Assessing Hypersonic Boundary Layer Stability in the Presence of Panel Scale Protuberances

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Motivation

Responsive, Reusable Hypersonic Cruise Vehicles

- Strong emphasis on hot structures
- Primary design consideration is reducing aerodynamic heating loads [Reshotko 2006]
- Structural design of optimal-weight vehicles requires accurate prediction of aerodynamic heating

Design Approaches

1. Conservative assumption: fully turbulent
   - Increases vehicle TPS weight
2. Accurate Prediction of transition location
   - 3-8X increase in aeroheating from laminar to turbulent
   - Reduces TPS weight

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1 Rose – 2008; Mansour et. al – 2007; Dolvin – 2008; McClinton – 2006
2 Zuchowski, Selby, Macguire, and McAuliffe – 2011; Liguore and Tzong – 2011
Previous Work

Physics based prediction tools for Hypersonic Boundary Layer Transition (HBLT)\(^1\)

- Limited consideration of surface compliance/roughness\(^2\)

Fluid Thermal Structural Interactions (FTSI)

- Deformations on the order of the boundary layer thickness (BLT)\(^3\)
- Potentially transient in nature due to fluctuating pressures from the flow \(^4\)
- Lead to increased spatial variation in the surface temperature\(^5\)
- Combined wall temperature variation and surface deformation is a concern since the BLT changes with wall temperature [Schneider 2008]

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\(^1\) Malik – 1990; Stuckert and Reed – 1994; Adam and Hornung – 1997; Johnson and Candler – 2005
\(^3\) Weiting et. al – 1988; Glass and Hunt – 1988; Miller et. al – 2011
\(^4\) Blevins et. al – 1993; Gordon and Hollkamp – 2009
\(^5\) Weiting et. al – 1988; Glass and Hunt – 1988; Culler and McNamara -- 2010
Overall Goal: Investigate the effect of FTSI on HBLS
- representative thermo-mechanical surface panel responses
- Parameters: Buckling direction, panel location, multiple series panels, and rate of panel response

Conclusion: Impact of FTSI on BLS depends on the state of the boundary layer growth
- Rapid growth $\rightarrow$ Decreased stability
- Slow growth $\rightarrow$ Improved stability
Goal: Investigate the importance of FTSI in the design and analysis of hypersonic vehicles using geometries and operating conditions extracted from prior research on hypersonic FTSI.

1. NASP Ramp Panel [Culler and McNamara 2011]
2. Spherical Dome Protuberances [Glass and Hunt 1986]
3. X-33 Bowed Panel Array [Berry, Horvath, Kowalkowski, and Liechty 1999]
4. 3-D instability characterization
Methodology

Geometry → Mesh → Flow Solution → Stability Analysis

STABL

Flow

1 Johnson and Candler – 2005
Stability Theory Derivation

Linearized disturbance equations,

\[ \Gamma \frac{\partial \phi}{\partial t} + A \frac{\partial \phi}{\partial x} + B \frac{\partial \phi}{\partial y} + C \frac{\partial \phi}{\partial z} + D \phi + V_{xx} \frac{\partial^2 \phi}{\partial x^2} + V_{yy} \frac{\partial^2 \phi}{\partial y^2} + V_{zz} \frac{\partial^2 \phi}{\partial z^2} + V_{xy} \frac{\partial^2 \phi}{\partial x \partial y} + V_{xz} \frac{\partial^2 \phi}{\partial x \partial z} + V_{yz} \frac{\partial^2 \phi}{\partial y \partial z} + F^n = 0 \]

\[ \phi = (\rho_1', \rho_2', ..., \rho_{ns}', u', v', w', T', T_v')^T \]

Assuming disturbances to be spanwise (z) and temporally periodic,

\[ \phi = \psi(\xi, \eta) \Lambda(\xi) e^{i(kz-\omega t)} \]

Linear Stability Theory (LST) \quad Parabolized Stability Equations (PSE)

\[ \hat{D}\psi + \hat{A} \frac{\partial \psi}{\partial \eta} + \hat{V}_{\eta\eta} \frac{\partial^2 \psi}{\partial \eta^2} = 0 \]

\[ \hat{D}\psi + \hat{A} \frac{\partial \psi}{\partial \xi} + \hat{B} \frac{\partial \psi}{\partial \eta} + \hat{V}_{\eta\eta} \frac{\partial^2 \psi}{\partial \eta^2} = 0 \]

- LST for qualitative assessment of boundary layer stability over entire body
- PSE accounts for spatial history of disturbances and streamwise variation of flow
- Only provide insight into state of BL and the initial breakdown of laminar flow

Do not predict transition!
Transition Prediction

- Semi-Empirical $e^N$ Method
- Transition prediction from degree of disturbance amplification
- N-factor is the integrated growth rate of a constant frequency disturbance

$$N(\omega, S) = -\int_{S_o}^{S} \sigma dS$$

$$\sigma = \alpha_i(S, \omega) + \frac{1}{2E} \frac{dE}{dS}$$

- Requires experimental correlation for N-factor corresponding to transition
  - Typically 8-11 for smooth bodies in quiet flow
  - Approximately 5.5 for non-quiet wind tunnels
Example LST/PSE Results

LST Diagram

- Disturbances propagate between wall and sonic line within the boundary layer
- Disturbance frequency $\sim \text{BLT}^{-1}$
- Laminar boundary layer grows as $\sqrt{s} \rightarrow$ instability curve decreases as $\frac{1}{\sqrt{s}}$

