

Delay of Crossflow Transition on a Yawed Cone at Mach 6

Pedro Paredes Meelan Choudhari Fei Li

Computational AeroSciences Branch, NASA's Langley Research Center

AIAA Scitech 2026, AIAA Paper 2026-0000

FD-61: Instability and Transition VIII

3:30PM-3:50PM EST, Wednesday, Jan 14, 2026

Room Coral Spring I, Hyatt Regency. Orlando, FL



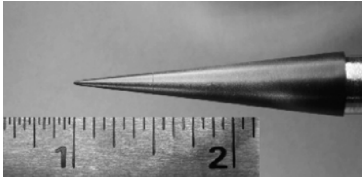
Outline

- 1 Motivation
- 2 Theory
- 3 Results
- 4 Summary and Concluding Remarks

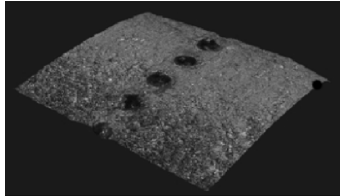
Laminar Flow Control for Yawed Circular Cone

- Laminar flow control (LFC) seeks to delay the onset of BLT to improve aerothermodynamic performance
- Transition over cone acreage under quiet flow induced by stationary crossflow (CF) instability
- Distributed roughness elements (DREs) shown to effectively manipulate initial amplitude of CF¹
 - ▶ Air Force Academy Ludwig tube at Mach 6 with a 7° half-angle cone at $AoA = 6^\circ$
 - ▶ Different transition locations between DREs with critical ($m_c = 45$) and subcritical ($m = \frac{3}{2}m_c = 68$) spacings
 - ▶ No indication of transition delay with respect to unperturbed case

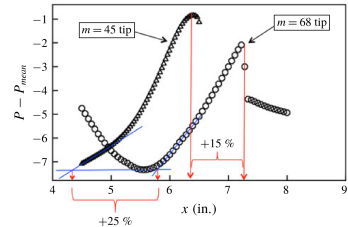
• Cone tip



• Zoom to DREs (dimples)



• Total pressure measurements



¹T. Corke et al. "Control of stationary cross-flow modes in a Mach 6 boundary layer using patterned roughness". In: *Journal of Fluid Mechanics* 856 (2018), pp. 822–849.

Objectives

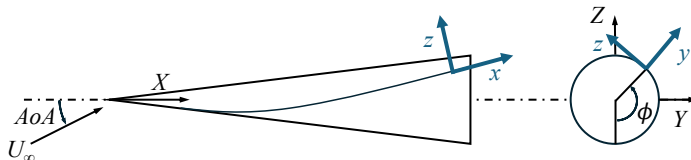
- **What?** Computationally investigate the potential of DREs to delay the onset of crossflow-induced transition in a yawed cone at high-speed conditions, via the generation of subdominant CF modes to reduce the growth of naturally dominant CF vortices and, subsequently, weaken the amplification of secondary instabilities driving laminar-to-turbulent breakdown
- **How?** Following a holistic transition prediction criterion that accounts for receptivity characteristics as well as for the simultaneous evolution of multiple CF disturbances and its effects on the laminar-to-turbulence breakdown process via secondary instabilities

Outline

- 1 Motivation
- 2 Theory**
- 3 Results
- 4 Summary and Concluding Remarks

Transition Prediction Criterion

- **Primary Stability Analysis** Linear instability characteristics of 3D boundary layer along inflection lines for CF vortices and streamlines for Mack's second modes (MM)
- **Receptivity Analysis** Linear receptivity of crossflow to surface roughness along vortex trajectories
- **Secondary Stability Analysis** Nonlinear evolution of SCF along inflection line trajectory and linear secondary instability analysis of finite-amplitude SCF vortices to predict transition onset location



- Decomposition of flow variables for stability analysis along selected inflection line

$$\mathbf{q}(x, y, z, t) = \bar{\mathbf{q}}(x, y) + \tilde{\mathbf{q}}_p(x, y, z) + \tilde{\mathbf{q}}_s(x, y, z, t)$$

