Rapid Prediction of Unsteady Aeroelastic Loads in Shock-Dominated Flows

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Motivation: Reusable Hypersonic Cruise Vehicles

- Strong interest in reusable hypersonic vehicles
- Require rapid and accurate loads prediction
  - Complex flow physics
  - Potential for strong fluid-structural coupling
  - Long time scale evolution of the structure
  - Expectation of many design iterations
- Shocks represent a critical loading concern for structural design of reusable hypersonic structures [Zuchowski – 2010, 2012]

Require rapid prediction tools for unsteady loads in shock-dominated flows
Previous Work

• Computational investigation of shock impingement in inviscid and laminar flows [Visbal – 2012, 2014]
  – Panel flutter disappears for a weak shock
  – Dynamic pressure required to incite flutter reduced
  – Unsteady CFD is impractical for detailed exploration of the parameter space of complex structures

• Experimental investigation of shock impingements [Spottswood et al. – 2012; Willems et al. – 2013]
  – Evidence of strong fluid-structural coupling
  – Limitations in measurement capabilities

Require improved understanding of structural responses in shock-dominated flows
Rapid and accurate loads prediction is critical

- Complex flow physics
  - Three-dimensionality
  - Strong inviscid-viscous interactions
  - Shock waves

Potential for strong, dynamic fluid-structural coupling

Long time scale evolution of the structure

Expectation of many design iterations

There is a basic need for efficient models with sufficient accuracy
Model Reduction

- Model reduction of supersonic/hypersonic flows
  \[ [\text{Crowell, Miller, and McNamara – 2011; Crowell and McNamara – 2012}] \]
  \[
P(x, y, t) = P_{SS, CFD}(x, y, t) + P_{US, PT}(x, y, t)
\]
  Kriging model
  Unsteady piston theory correction

- Applied to simple panels and 3-D lifting surfaces
- Accurate and efficient prediction tool for unsteady loads
- Invalid for external flow discontinuities
Examine a modeling approach, based on local piston theory, to correct steady-state CFD for dynamic fluid-structural coupling in the presence of flow discontinuities

1. Unsteady pressure prediction for forced vibrations of 2-D and 3-D panels, subject to shock impingements

2. Aeroelastic response calculations for shock-induced limit cycle oscillations

3. Comparison of computational expense
Rapid Prediction of Unsteady Aeroelastic Loads in Shock-Dominated Flows

I. Methodology
   a. Piston Theory
   b. Local Piston Theory
   c. Unsteady correction

II. Key Results
   a. Prescribed oscillations of a 2-D and 3D surface panel subject to shock impingement
   b. Shock-excited aeroelastic response prediction
   c. Comparison of computational expense
Methodology: Classical Piston Theory

- Consider the exact piston pressure
  \[
  \frac{P}{P_\infty} = \left(1 + \frac{\gamma-1}{2} \frac{v_n}{a_\infty}\right)^{\frac{2\gamma}{(\gamma-1)}} \quad v_n = \frac{\partial Z}{\partial t} + U_\infty \left\{ \frac{\partial Z}{\partial x} \right\}
  \]

- Binomially expanded to third order
  \[
  P = P_\infty + \gamma P_\infty \left\{ \frac{v_n}{a_\infty} + \frac{\gamma+1}{4} \left( \frac{v_n}{a_\infty} \right)^2 + \frac{\gamma+1}{12} \left( \frac{v_n}{a_\infty} \right)^3 \right\}
  \]

- Freestream quantities valid for shocks resulting from structural motion/surface inclination

- Update using local quantities for external influences
Methodology: Local Piston Theory

Exact piston pressure:

\[ \frac{P}{P_\infty} = \left( 1 + \frac{\gamma - 1}{2} \frac{v_n}{a_\infty} \right)^{\frac{2\gamma}{(\gamma-1)}} \]

Update using local quantities:

\[ \frac{P}{P_{loc}} = \left( 1 + \frac{\gamma - 1}{2} \frac{\dot{Z}}{a_{loc}} \right)^{\frac{2\gamma}{(\gamma-1)}} \]
Unsteady Local Piston Theory Correction

Surface pressure:

\[ P = P_{loc} + P_{LPT} \]

Exact correction:

\[ P_{LPTe} = P_{loc} \left\{ 1 + \frac{\gamma - 1}{2} \frac{\dot{Z}}{a_{loc}} \right\}^{\frac{2\gamma}{(\gamma - 1)}} - 1 \]

