Unsteady Pressures on a Generic Capsule Shape

Jim Ross & Nathan Burnside
NASA Ames Research Center

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Outline

• Background
• Test Objectives
• Test Description
  – Model design
  – Instrumentation
  – Flow conditions tested
• Unsteady Pressure Processing
• Selected Results
• Concluding Remarks
Background

• Agreement between CFD and experiments for Orion CM was poor below Mach 0.7
  – Uncertainty in the CFD-determined capsule flow
  – Wind-tunnel and CFD did not match low-M results from pad-abort flight test

• Wind-tunnel testing of Orion showed boundary-layer state on heat shield significantly affected CM aerodynamics
  – Reynolds number sensitive for Mach numbers below about 0.7
  – Method of tripping flow also had an effect on the aerodynamics

• NASA Engineering and Safety Center funded study to make measurements on and around an idealized Orion Crew Module shape

• General test overview and preliminary results
Objectives

• Detailed characterization of the flow around a capsule shape for subsonic/transonic flight
• Document effect of heat-shield roughness
  – Post-entry Avcoat is very rough
• Comprehensive measurement suite
  – 44 Unsteady pressures around heat-shield shoulder and on back shell
  – Wake velocity from near the capsule to ~5.5 capsule diameters downstream - Particle Image Velocimetry (PIV)
  – Detailed pressure over entire model surface - Pressure Sensitive Paint (PSP)
  – Boundary-layer transition and separation locations - IR Thermography
  – Boundary-layer profiles at one location on the heat shield
  – High-speed shadowgraph videos (6,000 frames per second)
Model Description

• Model is axi-symmetric based on the analytic description of the Orion CM
  – Smooth heat shield
  – Rough heat shield to represent post-entry Avcoat roughness pattern
• Struts used for support
  – Side entry to keep the strut wakes out of measurement plane
  – Stiff support to minimize model deflections and motion
  – Provide optical access for all of the cameras
Heat Shield Details

- Two-layer heat shield fabrication
  - ¼” aluminum structural layer
  - ¼” polycarbonate outer surface
- Provides enhanced IR signatures for transition/separation visualization
Rough Heat Shield
Micrograph of Dimpling

- Hex pattern scaled from post-entry Avcoat honeycomb roughness (Orion and Apollo)
- ~75,000 dimples machined into plastic outer layer
- PSP coating ~0.002” thick
Tunnel Installation

Stabilizing Cables
# Test Conditions for Various Measurements

## PSP, IR Thermography, Unsteady Pressures, Shadowgraph

<table>
<thead>
<tr>
<th>Heat Shield</th>
<th>Angle of Attack</th>
<th>Mach 0.3</th>
<th>Mach 0.5</th>
<th>Mach 0.7</th>
<th>Mach 0.9</th>
<th>Mach 1.05</th>
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<tbody>
<tr>
<td>Smooth</td>
<td>30°</td>
<td></td>
<td></td>
<td>1.3x10^6</td>
<td></td>
<td>1.3x10^6</td>
</tr>
<tr>
<td>Smooth</td>
<td>30°</td>
<td>5.3x10^6</td>
<td>8.7x10^6</td>
<td>10x10^6</td>
<td>10x10^6</td>
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<tr>
<td>Rough</td>
<td>15°</td>
<td>5.3x10^6</td>
<td>8.7x10^6</td>
<td>10x10^6</td>
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</tr>
</tbody>
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## Boundary-Layer Surveys, Skin Friction, IR Thermography

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<th>Heat Shield</th>
<th>Angle of Attack</th>
<th>Mach 0.3</th>
<th>Mach 0.5</th>
<th>Mach 0.7</th>
<th>Mach 0.9</th>
<th>Mach 1.05</th>
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</thead>
<tbody>
<tr>
<td>Rough</td>
<td>0°</td>
<td>5.3x10^6</td>
<td>8.7x10^6</td>
<td>10x10^6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough</td>
<td>15°</td>
<td>5.3x10^6</td>
<td></td>
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<td></td>
<td>6.6x10^6</td>
</tr>
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<td></td>
<td>6.6x10^6</td>
</tr>
</tbody>
</table>

## PIV, Unsteady Pressures, Shadowgraph - Rough heat shield

<table>
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<tr>
<th>Model Position</th>
<th>Angle of Attack</th>
<th>Mach 0.3</th>
<th>Mach 0.5</th>
<th>Mach 0.7</th>
<th>Mach 0.9</th>
<th>Mach 1.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downstream</td>
<td>15°</td>
<td>5.3x10^6</td>
<td>8.7x10^6</td>
<td>10x10^6</td>
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<td></td>
</tr>
<tr>
<td>Upstream</td>
<td>15°</td>
<td>5.3x10^6</td>
<td>8.7x10^6</td>
<td>10x10^6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Numbers in green boxes indicate Reynolds number tested.

Black boxes indicate conditions not tested.
Unsteady Processing Parameters

- Sample rate of 6400 samples / sec
  - 2.5 kHz bandwidth
- 4096 point FFT
- 25% overlap
- Energy corrected Hanning window
- 30 to 50 averages
- $C_p'$ spectra
  - $dB = 20 \log_{10}(C_p')$
Separation Rough Heat Shield, $M = 0.7$, $\alpha = 30^\circ$, $Re_D = 10 \times 10^6$

Color of the boxes represents SPL in the $\frac{1}{3}$-octave bins for each sensor.
Effect of Heat Shield Roughness on Capsule Flow

M = 0.7, \( \alpha = 30^\circ \), Re\(_D\) = 10x10\(^6\)

Figure 10. Infrared thermographs of the smooth and rough heat shield at M = 0.7 and \( \alpha = 30^\circ \). Images at top are with Re = 1.3x10\(^6\) and at bottom at Re = 10x10\(^6\). Darker areas indicate lower temperature.
Effect of Reynolds Number on Spectral Amplitude
M = 0.7, ° = 30°

Figure 11. Effect of Reynolds number on narrowband $C_p'$ versus Strouhal number at various locations around the rough heat shield shoulder. $M = 0.7$, $\alpha = 30°$.

Before Separation

After Separation

- $\Phi \approx 0°$
  - $Re = 1.3 \times 10^6$
  - $Re = 10 \times 10^6$

- $\Phi \approx 180°$

- $\Phi \approx 270°$
Effect of Reynolds Number on Shedding Frequency
M = 0.7, ° = 30°

\[ \text{Re}_D = 1.3 \times 10^6 \quad \text{Re}_D = 10 \times 10^6 \]

Effect of Mach Number on Shedding Spectra
" = 30°, # = 0, High Re

Rough

Smooth
Effect of Mach Number on Azimuthal Correlation
"α = 30°, High Re, Rough Heat Shield"

Referenced to K01
Helical Shedding Mode
M = 0.7, \( \alpha = 30^\circ \), \( \text{Re}_D = 10 \times 10^6 \), Rough Heat Shield

![Correlation vs time graphs for Kulites referenced to K24, K32, K03, and K17.](image-url)
Summary

- Comprehensive data set now available of flow around generic capsule at variety of subsonic/transonic conditions
- Unsteady pressure results
  - Spectra is a good indicator of separation
  - Spectra is Reynolds dependent
  - Shedding frequency shifts for rough heat shield at high Re
  - Capsule is more stable at higher Mach
  - Helical shedding is similar to CFD results