Low Density Supersonic Decelerator (LDSD)
Supersonic Flight Dynamics Test (SFDT)
Plume Induced Environments Modelling

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Agenda

- Background
- Analysis Objectives
- Approach
- Vehicle Impacts & Results
- Conclusions & Lessons Learned
Background

- **LDSD Supersonic Flight Dynamics Tests (SFDT-1, 2)**
  - Test supersonic deceleration technologies in Earth’s upper stratosphere
  - Balloon launched test vehicle, accelerated using a solid rocket motor (SRM) to achieve freestream test conditions (simulate Mars entry)
  - SFDT-1 & 2 Deceleration Technologies
    - Supersonic Inflatable Aerodynamic Decelerator - Robotic class (SIAD-R)
    - Parachute Deployment Device (PDD) – Ballute – parachute extraction
    - Supersonic Disk Sail (SFDT-1), Ring Sail (SFDT-2) Parachutes

- **Marshall Space Flight Center - Aerosciences - Roles**
  - Program onset - provide plume induced heating predictions throughout powered flight (main SRM)
  - Spin motor plume impingement (heating and impact pressures)
  - Plume induced aerodynamics (post-SFDT-1 / pre-SFDT-2)
• LDSD Test Vehicle and Trajectories (Best Equivalent)
Background

Orbital-ATK Star-48B Long Nozzle Solid Rocket Motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion Ratio (A/A*)</td>
<td>54.8 (47.2 avg. nozzle erosion)</td>
</tr>
<tr>
<td>Throat Diameter</td>
<td>3.98 in / 10.11 cm</td>
</tr>
<tr>
<td>Exit Diameter</td>
<td>29.5 in / 74.93 cm</td>
</tr>
<tr>
<td>Nozzle Length</td>
<td>35.8 in / 90.93 cm</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>Approximately 600 PSIA (@ t=0 sec)</td>
</tr>
<tr>
<td>Propellant (Approx. % Weight)</td>
<td>Ammonium Perchlorate 71%</td>
</tr>
<tr>
<td></td>
<td>Hydroxyl Terminated Polybutadiene (HTPB) 11%</td>
</tr>
<tr>
<td></td>
<td>Aluminum 18%</td>
</tr>
<tr>
<td>Duration:</td>
<td>Offloaded approx. 20% (400kg) to reduce burn time from 84 to 68 seconds</td>
</tr>
</tbody>
</table>

Nammo Talley, Inc. Solid Rocket Spin Motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion Ratio (A/A*)</td>
<td>6.47</td>
</tr>
<tr>
<td>Throat Diameter</td>
<td>0.86 in / 2.2 cm</td>
</tr>
<tr>
<td>Exit Diameter</td>
<td>2.2 in / 5.59 cm</td>
</tr>
<tr>
<td>Nozzle Length</td>
<td>1.82 in / 4.63 cm</td>
</tr>
<tr>
<td>Chamber Pressure</td>
<td>Approximately 3057 PSIA (mean)</td>
</tr>
<tr>
<td>Propellant (Approx. % Weight)</td>
<td>Ammonium Perchlorate 83%</td>
</tr>
<tr>
<td></td>
<td>Aluminum 1.5%</td>
</tr>
<tr>
<td></td>
<td>HTPB 9%</td>
</tr>
<tr>
<td></td>
<td>Fe₂O₃ 1.5%</td>
</tr>
<tr>
<td></td>
<td>Plasticizer 5%</td>
</tr>
<tr>
<td>Duration:</td>
<td>0.25 seconds</td>
</tr>
</tbody>
</table>
Analysis Objectives

• 2012–2013 LDSD Thermal Design Support
  – Star 48 Plume Induced Base Heating
    • Radiation heat flux from $\text{Al}_2\text{O}_3$ particles and plume gases
    • Convection from plume-air recirculation
  – Spin Motor Plume Impingement
    • Predict plume heating from convection and $\text{Al}_2\text{O}_3$ particle impingement
    • Plume induced forces & moments

• 2014–2015 Plume Induced Aerodynamics Support
  • Predict aerodynamic coefficients (forces & moments) during subsonic and transonic powered flight
  • Investigate plume flow field modeling sensitivities to aerodynamics
Approach

