Characterization of Structural Response to Hypersonic Boundary Layer Transition

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Challenges

• A primary design consideration in the development of hypersonic cruise vehicles is the aerodynamic heat load as it; [Zuchowski – 2010,2012]
  ▪ Induces thermal stresses
  ▪ Changes material properties
  ▪ Can result in damage (creep + plasticity)
  ▪ Affects strength sizing → structural weight

• Accurately predicting and minimizing the aerodynamic heating requires knowledge of the boundary layer state [Reshotko – 2006]
  ▪ 3-8X increase in aeroheating from laminar to turbulent flow
  ▪ Transitional overshoot in aerothermodynamic loads¹ (heat flux, fluctuating pressure)

¹Wadhams et al – 2008; Casper et al – 2009; Franko and Lele – 2013
Challenges

- Boundary layer stability varies during flight due to:
  - Operating conditions (Mach, altitude variation)
  - Surface temperature variation
  - Structural deformations

Lockheed, funded by the AFRL Structural Sciences Center, has identified vehicle regions which present unique challenges due to aerothermodynamic loads associated with the hypersonic environment [Zuchowski – 2012]

“...high dynamic pressure, thermally induced stress, and material property change cause aero-elastic stability to be of primary concern.”

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3Hollis et al – 2002; Riley et al – 2014
Challenges

Takeaway

Transition front may interact with the aerothermoelastic response of the structure

Lockheed, funded by the AFRL Structural Sciences Center, has identified vehicle regions which present unique challenges due to aerothermodynamic loads associated with the hypersonic environment [Zuchowski – 2012]

...high dynamic pressure, thermally induced stress, and material property change cause aero-elastic stability to be of primary concern.”
Boundary layer state is coupled to the response of the structure

- How does boundary layer transition affect the structural response of the vehicle?
- Must transition be taken into account in the vehicle design?
- Does turbulent flow remain conservative with respect to transitional overshoot?

Iyer, Muppidi, and Mahesh – 2012

Heat flux overshoot

Wadhams et. al – 2008
Investigate the impact of **transitional aerothermodynamic loading** on the structural response of hypersonic vehicle surface panels

1. Enhance existing aerothermoelastic framework with transitional aerothermodynamic load models
2. Obtain and compare panel responses due to laminar, transitional, and turbulent flow
3. Investigate the effect of transition onset location, transition length, and transitional overshoot in heat flux and pressure
Characterization of Structural Response to Hypersonic Boundary Layer Transition

I. Aerothermoelastic (ATE) framework
   a. Thermal & structural solvers
   b. Transitional heat flux model
   c. Transitional fluctuating pressure model

II. Problem Description

III. Key Results
   a. Impact of transitional aerothermodynamic loading on flutter onset
   b. Effect of transitional overshoot on the conservative assumption of turbulent flow
   c. Combined effect of overshoot and material temperature dependence on the flutter boundary
Aerothermoelastic framework

- Aerothermodynamics
  - Boundary Layer Edge Conditions
    - Mean Flow Pressure
    - Fluctuating Pressure
    - Heat Flux
  - Overall Pressure Load
  - Surface Temperature
  - Surface Heat Flux
  - Heat Transfer
  - 2D Heat Equation

- Structural Dynamics
  - von Kàrmàn panel in cylindrical bending

- Third Order Piston Theory
- Surface Geometry & Dynamics
- Eckert’s Reference Enthalpy
Thermal and structural solvers

Thermal solver:

- 2-D FE formulation of the transient heat transfer equation
- Temperature-dependent specific heat ($c$) and thermal conductivity ($k$)
Thermal and structural solvers

Thermal solver:
- 2-D FE formulation of the transient heat transfer equation
- Temperature-dependent specific heat \( c \) and thermal conductivity \( k \)

Structural solver:
- Thermal loading due to non-uniform temperatures \( T = T(x,z) \)
- Temperature-dependent modulus of elasticity \( E(T^*) \) and thermal expansion coeff. \( \alpha(T^*) \)
Transitional heat flux model

