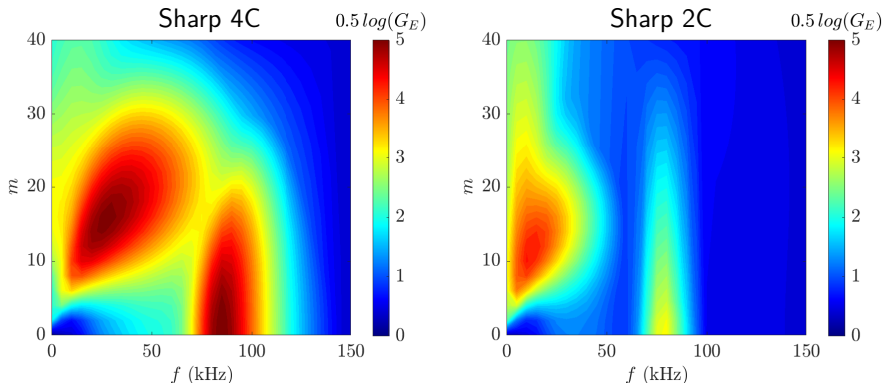
Linear Nonmodal Analysis vs Experimental Data

- Blunt 4C



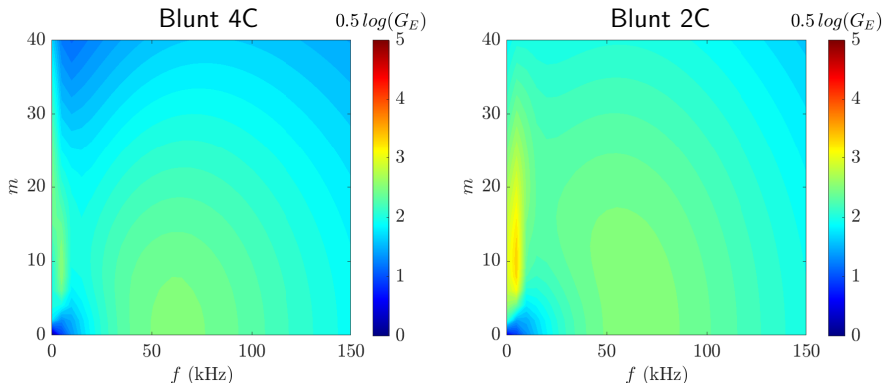
- No clear peaks, broadband disturbances

Linear Nonmodal Analysis Contours at PCB 3



- Weaker second mode than first mode for lower caliber (larger ogive half-angle)
- Smaller bandwidth and frequency values for oblique first mode

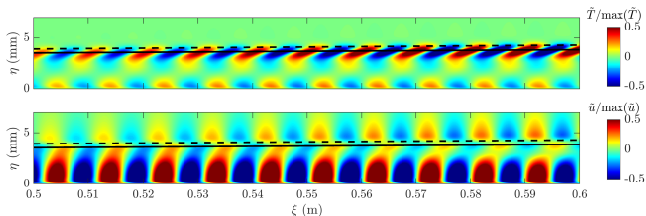
Linear Nonmodal Analysis Contours at PCB 3



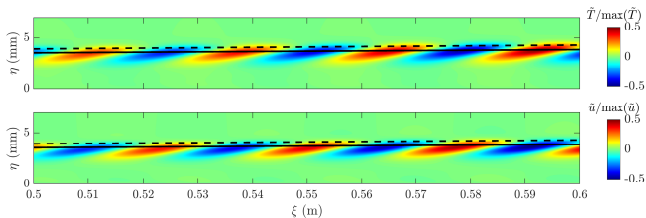
- Weaker overall amplification for blunter tips
- Broadband entropy-layer disturbances
- Peak associated with low frequency, oblique disturbances persists

Contours of Flow Perturbations - Sharp 4C

- Planar: $f = 85$ kHz $\rightarrow$ rope-like structures of Mack's second mode

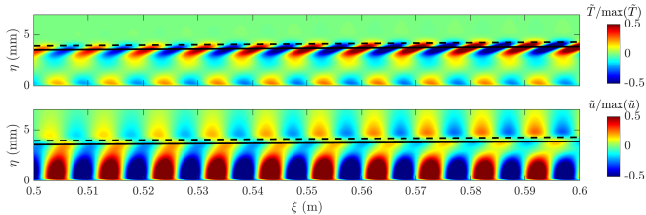


- Oblique: $f = 30$ kHz, $m = 16$

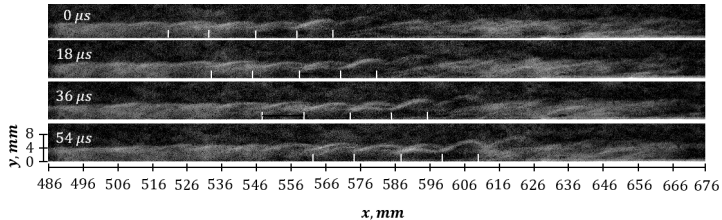


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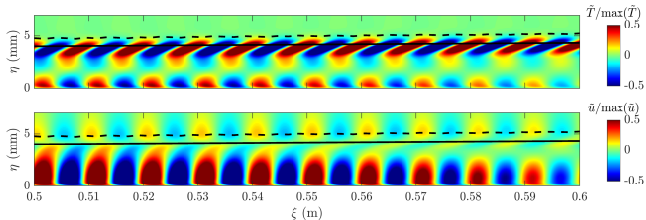