LST Diagram highlights two factors which can lead to transition

1. Disturbance amplification
2. Distance along the body a constant frequency disturbance is amplified
Example LST/PSE Results

LST Diagram

- N factor increases when disturbance is within instability curve
- N factor decreases as disturbance exits instability curve
Example LST/PSE Results

**LST Diagram**

- `freq (kHz)`
- `S (m)`

**PSE Maximum N Factors**

- 140 kHz
- 160 kHz
- 180 kHz
- 200 kHz
Example LST/PSE Results

LST Diagram

PSE Maximum N Factors

Maximum Envelope
Example LST/PSE Results

LST Diagram

PSE Maximum N Factors

PSE- Chem Transition Prediction

- Prediction based on max N factor envelope for entire frequency spectrum
- Smooth structure in quiet flow → Transition occurs $8 < N < 11$
- Transition due to disturbances with frequencies of $139 - 172 \text{ kHz}$
Study: NASP Ramp Panel

- Mach 2-12 ascent trajectory
- Dynamic pressure = 2000 psf
- Centerline disp. from 90-300 sec (5< M <12)
- As Mach/altitude ↑ ~ Re ↓
- Shift in dominant deformation mode between 210-240 sec

Wedge Geometry

- Wedge length set to approx. NASA X-43A
- Panel placed at engine inlet
- Two wall temperatures
  - Cold wall (294 K)
  - Radiative Equilibrium

* Dimensions in meters

• Max N-factor ↓ ~ w/ Mach number ↑ and Re_L ↓
• Prior research found ↑ in M (>4) and unit Re improves stability [Stetson 1990]
  • Independent characterizations may not capture combined effect
  • Boundary layer stability is more sensitive to Mach number changes
• Ascent at constant q_∞ has stabilizing effect on BL
• RE produces lower N-factors than cold wall BC’s
Wall Temperature

Cold Wall

Radiative Equilibrium

Instability Curve

Lower Freq’s
Panel Compliance

- Decreased N-factor growth rate for higher mode deformation
- N-factors continue to decrease as higher mode deformation increases
Deformation Mode

BLT Comparison

- Rigid CW
- Rigid RE
- Compliant CW
- Compliant RE
- Wedge

LST Diagrams

- ai
- 18.95
- 15.79
- 12.63
- 9.47
- 6.32
- 3.16
- 0.00

NASDAQ Ramp Panel
Spherical Dome Protuberances
X-33 Bowed Panel Array
3-D effects
Study: Spherical Dome Protuberances

- Aerothermal tests in NASA Langley HTT at Mach 6.5
- Dome lengths of 17.8, 35.6, 71.1 cm
- Effective altitude of 30.2 km
- Unit Re = 3.543x10^6 m\(^{-1}\)

Domes 1-3
- LE = 1.89m

Domes 4-6
- LE = 1.80m

Domes 7-8
- LE = 1.47m

H/L of 1.43-2.86%

L = 17.78 cm  →  L = 35.56 cm

N Factor vs. S (m)

- Rigid CW
- Rigid RE
- SS CW
- SS RE
- CC CW
- CC RE

3-D effects

NASP Ramp Panel
Spherical Dome Protuberances
X-33 Bowed Panel Array
Largest Protuberance

\[ H/L = 1.43\% \quad \text{and} \quad H/L = 2.86\% \]

- RE wall shows same trend as observed for smaller panels
- For CW, different panel BCs lead to different N-factor growth over panel
Similar BL for both BCs at H/L of 1.43%

At H/L of 2.86% simple-supports (SS) result in severe, abrupt changes in BLT

Clamped (CC) supports lead to smoothly varying BL over panel location
Clamped (CC)

- Clamped: disturbance frequencies excited just before panel LE continue to grow

Simply-Supported (SS)

- Simply-Supported: abrupt shift in BLT suddenly excites lower frequency disturbances → decreases N-factors
Study: X-33 Bowed Panel Array

- Experiments in NASA LaRC 20-Inch Mach 6 Air Tunnel to examine BL transition and impact on aeroheating
- 14 centerline panels
- Mach 6 $Re_L = 3.5 \times 10^6$
- Cold wall conditions

X-33 Bowed Panel Array

1.32% Scale X-33 model (dimensions in inches)
Flow Solution & LST

Simply-Supported

Clamped

3-D effects
• Increased N-factor growth near leading edge
• Decreased N-factors further downstream (4-10 m)
• Consistent with findings of prior research [Riley 2012]
• Significant reduction in N-factors for panel array beginning at 4m from LE of wedge
3-D Effects

- Percent Crossflow

\[ \% CF = \frac{W_{\text{max}}}{U_{\text{edge}}} \]

- \( \% CF \leq 4.4\% \) for each geometries

Glass and Hunt Dome 8

X-33 Single Panel
Conclusions

1. Constant dynamic pressure ascent, with increasing Mach number and decreasing Re, improved boundary layer stability
2. Radiative equilibrium wall condition is more stabilizing than cold wall
3. Higher mode dominant panel deformations excite a wider range of disturbance frequencies than first mode
4. Significant reduction in N-factor when the displacement ratio increases from 1.43 to 2.86%
5. Wall temperature has a more prominent effect on boundary layer stability than structural boundary condition
6. Structural boundary condition negligible for all but largest panel and deformation
7. Multiple panels in series disrupt the unstable growth of disturbances and improve stability in regions of slow boundary layer growth
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