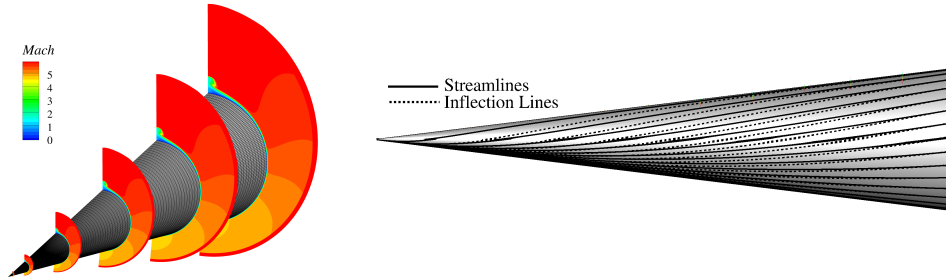
- ▶ $\bar{\mathbf{q}}(x, y)$: Laminar boundary layer flow (assumed $\partial \bar{\mathbf{q}} / \partial z = 0$)
- ▶ $\tilde{\mathbf{q}}_p(x, y, z)$: Finite-amplitude, SCF vortices
- ▶ $\tilde{\mathbf{q}}_s(x, y, z, t)$: Traveling, three-dimensional, secondary instabilities

Outline

- 1 Motivation
- 2 Theory
- 3 Results**
- 4 Summary and Concluding Remarks

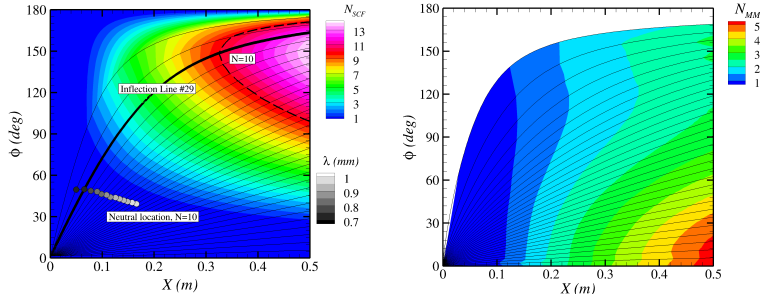
Laminar Flow Over a Yawed Circular Cone

- Sharp ($r_n = 10^{-4}L$), 7° half-angle cone with $L = 0.5$ m
- Flow conditions corresponding to Boeing/AFOSR Mach-6 Quiet Tunnel (BAM6QT):
 - ▶ $M_\infty = 6.0$, $Re_\infty = 10.8 \times 10^6 \text{ m}^{-1}$, $T_\infty = 52.4 \text{ K}$, $T_w = 300.0 \text{ K}$, $AoA = 6^\circ$
- Solution computed with second-order finite-volume, structured VULCAN-CFD solver
- Boundary-layer profiles extracted along streamlines and inflection lines for stability analysis



Linear Stability Characteristics

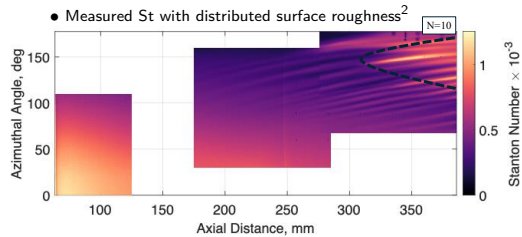
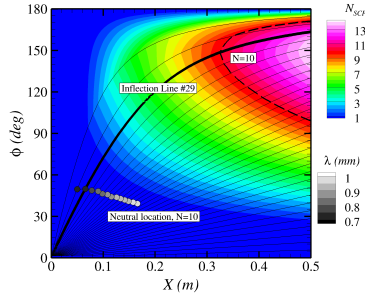
- PSE: $\tilde{\mathbf{q}}(x, y, z, t) = \tilde{\mathbf{q}}(x, y) \exp[i(\beta z - \omega t)]$, $\tilde{\mathbf{q}}(x, y) = \hat{\mathbf{q}}(x, y) \exp(i \int_x \alpha(x') dx')$
 - ▶ MM: Planar waves along 31 inviscid streamlines ($\omega \neq 0$, $\beta = 0$, $\alpha \neq 0$)
 - ▶ SCF: Stationary waves along 31 inflection lines ($\omega = 0$, $\beta \neq 0$, $\alpha \neq 0$)
- N-factor envelope contours based on $|\tilde{u}|_{max}$ for SCF and MM



- SCF substantially more amplified reaching $N > 13$ around $\phi = 150^\circ$
- Transition front inferred from measured Stanton number contours with sandblasted surface resembles $N = 10$
- Critical $N = 10$ is first reached along inflection line #29 at $X_T = 0.33$ m and $\phi \approx 148^\circ$

