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
  - 0.5" aluminum structural layer
  - 0.5" polycarbonate outer surface

- Provides enhanced IR signatures for transition/separation visualization
Rough Heat Shield
• 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></td>
<td>1.3x10^6</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>
<tr>
<td>Rough</td>
<td>15°</td>
<td>5.3x10^6</td>
<td>8.7x10^6</td>
<td>10x10^6</td>
<td>10x10^6</td>
<td>6.6x10^6</td>
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<tr>
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<td>6.6x10^6</td>
</tr>
</tbody>
</table>

Numbers in green boxes indicate Reynolds number tested. Black boxes indicate conditions not 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>
</tr>
</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>
<td>10x10^6</td>
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<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>
</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>
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
  - $\text{dB} = 20 \log_{10}(C_p')$
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

View looking downstream

<table>
<thead>
<tr>
<th>0°</th>
<th>Separated</th>
<th>Attached</th>
</tr>
</thead>
<tbody>
<tr>
<td>330°</td>
<td>Separated</td>
<td>Attached</td>
</tr>
<tr>
<td>270°</td>
<td>Separated</td>
<td>Attached</td>
</tr>
<tr>
<td>180°</td>
<td>Separated</td>
<td>Attached</td>
</tr>
</tbody>
</table>

Wind is into the page

Pressure Taps on Back Shell

- Row 1: K11 - K20, K31 - K40
- Row 2: K21 - K30
- Row 3: K31 - K40

Tap 59 is at top center of model and tap 44, 45, 57, and 58 are 30° off of sensor axis distribution without the tap on the Kulite side of back shell

Kulite numbering run from heat shield to Kulite side of back shell

- Taps 1 - 10 and Taps 21 - 30 are at same radius as upstream.
- Taps 29 and 30 are at same radius as P29.
- Taps 31 and 32 are at same radius as P32.

1/3-Octave Frequency

- 8 Hz
- 16 Hz
- 31.5 Hz
- 63 Hz
- 125 Hz
- 250 Hz
- 500 Hz
- 1K Hz
- 2K Hz

Figure 9. Map showing unsteady pressures in 1/3-octave bands. Blue is low sound pressure level (SPL), red is high. M = 0.7, \( \alpha = 30^\circ \), Re\(_D\) = 10\(\times\)10\(^6\).
Effect of Heat Shield Roughness on Capsule Flow

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

Figure 10. Infrared thermographs of the smooth and rough heat shield at $M = 0.7$ and $\alpha = 30^\circ$. Images at top are with $Re = 1.3 \times 10^6$ and at bottom at $Re = 10 \times 10^6$. Darker areas indicate lower temperature.
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, α = 30°.
Effect of Reynolds Number on Shedding Frequency
\[ M = 0.7, \alpha = 30^\circ \]

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

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

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

Rough

Smooth

Figure 16. Effect of Mach number on shedding frequency. Rough heat shield, α = 30°, high Reynolds number, Φ ≈ 0°.

Figure 17. Effect of Mach number on shedding frequency. Smooth heat shield, α = 30°, high Reynolds number, Φ ≈ 0°.
Effect of Mach Number on Azimuthal Correlation
" = 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

![Correlation vs time for Kulites referenced to K24](Run 46, Mach 0.7, Alpha 29.25°, ReD 9.9997 million)

- C) Referenced to K24 ($\Phi \approx 270^\circ$)
- D) Referenced to K33 ($\Phi \approx 330^\circ$)

![Correlation vs time for Kulites referenced to K32](Run 46, Mach 0.7, Alpha 29.25°, ReD 9.9997 million)

- A) Referenced to K03 ($\Phi \approx 0^\circ$)
- B) Referenced to K17 ($\Phi \approx 180^\circ$)
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