- Simulate plumes throughout a “nominal” flight trajectory at discrete points in time in a quasi-steady fashion
  - Two step approach, model nozzle flows using MSFC engineering codes
  - Nozzle solutions (near nozzle exit plane) used as boundary conditions to CFD domain
- Nozzle Flow Field
  - Model chamber and nozzle flow field chemistry using the NASA Glenn Chemical Equilibrium Combustion (CEC) program
  - Model two-phase nozzle flow, core and boundary layer, using the Reacting and Multiphase Program (RAMP2) & Boundary Layer Integral Matrix Procedure (BLIMPJ) engineering codes (MOC codes)
- Plume Flow Field - Loci-CHEM 3.3 p4 - CFD code
- Radiation – Reverse Monte Carlo – radiation code
Approach

- Grid Challenges
  - Variation of motor firing configurations (1, 2, 4)
  - Variable angles of attack
  - Subsonic / supersonic free stream conditions (shock refinement)

- Grid Characteristics
  - ANSA 14, Solid Mesh 5.9.9 – Surface Grids
  - AFLR3 – Unstructured – Volume Grids
  - Cell Count
    - Spin Motor Cases – Approximately 174 Million Cells (Initial/Final)
    - Star 48 Cases – Approximately 136 Million (Initial), 192 Million (Final)
**CFD Settings**

<table>
<thead>
<tr>
<th>Category</th>
<th>CFD Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Description</td>
<td>Star 48 Ascent, Spin-Up, Spin-Down Motors</td>
</tr>
<tr>
<td>Vehicle/Mesh Geometry</td>
<td>Fully 3D</td>
</tr>
<tr>
<td>α, β Angles</td>
<td>Spin-Up Case: α = 163⁰, β = 0⁰ / Star 48 - Trajectory</td>
</tr>
<tr>
<td>Chemistry</td>
<td>Frozen</td>
</tr>
<tr>
<td>No. Species</td>
<td>2 - Equivalent air &amp; equivalent plume gas</td>
</tr>
<tr>
<td>Thermodynamic Properties</td>
<td>Thermally perfect, specie Cp varies with temperature</td>
</tr>
<tr>
<td>Viscosity Model</td>
<td>Transport Fit (μ(T), k(T))</td>
</tr>
<tr>
<td>Diffusion Model</td>
<td>Laminar-Schmidt</td>
</tr>
<tr>
<td>Turbulence Model</td>
<td>Menter’s Shear Stress Transport, SST</td>
</tr>
<tr>
<td>Compressibility Correction</td>
<td>Sarkar</td>
</tr>
<tr>
<td>Urelax (m/s)</td>
<td>0.1</td>
</tr>
<tr>
<td>Dt Max (sec)</td>
<td>0.001-0.00001</td>
</tr>
<tr>
<td>Accuracy</td>
<td>2nd Order</td>
</tr>
<tr>
<td>Wall Temperature</td>
<td>0⁰ F / 255 K (Star 48), 255, 973, 1773 K (Spin Motor)</td>
</tr>
<tr>
<td>Boundary Conditions</td>
<td>No-slip walls, vehicle spin rate applied</td>
</tr>
<tr>
<td>Vehicle Spin (RPM)</td>
<td>0, 50 RPM</td>
</tr>
<tr>
<td>Internal Nozzle Wall Thermal BC</td>
<td>Adiabatic</td>
</tr>
</tbody>
</table>

**STAR 48 Case Conditions**

<table>
<thead>
<tr>
<th>Trajectory Atmospheric Conditions</th>
<th>Star48 Chamber Conditions</th>
<th>Vehicle Attitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt (km)</td>
<td>M∞</td>
<td>q∞ (Pa)</td>
</tr>
<tr>
<td>---------</td>
<td>----</td>
<td>--------</td>
</tr>
<tr>
<td>36.322</td>
<td>0.100</td>
<td>3.458</td>
</tr>
<tr>
<td>36.390</td>
<td>0.200</td>
<td>13.711</td>
</tr>
<tr>
<td>36.514</td>
<td>0.300</td>
<td>30.303</td>
</tr>
<tr>
<td>36.993</td>
<td>0.500</td>
<td>78.750</td>
</tr>
<tr>
<td>37.617</td>
<td>0.700</td>
<td>141.599</td>
</tr>
<tr>
<td>38.449</td>
<td>0.900</td>
<td>208.656</td>
</tr>
<tr>
<td>38.681</td>
<td>0.950</td>
<td>225.535</td>
</tr>
<tr>
<td>39.469</td>
<td>1.100</td>
<td>271.040</td>
</tr>
<tr>
<td>39.936</td>
<td>1.200</td>
<td>304.416</td>
</tr>
</tbody>
</table>
INITIAL ANALYSIS