Model inputs:
1. laminar and turbulent heat flux
2. transition onset location \(x_{on}\)
3. transition overshoot location \(x_{os}\)
4. overshoot parameter \(Q_{os}\)

\[ Q_{tran} = (1 + Q_{os})Q_{turb}|_{x_{os}} \exp \left[ - \frac{(x-x_{os})^2}{2\sigma^2} \right] \]
Transitional fluctuating pressure model

Model inputs:
1. transition onset ($x_{on}$) and overshoot ($x_{os}$)
2. end of transition ($x_{end}$)
3. pressure overshoot parameter ($p_{os}$)

\[ P(x, t) = P_{MEAN}(x, t) + P_{FLUC}(x, t) \]

\[ P_{FLUC} = f(\tilde{p}, q_e, H) \]

\[ \tilde{p}_{turb} \left( 1 + \tilde{p}_{os} \exp \left[ - \frac{(x-x_{os})^2}{2\sigma^2} \right] \right) \]
Problem Description

- Represents a surface panel oriented near the nose of a hypersonic vehicle
- Examined in prior works [Miller et. al – 2011, 2014, Deshmukh et. al -- 2013]
- Examine effect of:
  1. Transition onset \((0.1 < x_{on}/L < 0.7)\)
  2. Transition length \((0.05 < x_{tran}/L < 0.8)\)
  3. No overshoot \((Q_{os}=0, p_{os}=0)\) vs. overshoot \((Q_{os}=0.5, p_{os}=1.0)\)
Transitional loading neglecting the effect of overshoot

- Each line corresponds to a different onset location
- $x$-axis provides the overshoot location (i.e. end of transition)
Time to flutter increases as transition onset moves downstream

No overshoot:
Larger flutter time as:
1. Onset moves downstream
Time to flutter increases with transition length

No overshoot:
Larger flutter time as:
1. Onset moves downstream
2. Transition length increases

\[ x_{on}/L = 0.1 \]
\[ x_{on}/L = 0.3 \]
\[ x_{on}/L = 0.5 \]
\[ x_{on}/L = 0.7 \]
Time to flutter increases with transition length

No overshoot:

Larger flutter time as:

1. Onset moves downstream
2. Transition length increases
No overshoot vs. overshoot in heat flux and fluctuating pressure loads

No overshoot:
- Larger flutter time as:
  1. Onset moves downstream
  2. Transition length increases

Overshoot:
- Reduces flutter time

\[ x_{on}/L = 0.1 \]
\[ x_{on}/L = 0.3 \]
\[ x_{on}/L = 0.5 \]
\[ x_{on}/L = 0.7 \]

\[ t_F (sec) \]

\[ x_{os}/L \]
Transitional overshoot results in non-monotonic increase in flutter time with transition length

No overshoot:
- Larger flutter time as;
  1. Onset moves downstream
  2. Transition length increases

Overshoot:
- Reduces flutter time
- Non-monotonic growth in flutter time as transition length increases
- Flutter time decreases for transition overshoot occurring over 3rd quarter of the panel
Turbulent conditions conservatively predict flutter onset

- No overshoot:
  1. Onset moves downstream
  2. Transition length increases

- Overshoot:
  - Reduces flutter time
  - Non-monotonic growth in flutter time as transition length increases
  - Flutter time decreases for transition overshoot occurring over 3rd quarter of the panel
  - Transitional flutter times are bounded by laminar and turbulent conditions

\[ x_{on}/L = 0.1 \]
\[ x_{on}/L = 0.3 \]
\[ x_{on}/L = 0.5 \]
\[ x_{on}/L = 0.7 \]

Laminar (142.5 sec)

Turbulent (24.8 sec)
Thermo-structural response of transitional cases neglecting overshoot in heat flux and pressure

- Qualitatively similar plots indicate that displacement is largely driven by the average temperature.