Linear Stability Characteristics

- PSE: $\tilde{\mathbf{q}}(x, y, z, t) = \tilde{\mathbf{q}}(x, y) \exp[i(\beta z - \omega t)]$, $\tilde{\mathbf{q}}(x, y) = \hat{\mathbf{q}}(x, y) \exp(i \int_x \alpha(x') dx')$
 - ▶ MM: Planar waves along 31 inviscid streamlines ($\omega \neq 0$, $\beta = 0$, $\alpha \neq 0$)
 - ▶ SCF: Stationary waves along 31 inflection lines ($\omega = 0$, $\beta \neq 0$, $\alpha \neq 0$)
- N-factor envelope contours based on $|\tilde{u}|_{max}$ for SCF

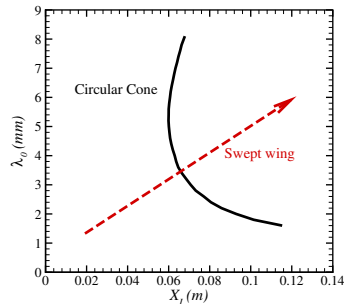
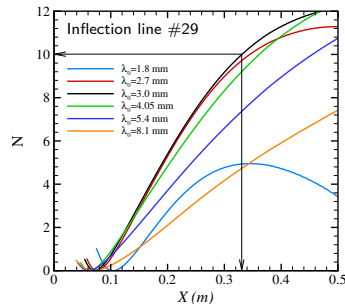
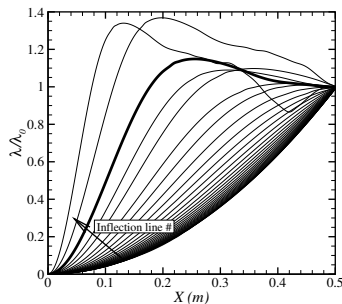


- SCF substantially more amplified reaching $N > 13$ around $\phi = 150^\circ$
- Transition front inferred from measured Stanton number contours with sandblasted surface resembles $N = 10$
- Critical $N = 10$ is first reached along inflection line #29 at $X_T = 0.33$ m and $\phi \approx 148^\circ$

²J. Edelman and S. Schneider. *Using Discrete and Distributed Roughness to Generate Stationary Crossflow Waves in a Mach 6 Quiet Tunnel*. AIAA Paper 2019-2968. 2019.

Linear Amplification of SCF Instabilities

- Development of disturbance wavelength (λ/λ_0) is determined by the diffuence of the trajectories³
- Nonmonotonic evolution of neutral locations X_I as a function of $\lambda_0 = \lambda(X_0 = 0.5m)$



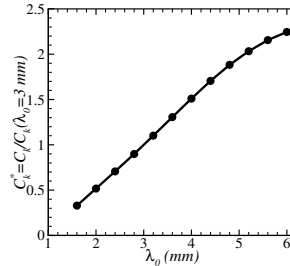
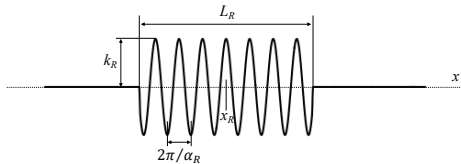
- Axial variations in λ/λ_0 and BL thickness lead to different $X_I(\lambda_0)$ evolution than swept wing (constant λ/λ_0)
- CF vortex that first reaches $N = 10$ corresponds to $\lambda_0 = 3$ mm ($\lambda_I = 0.82$ mm at $X_I = 0.071$ m)
- **This transition criterion does not account for either the effect of roughness variations or for nonlinear interactions between CF vortices**

³P. Paredes et al. "Modal Instabilities over Blunted Cones at Angle of Attack in Hypersonic Flow". In: *Journal of Spacecraft Rockets* 60.4 (2023), pp. 1188–1200.