- Schlieren rope-like structure

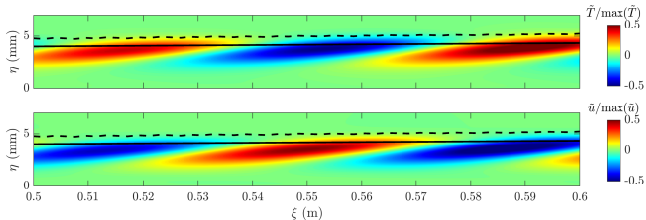


Contours of Flow Perturbations - Sharp 2C

- Planar: $f = 80$ kHz

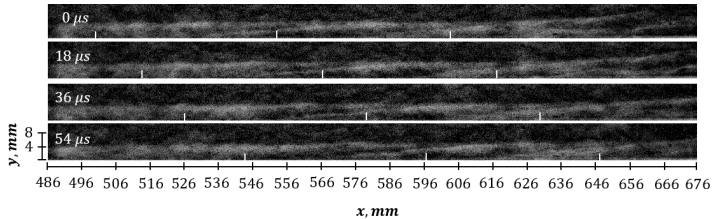


- Oblique: $f = 10$ kHz, $m = 10 \rightarrow$ elongated structures of Mack's first mode

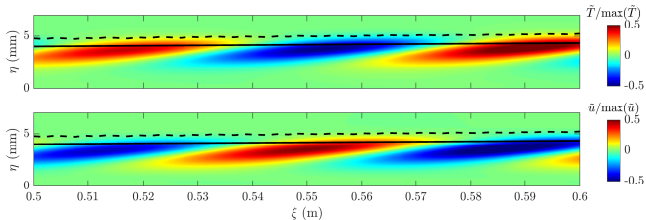


Contours of Flow Perturbations - Sharp 2C

- Schlieren elongated structures

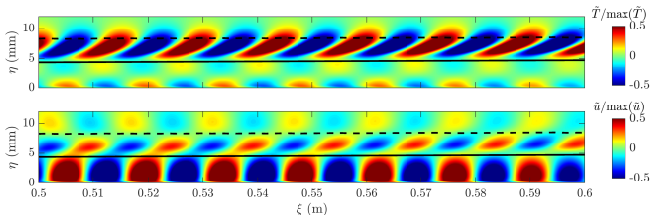


- Oblique: $f = 10$ kHz, $m = 10 \rightarrow$ elongated structures of Mack's first mode

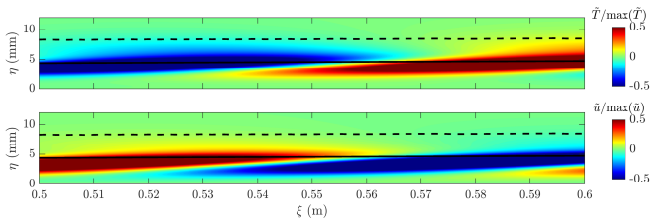


Contours of Flow Perturbations - Blunt 4C

- Planar: $f = 60$ kHz $\rightarrow$ wisp-like structures

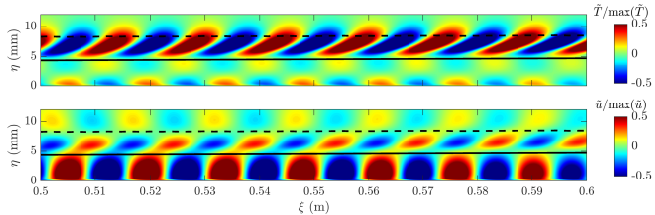


- Oblique: $f = 5$ kHz, $m = 10$

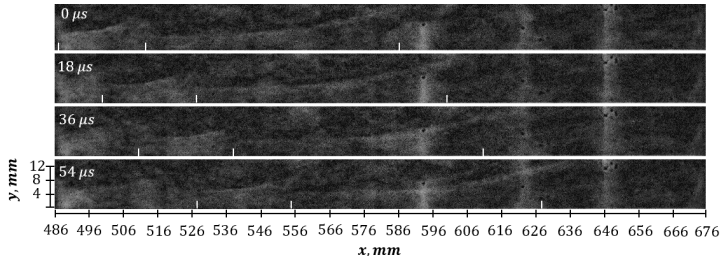


Contours of Flow Perturbations - Blunt 4C

- Planar: $f = 60$ kHz $\rightarrow$ wisp-like structures



- Schlieren wisp-like structure



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Concluding Remarks

- Frequencies of maximum N -factor for planar Mack's second mode match PCB and Kulite measurements
- Increasing ogive angle leads to a switch from high frequency second mode disturbances to low frequency, oblique first mode disturbances
- Experimental schlieren and FLDI on sharp 4C (14°) and 2C (28°) shows switch between rope-like to elongated disturbances in agreement with predicted amplification of first and second modes
- Modal analysis for blunt tips does not capture any linear disturbance amplification
- Nonmodal analysis for blunt tips identifies broadband entropy-layer disturbances, similar to PCB and Kulite measurements
- Wisp-like disturbances identified by schlieren akin to nonmodal entropy-layer disturbances for blunt tips

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.