Linear correction:

\[ P_{LPTl} = P_{loc} \left\{ \frac{\dot{Z}}{a_{loc}} \right\} \]
Local Temperature in Viscous Flows

Define $a_{loc}$ as a function of $T_{loc}$

$$a_{loc} = \sqrt{\gamma R T_{loc}}$$

Not constant through the boundary layer

Define local temperature at boundary layer edge

$$\delta(x)_{Lam.} = \frac{5.0x}{\sqrt{\text{Re}_x}}$$

$$\delta(x)_{Turb.} = \frac{0.37x}{\text{Re}^{1/5}_x}$$
Prescribed Oscillations of a Surface Panel

### Reduced Frequency, $k = fL/U$

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>2-D Panel</strong></td>
<td>$0.02 &lt; k &lt; 0.15$</td>
</tr>
<tr>
<td><strong>3-D panel</strong></td>
<td>$k = 0.014$</td>
</tr>
<tr>
<td><strong>Shock</strong></td>
<td>$k = 0.001$</td>
</tr>
</tbody>
</table>

### Correction Assessment

- **2-D flow**: stationary and oscillating shock
- **3-D flow**: oscillating shock

### Fluid Model

- NASA Langley CFL3D
- Menter $k-\omega$ SST turbulence model
- Shock generator varies sinusoidally in time
- Panel oscillations in modes 1-3
Error Metrics

Comparison using generalized aerodynamic force:

\[ GAF(t) = \frac{1}{2} \rho_\infty U_\infty^2 \iint (\Phi(x, y) C_p(x, y)) dx dy \]

Error metrics:

\[ E_{\text{mean}}(\%) = \frac{1}{p} \sum_{i=1}^{p} \left( \frac{|\text{MODEL}^{(i)} - \text{CFD}^{(i)}|}{\text{RMS}} \right) \times 100 \]

\[ E_{\text{max}}(\%) = \text{Max} \left( \frac{|\text{MODEL}^{(i)} - \text{CFD}^{(i)}|}{\text{RMS}} \right) \times 100 \]

\[ E_{\text{max, dim}} = \text{Max} \left( |\text{MODEL}^{(i)} - \text{CFD}^{(i)}| \right) \]

Normalized using root mean square:

\[ \text{RMS} = \sqrt{\frac{1}{p} \sum_{i=1}^{p} (\text{CFD}^{(i)})^2} \]
Full Generalized Force: Stationary Shock (2-D)

Mode 1, $k_{\text{panel}} = 0.03$

Inviscid flow theory inaccurate due to boundary layer displacement effects

Mean values dominated by steady-state effects

$E_{\text{Mean}} = 48.6\%$

$E_{\text{Max}} = 53.5\%$

Full Generalized Aerodynamic Force (GAF, N)
Unsteady Generalized Force: Stationary Shock (2-D)

Mode 1, \( k_{\text{panel}} = 0.03 \)

Inviscid theory captures unsteady component of viscous solution

Unsteady Component of GAF (N)
Unsteady Generalized Force: Stationary Shock (2-D)

Mode 1, \( k_{\text{panel}} = 0.03 \)

- Local piston theory good approximation to Euler solution
- Rapid convergence of local piston theory correction

Unsteady Component of GAF (N)
Generalized Force: Stationary Shock (2-D)

Mode 1, $k_{\text{panel}} = 0.03$

Correction introduces phase shift to the steady-state

Full Generalized Aerodynamic Force (GAF, N)

Unsteady Component of GAF (N)
Generalized Force: Oscillating Shock (2-D)

Mode 1, $k_{\text{panel}} = 0.022, k_{\text{shock}} = 0.001$

Inviscid flow theory is inaccurate for the full GAF (47% mean error)

Full Generalized Aerodynamic Force (GAF, N)

Unsteady component accurately captured using inviscid flow theory

Unsteady Component of GAF (N)
Generalized Force: Oscillating Shock (3-D)

Mode 1, $k_{\text{panel}} = 0.014, \quad k_{\text{shock}} = 0.001$

- Visous effects important (23% maximum errors)
- Inviscid captures phase of unsteady component

Full Generalized Aerodynamic Force (GAF, N)  
Unsteady Component of GAF (N)
Aeroelastic Response Prediction of a Surface Panel

Shock strength specified using $P_3/P_1$ ratio

Cylindrical bending of a simply supported panel with nonlinear von Kármán strains

