Reaction Control system Design Considerations for Mars Entry Vehicles

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Overview

- Past Mars missions landed within 100s of km from designated target
  - Unguided lifting (Viking 1, 2)
  - Unguided ballistic (Pathfinder, MER)
- New generation of Mars landers to deliver massive payloads to within 10s of km from sites of interest
  - Lifting actively guided entry (MSL)
  - High lift-to-drag ratio
- Guided entry requires a reaction control system (RCS)
  - Active control of direction of the lift vector
  - Rate damping
- Guidance maneuvers take advantage of dynamic pressure, so they take place in hypersonic and supersonic segments of the entry
  - Effect of RCS on aerothermal environment can be significant, impacting TPS
  - RCS interference in aerodynamic characteristics needs to be understood to reliably predict flight
Near-capsule flowfield

Flow around MSL Capsule at Mach 18.1
Reaction Control Systems

Viking Lander RCS

MPL/Phoenix RCS

Parachute Cover
Parachute Cone
RCS Window
Backshell
Heatshield
Reaction Control Systems (cont.)

Several Candidate MSL RCS

Thrust Aft of CG

Thrust Ahead of CG
Jet-Wake Interaction

- Interaction of an underexpanded jet with crossflow extensively studied
  - Applicability of existing analyses to scientific planetary entry vehicles is limited
  - Massively separated wake, jet is penetrating flows of changing character
- Analyses and results are configuration specific
  - Interaction with attached vs. separated flow, local flow conditions
  - Pointing of the jet, location on the aftshell
Aerodynamic Effects

Viking-derived base correction

\[ C_{A(\text{base})} = C_{p,b} = a_0 + \frac{a_1}{M_\infty} + \frac{a_2}{M_\infty^2} + \frac{a_3}{M_\infty^3} \]

where

\[ a_0 = 8.325E-03 \]
\[ a_1 = 1.129E-01 \]
\[ a_2 = -1.801E+00 \]
\[ a_3 = 1.289E+00 \]
Aerothermal Effects
Apollo

  - Apollo 7 reentry: "considerable pitch and yaw control activity in the transonic region during the final 2 min before drogue deployment", from simulation they concluded that this was a result of thruster jet interaction with flow around the vehicle and strong winds.
- NASA TM-X-1063, R. Jones, J. Hunt, Effects of cavities, protuberances, and reaction control jets on heat transfer to the Apollo Command Module
  - Mention of interference patterns on aftbody caused by RCS jets
- NASA TN-D-6028, Dorothy B. Lee, John J. Bertin, Winston D. Goodrich, Heat transfer rate and pressure measurements obtained during Apollo orbital entries
  - Heating on the leeside of the spacecraft increased during RCS firings up to 5 times that measured between firings

Viking

  - Aero/RCS interaction estimated in wind tunnel tests at M=20 using solid bodies to represent thruster plumes
  - The data were inconclusive due to insufficient accuracy of the low AOA data
  - The recommendation was use a balance designed to measure small $C_N$ and $C_m$, and large $C_A$ to minimize data uncertainties, but this apparently was never accomplished for Viking
Summary

• RCS can interfere with the aerodynamic characteristics of entry vehicle
  – Changes in aerodynamics occur in both supersonic and hypersonic segments of the entry trajectory
    • Control gain and aerodynamic cross coupling can occur
    • In extreme cases the authority of RCS can be negated
  – Computational and experimental analyses help bound the phenomena
    • Difficulties in both computational methods (wakes are hard to solve) and experiment
      (moments are small in comparison to the forebody moments)

• Impact of RCS on aerothermal environments can be significant
  – Aeroheating increase by an order of magnitude depending on the specifics of the jet interaction
  – Impact on TPS selection, cost, schedule

• Based on analyses performed to date, jet interaction with the flow around entry vehicle is better understood
  – Paradigms have been developed to minimize destructive interference of RCS jets
BACKUP
### Table 1. Comparison of Mars Entry Capsules