![Chord-wise average temperature at flutter](image1)

![Maximum displacement prior to flutter](image2)
No overshoot vs. overshoot

- Overshoot produces larger variation in temperature and displacement for a fixed onset as the transition length varies.

Chord-wise average temperature at flutter

Maximum displacement prior to flutter
Turbulent loading does not always conservatively predict the pre-flutter thermo-structural response

- Overshoot produces larger variation in temperature and displacement for a fixed onset as the transition length varies
- Transitional loading can lead to average temperatures and peak displacements exceeding turbulent conditions

Transitional > turbulent

\( x_{on}/L = 0.3, x_{os}/L = 0.5 \)

Chord-wise average temperature at flutter

Turbulent

\( T = 389 \text{ K} \)

Maximum displacement prior to flutter

Transitional > turbulent

Turbulent

\( w/h = 12.3 \)
Transitional loading can produce larger displacements than turbulent flow

- Turbulent fluid loading conservatively predicts flutter time
- Transitional displacements exceed that of turbulent prior to flutter

Transitional overshoot case: \( \frac{x_{on}}{L} = 0.3 \), \( \frac{x_{os}}{L} = 0.5 \)

Comparison of panel displacement resulting from transitional and turbulent fluid loading
Turbulent flow does not always conservatively predict the thermal response of the panel.

Transitional flow results in ...

- Large thermal gradients
- Higher maximum temperatures at the same instant in time
- Higher average temperatures at flutter onset

How does the thermal gradient impact the material properties?

Panel temperature distribution due to laminar, transitional, and turbulent fluid loading.

Transitional overshoot case: $x_{on}/L = 0.3$, $x_{os}/L = 0.5$
Transitional loading results in large variation in material properties across the panel

- Transitional cases with $x_{on} = 0.3$, $x_{os} = 0.5$, 0.6, 0.7
- Decrease in flutter time as overshoot location moves aft along the panel
- Decrease in $T \sim$ increase in $E$ + decrease in $\alpha$

Is reduction in flutter onset a product of the material temperature-dependence?

![Graph showing variation in $E$ and $\alpha$ with $x_{os}/L$]

- Modulus of Elasticity ($E$) with $x_{os}/L = 0.5$, 0.6, 0.7
- Thermal Expansion Coefficient ($\alpha$) with $x_{os}/L = 0.5$, 0.6, 0.7
Material temperature-dependence impacts flutter onset

- Time to flutter increases for constant material properties
- Local reduction in flutter onset time not observed for cases with constant properties

**Graph:**

- **Y-axis:** $t_f$ (sec)
- **X-axis:** $x_{os}/L$

**Legend:**
- Constant Properties @ 300 K
- Temperature dependent

**Graph Description:**

- The graph shows the relationship between flutter time ($t_f$) and the ratio $x_{os}/L$ for different material temperature conditions.
- A shaded area indicates the constant properties at 300 K.
- The graph illustrates the impact of temperature dependence on flutter onset time.
An aerothermoelastic framework accounting for transitional aerothermodynamic loading was developed to:

• Compare panel responses subject to laminar, transitional, and turbulent flows
• Investigate the effect of transition onset, length, and transitional overshoot in heat flux and fluctuating pressure

Key findings were presented pertaining to the:

1. Impact of transitional aerothermodynamic loading on flutter onset
2. Effect of transitional overshoot on the conservative assumption of turbulent flow
3. Effect of overshoot and material temperature dependence on the flutter boundary
Conclusions

1. Turbulent conditions conservatively predict the flutter onset time.
   • Transitional overshoot, in heat flux and fluctuating pressure, reduces the onset to flutter time relative to no overshoot.

2. Turbulent conditions do not always conservatively predict the thermo-structural response.
   • Transitional flow yields significantly increased thermal gradients and can result in larger maximum temperatures.
   • Transitional overshoot, near the mid-chord, can yield average temperatures and peak displacements exceeding that resulting from turbulent flow.

3. Material temperature dependence produces non-monotonically varying aerothermoelastic stability boundaries in transitional flows with overshoot.
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