Roughness-Induced Receptivity of SCF

- HLNSE: $\tilde{\mathbf{q}}(x, y, z, t) = \tilde{\mathbf{q}}(x, y) \exp[i(\beta z - \omega t)]$
- Linear roughness-induced forcing modeled by inhomogenous boundary conditions⁴
- Receptivity coefficient $C_k = (u_I/k)_{\max}$: maximum $u_I = |\tilde{u}|_{\max}(x_I)/U_\infty$ scaled by $k = k_R/k_r$ with $k_r = 1 \mu\text{m}$

$$\tilde{\mathbf{q}}_w(x) = -h_R(x) \left. \frac{\partial \tilde{\mathbf{q}}}{\partial y} \right|_w, \quad h_R(x) = \frac{k_R}{2} \{ \text{erf}[\sigma_x(x - x_R + L_R/2)] - \text{erf}[\sigma_x(x - x_R - L_R/2)] \} \cos(\alpha_R(x - x_R))$$

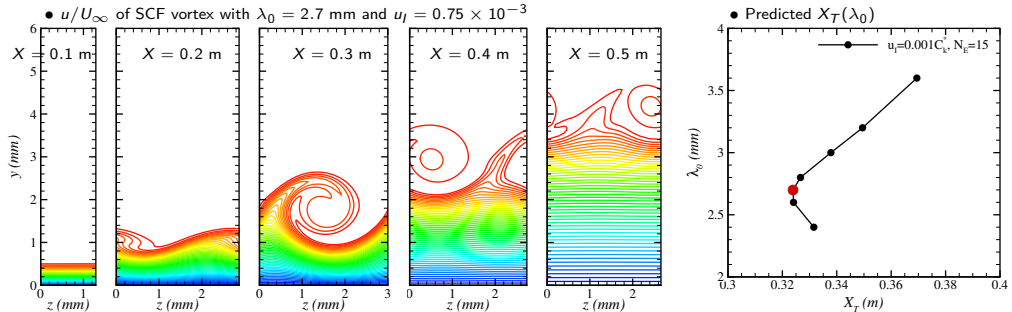


- Most effective roughness with $x_R = x_I$: $L_R/\lambda_I \approx 35$, $\alpha_R = 0$ (aligned with inflection line trajectory)
- $C_k^*(\lambda_0) = C_k(\lambda_0)/C_k(\lambda_{0,r})$ spectrum provides variation in effective CF amplitude associated with natural roughness

⁴M. Choudhari. "Roughness-Induced Generation of Crossflow Vortices in Three-Dimensional boundary Layers". In: *Theoretical and Computational Fluid Dynamics 6* (1994), pp. 1–30.

Secondary Instability of SCF

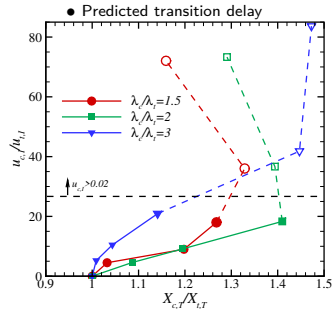
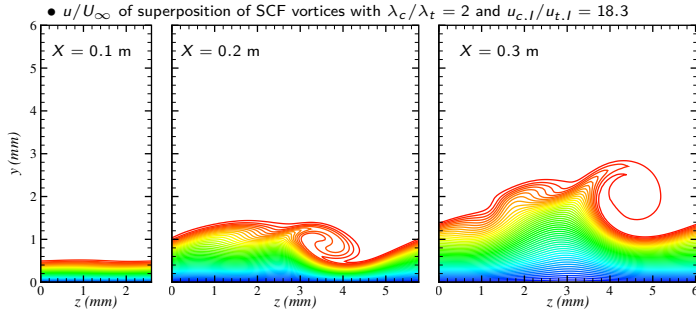
- Plane-Marching PSE: $\tilde{\mathbf{q}}(x, y, z, t) = \tilde{\mathbf{q}}(x, y, z) \exp(-i\omega t)$, $\tilde{\mathbf{q}}(x, z, y) = \hat{\mathbf{q}}(x, y, z) \exp(i \int_x \alpha(x') dx')$
 - ▶ Nonlinear evolution of SCF modes along inflection line #29 ($\omega = 0$, $\alpha = 0$)
 - ▶ Linear, secondary stability analysis of finite-amplitude SCF disturbance ($\omega \neq 0$, $\alpha \neq 0$)
- Assumed natural surface roughness inducing $u_I = 10^{-3}$ for $\lambda_{0,r} = 3$ mm: $u_I(\lambda_0) = 10^{-3} C_k^*(\lambda_0)$
- Transition criterion based on HIFiRE-1 and HIFiRE-5b correlations: $N_E = 15$



- Critical $N_E = 15$ is first reached along inflection line #29 at $X_T = 0.324$ m for $\lambda_0 = 2.7$ mm
- Primary target for transition control is SCF mode with $\lambda_0 = 2.7$ mm and $u_I = 0.001 C_k^* = 0.75 \times 10^{-3}$

