Unsteady Pressures on a Generic Capsule Shape

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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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</thead>
<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>
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<tr>
<td>Rough</td>
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<td>5.3x10^6</td>
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<td>6.6x10^6</td>
</tr>
</tbody>
</table>

**Numbers in green boxes indicate Reynolds number tested**

### Boundary-Layer Surveys, Skin Friction, IR Thermography

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<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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</thead>
<tbody>
<tr>
<td>Rough</td>
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<td>5.3x10^6</td>
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<td>10x10^6</td>
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<tr>
<td>Rough</td>
<td>15°</td>
<td>5.3x10^6</td>
<td></td>
<td>10x10^6</td>
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<td>6.6x10^6</td>
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<tr>
<td>Rough</td>
<td>30°</td>
<td>5.3x10^6</td>
<td></td>
<td>10x10^6</td>
<td></td>
<td>6.6x10^6</td>
</tr>
</tbody>
</table>

**Black boxes indicate conditions not tested**

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

<table>
<thead>
<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>
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</thead>
<tbody>
<tr>
<td>Downstream</td>
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<tr>
<td>Upstream</td>
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<td>8.7x10^6</td>
<td>10x10^6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
• 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\(_D\) = 10x10\(^6\)

Figure 9. Map showing unsteady pressures in \( \frac{1}{3}\)-octave bands. Blue is low sound pressure level (SPL), red is high. M = 0.7, \( \alpha = 30^\circ \), Re\(_D\) = 10x10\(^6\).

Color of the boxes represents SPL in the \( \frac{1}{3}\)-octave bins for each sensor.

View looking downstream.

[Diagram of heat shield with pressure tap locations and color-coded SPL distribution]
Effect of Heat Shield Roughness on Capsule Flow

$M = 0.7$, $\alpha = 30^\circ$, $Re_D = 10 \times 10^6$

![Infrared thermographs of the smooth and rough heat shield at $M = 0.7$ and $\alpha = 30^\circ$. Images at top are with $Re = 1.3 \times 10^6$ and at bottom at $Re = 10 \times 10^6$. Darker areas indicate lower temperature.](image)

- **Smooth heat shield**
- **Rough heat shield**

**Re = 1.3 \times 10^6**

**Re = 10 \times 10^6**
Effect of Reynolds Number on Spectral Amplitude
M = 0.7, θ = 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, θ = 30°.
Effect of Reynolds Number on Shedding Frequency
\( M = 0.7, \alpha = 30^\circ \)

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

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

M = 0.3
M = 0.5
M = 0.7

M = 0.9
M = 1.07
Helical Shedding Mode

$M = 0.7$, $\alpha = 30^\circ$, $Re_D = 10 \times 10^6$, Rough Heat Shield
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