$M_1 = 2$

$x_i/L = 0.5$
Local piston theory over-predicts flutter conditions

Initial comparisons made using local piston theory

\[ P = P_{loc} + \gamma P_{loc} \left\{ \frac{v_n}{a_{loc}} + \frac{\gamma + 1}{4} \left( \frac{v_n}{a_{loc}} \right)^2 + \frac{\gamma + 1}{12} \left( \frac{v_n}{a_{loc}} \right)^3 \right\} \]

\[ v_n = \frac{\partial Z}{\partial t} + U_{loc} \left\{ \frac{\partial Z}{\partial x} \right\} \]

For Mach numbers ≤ 2, Van Dyke’s equation preferred

\[ P = P_{loc} + \gamma P_{loc} \left\{ \frac{M_{loc} v_n}{\beta} + \frac{M_{loc}^4 (\gamma + 1) - 4\beta^2}{4\beta^4} \left( \frac{v_n}{a_{loc}} \right)^2 \right\} \]

\[ \beta = \sqrt{M_{loc}^2 - 1} \]

Second order expressions become equivalent as \( M_{loc} \) increases
Shock-Excited Flutter

\[ k = \frac{fL}{U} \]

--- Visbal* --- Approx.

*Visbal – 2012*
Shock-Excited Flutter

\[
\frac{P_3}{P_1} = \frac{fL}{U}
\]

--- Visbal* --- Approx.

* [Visbal – 2012]
Shock-Excited Flutter

\[ U_f L_k = \text{Visbal}^{*} \]

\[ k = \frac{f_L}{U} \]

--- Visbal* --- Approx.

* [Visbal – 2012]
Shock-Excited Flutter

\[ \frac{U}{fL} \approx k \]

\[ \frac{P_3}{P_1} \]

--- Visbal* --- Approx.

* [Visbal – 2012]
Shock-Excited Flutter

\[ f_L \approx \frac{U}{k} \]

* [Visbal – 2012]
Local approach maintains computational efficiency

Wall times of models for 2-D panel subject to impinging shock

<table>
<thead>
<tr>
<th>Method</th>
<th>1 Iteration of Pressure (sec.)</th>
<th>1 Hour of Response (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Piston Theory\textsuperscript{a,b}</td>
<td>$1.18 \times 10^{-2}$</td>
<td>$7.08 \times 10^{0}$</td>
</tr>
<tr>
<td>Full-Order CFD\textsuperscript{b}</td>
<td>$1.11 \times 10^{2}$</td>
<td>$6.66 \times 10^{4}$</td>
</tr>
</tbody>
</table>

Wall times of models for 3-D panel subject to impinging shock

<table>
<thead>
<tr>
<th>Method</th>
<th>1 Iteration of Pressure (sec.)</th>
<th>1 Hour of Response (min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local Piston Theory\textsuperscript{a,b}</td>
<td>$2.21 \times 10^{-2}$</td>
<td>$1.33 \times 10^{1}$</td>
</tr>
<tr>
<td>Full-Order CFD\textsuperscript{b}</td>
<td>$6.50 \times 10^{2}$</td>
<td>$3.90 \times 10^{5}$</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Assuming RANS Kriging surrogate
\textsuperscript{b} 32 (2-D), 94 (3-D) 2.60 GHz Opteron processors, 2.0 GB RAM each
\textsuperscript{c} Projected time
Prescribed oscillations of a surface panel

Comparison of viscous and inviscid

Local piston theory correction

Aeroelastic response prediction of shock-excited oscillations using local approach

Comparison of computational expense
Conclusion

- 2-D flows: stationary/oscillating shocks ($k < 0.15$)
  - Inviscid captures unsteady viscous component
  - Boundary layer effects dominate
  - Unsteady linear correction sufficient

- 3-D flows: oscillating shocks ($k < 0.014$)
  - Steady-state component dominates
  - Unsteady component of inviscid solution has large errors
  - Correction captures phase of unsteady component

- Predicts trends of Euler solutions for flutter behavior

- Efficient and accurate prediction of loads
Acknowledgements

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Backup Slides
Generalized Force: Stationary Shock (2-D)

Mode 2, $k_{\text{panel}} = 0.07$

Correction introduces phase shift to the steady-state

Full Generalized Aerodynamic Force (GAF, N)

Unsteady Component of GAF (N)
Generalized Force: Stationary Shock (2-D)

Mode 3, $k_{\text{panel}} = 0.15$

Correction introduces phase shift to the steady-state

Full Generalized Aerodynamic Force (GAF, N)  Unsteady Component of GAF (N)