Control of Crossflow-Induced Transition

- Target mode is the naturally dominant CF vortex: $\lambda_{t,0} = 2.7$ mm, $u_{t,I} = 0.75 \times 10^{-3} \rightarrow X_{t,T} = 0.324$ m
- Control mode is the DRE-induced subdominant CF vortex with $\lambda_c \neq \lambda_t$ and $u_{c,I} > u_{t,I}$
- Established strategy of $\lambda_c < \lambda_t$ for swept-wing configurations⁵ not successful due to different $X_I(\lambda_0)$
- Opposite strategy with $\lambda_c > \lambda_t$ found to yield significant transition delay



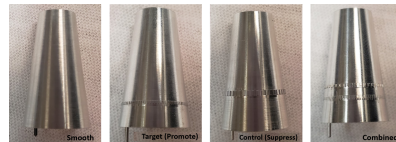
- **Optimal transition delay of 41% for $\lambda_c/\lambda_t = 2$ with $u_{c,I}/u_{t,I} < 25$ ($u_{c,I} < 0.02$ to avoid large roughness tripping)**

⁵W. Saric, R. Carillo, and M. Reibert. *Leading edge roughness as a transition control mechanism*. AIAA Paper 1998-0781. 1998.

Initial Experimental Evaluation⁶

- Target and control DREs of prismatic shape designed for inflection line #29 ($\phi \approx 160^\circ$ at $X = 0.42$ m)

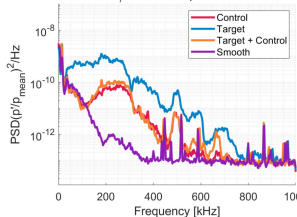
DRE	X (mm)	L (mm)	m	k (μm)	k_{measured} (μm)
Target (T)	58.4	6.45	84	57	64-97
Control (C)	55.9	6.45	42	146	188-200



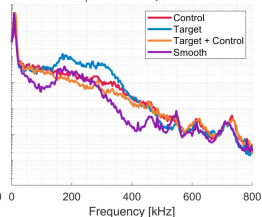
- Comparison between T and T+C tips shows reduction of

- ▶ wall pressure fluctuations measured by PCBs at $\phi = 140^\circ$
- ▶ heat transfer values measured by infrared thermography around $\phi = 160^\circ$

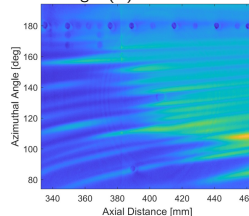
- PCB at $\phi = 140^\circ$, $X = 0.278$ m



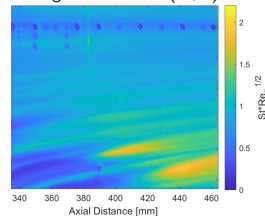
- PCB at $\phi = 140^\circ$, $X = 0.341$ m



- Target (T) DRE



- Target and Control (T+C) DREs



⁶C. Butler and J. Jewell. *Roughness Element Patterns for Control of Instability in Mach 6 Quiet Flow*. AIAA Paper 2024-4440. 2024.

Outline

- 1 Motivation
- 2 Theory
- 3 Results
- 4 Summary and Concluding Remarks**

Summary and Concluding Remarks

- To incorporate a comprehensive model of transition for control, we implemented a transition criterion that accounts for receptivity characteristics as well as evolution of multiple crossflow vortices and their effects on secondary instability amplification as the cause for laminar breakdown
- Linear receptivity provides initial amplitude spectrum excited via natural stochastic surface roughness
- Secondary instability used to identify target CF mode that drives transition
- Optimal transition delay of 41% is predicted for control modes with 2 times the target CF wavelength
- **Objective met:** Development of transition delay strategy based on DREs to excite subdominant CF modes and reduce the growth of naturally dominant CF vortices
- Initial experimental evaluation of the control strategy with DREs designed for inflection line #29 across the azimuth revealed a reduction in wall pressure fluctuations and heat transfer values for $\phi \geq 140$
- Further experimental studies are required to demonstrate the transition delay potential of this LFC strategy

Thank you for your attention

- Acknowledgements

- ▶ This material is based upon work supported by
 - ★ the NASA Hypersonic Technology Project (HTP) under the Aeronautics Research Mission Directorate (ARMD)
- ▶ Computational Resources supporting this work are provided by
 - ★ NASA K cluster at the Langley Research Center