<table>
<thead>
<tr>
<th></th>
<th>Viking 1/2</th>
<th>Pathfinder</th>
<th>MER A/B</th>
<th>Phoenix</th>
<th>MSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, m</td>
<td>3.5</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
<td>4.5</td>
</tr>
<tr>
<td>Entry Mass, kg</td>
<td>930</td>
<td>585</td>
<td>840</td>
<td>602</td>
<td>2919</td>
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<tr>
<td>Landed Mass, kg</td>
<td>603</td>
<td>360</td>
<td>539</td>
<td>364</td>
<td>1541</td>
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<tr>
<td>Landing Altitude, km</td>
<td>-3.5</td>
<td>-1.5</td>
<td>-1.3</td>
<td>-3.5</td>
<td>+1.0</td>
</tr>
<tr>
<td>Landing Ellipse, km</td>
<td>420 x 200</td>
<td>100 x 50</td>
<td>80 x 20</td>
<td>75 x 20</td>
<td>&lt; 10 x 10</td>
</tr>
<tr>
<td>Relative Entry Vel., km/s</td>
<td>4.5/4.42</td>
<td>7.6</td>
<td>5.5</td>
<td>5.9</td>
<td>&gt; 5.5</td>
</tr>
<tr>
<td>Relative Entry FPA, deg</td>
<td>-17.6</td>
<td>-13.8</td>
<td>-11.5</td>
<td>-13</td>
<td>-15.2</td>
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<tr>
<td>m/(C_D A), kg/m²</td>
<td>63.7</td>
<td>62.3</td>
<td>89.8</td>
<td>65</td>
<td>126</td>
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<tr>
<td>Turbulent at Peak Heating?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>Peak Heat Flux, W/cm²</td>
<td>24</td>
<td>115</td>
<td>54</td>
<td>56</td>
<td>243</td>
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<tr>
<td>Hypersonic α, deg</td>
<td>-11.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-15.5</td>
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<tr>
<td>Hypersonic L/D Control</td>
<td>0.18</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.24</td>
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<td></td>
<td>3-axis</td>
<td>Spinning</td>
<td>Spinning</td>
<td>3-axis</td>
<td>3-axis</td>
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<tr>
<td>Guidance</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
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</table>
Ideal Authority

Table 2. Comparison of ideal authority of Viking, MPL/Phoenix and MSL

<table>
<thead>
<tr>
<th></th>
<th>N-m</th>
<th>Kg-m²</th>
<th>deg/sec²</th>
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<tbody>
<tr>
<td></td>
<td>Mₓ</td>
<td>Mᵧ</td>
<td>Mₗ</td>
</tr>
<tr>
<td>Viking 1, 2</td>
<td>152.7</td>
<td>146/-159.4</td>
<td>108</td>
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<tr>
<td>MPL/Phoenix</td>
<td>10.7</td>
<td>58.07</td>
<td>10.06</td>
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<tr>
<td>MSL</td>
<td>675.4</td>
<td>980.7/-1160</td>
<td>705</td>
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EDL Sequence

Separate
Deorbit
Coast
Atmospheric entry, 243.8 km (800 000 ft)
Deploy parachute, 6 km (19 500 ft)
Jettison aeroshell
Engine ignition, 1.4 km (4600 ft)
Jettison parachute
Terminal propulsion descent
Landing

Separation-to-entry sequence, ≈ 3 hr
Entry-to-landing sequence, ≈ 10 min

Image courtesy …. 
Algorithm/Grids

• Calculations in LAURA using 8-species Mars gas + ammonia as propellant

• Grids
  – Baseline layout: coarse - 5M, fine - 40 M nodes
    • Created by Victor Lessard, extends to engine chambers
  – 2006 RCS and Proposed layout - 12M nodes
    • Created using RTF MORPH tool and doesn’t reflect any internal flow

• Solutions are computed at Mach 18.1, q=15.9 kPa
Geometric Considerations

- Same amount of pressure applied to different locations on the backshell will produce different moments about the CG.
- Moment arms ($L_X$, $L_Y$), computed from a surface-normal through a point and the location of the CG illustrate the regions of high sensitivity of capsule moments to changes in surface pressure.
  - In yaw, capsule moments are very sensitive to change in pressure on the far side, and on the parachute closeout cone.
  - In pitch, capsule moments are very sensitive to changes in wind/lee shoulder regions; the parachute closeout cone can also generate significant torques if shocks/plumes impinge on it.
Backshell Pressures
RCS Plumes of Candidate MSL RCS

Note:
Iso-surface bounds 30% propellant concentration
Pressure scale doesn't capture peaks (>2000 Pa at impingement)

Intersecting plumes
Backshell Heating