**SPIN-UP – 120 Kft (36.6 km),** \( P_\infty = 0.72 \text{ PSIA (499 Pa)} \) **– ALL SPIN-UP MOTORS “ON”**

- Surface Contours
- Solution Plane Contours

**Plume-Plume Interaction**
- Shock Off Motor Barrel
- Inboard Plume
- Outboard Plume
- Reflected Shock
Spin Motor Analysis

- Spin Motor Plume Impingement Environment Summary
  - Motor casings, bridle coverings - severe heating areas, heat rates in excess of 500 BTU/ft^2/sec (568 W/cm^2)
  - Camera mast, heating in excess of 200 BTU/ft^2/sec (170 W/cm^2)

- Thermal Design Impact - Two week “Tiger Team” to provide thermal protection options
  - Incorporated plume blast shields and deflectors
  - Additional thermal protection (TPS) on camera mast
  - Staggered firing configurations (driven by flight dynamics as well)
Analysis Impacts & Results

BEFORE

AFTER (MIRRORED PICTURE)

PLUME DEFLECTORS

MAST TPS

DECK SHIELDS

MOTOR BARREL BLAST SHIELDS
FOLLOW-UP ANALYSIS

**SPIN-UP** – 120 Kft (36.6 km), $P_\infty = 0.72$ PSIA (499 Pa) - ALL SPIN-UP MOTORS “ON”

- **Clip Plane, Mach Number**
- **Surfaces, Heat Flux (BTU/ft²·sec)**
- **Reverse Angle**
- **Shock, Flow Deflection**
- **Deck Impingement**
- **BL, Separation Region**
- **Impingement, Reattachment**
- **Corner Expansion**

**LDSD Spin-Up Motors #1 & #3 Firing**

$T_{wall} = 0^\circ F$

**LDSD Spin-Up Motors #2 & #4 Firing**

$T_{wall} = 0^\circ F$

**Surfaces, Heat Flux**

(W/cm²)
Impacts & Results

SFDT-1
Spin-Up Motor Firings

Pre-flight Heating Contours
Post-flight Charring
Star 48 Analysis

- SFDT-1 flight reconstruction revealed the test vehicle over shot the targeted altitude approximately 10Kft
  - Chamber pressure measurements failed, no distinct way to decouple thrust and drag (challenge on determination of $C_A$)
  - Reconstruction analysis revealed slightly over performing solid and over prediction of plume induced drag (higher predicted axial coefficient, $C_A$)
  - Over predicted total moment (pitch-yaw) coefficient, vehicle lofted more than expected
STAR48 PLUME INDUCED AERODYNAMICS

Mach = 0.7, Angle-of-Attack = 17.1°

Mach = 1.2, Angle-of-Attack = 11.5°

SFDT-1 Lofting Impact

Base Pressure Coefficient
Impacts & Results

SFDT-2 Powered Phase, $0.1 \leq M_\infty \leq 1.6$

- Best Equivalent Trajectory
- $\pm 3\sigma$
- Aerodynamic Database Ver. 1.7
- MSFC, Loci-CHEM 3.3 CFD

SFDT-2 Powered Phase, $0.1 \leq M_\infty \leq 4.1$

- Best Equivalent Trajectory
- $\pm 3\sigma$
- Aerodynamic Database Ver. 1.7
- MSFC, Loci-CHEM 3.3 CFD

SFDT-2 Powered Phase, $0.1 \leq M_\infty \leq 1.6$

- Best Equivalent Trajectory
- Aerodynamic Database Ver. 1.6.3
- MSFC, Loci-CHEM 3.3 CFD

SFDT-2 Base Pressure, $0 \leq M_\infty \leq 4.1$

- Base Pressure Transducer #1
- Base Pressure Transducer #2
- MSFC, Loci-CHEM 3.3 Pre-Flight Predicted

Static Pressure (Pa)

Mach Number
Conclusions & Lessons Learned

Summary

• Spin motor plume impingement - all thermal requirements met!
• Star48 power-on aerodynamic data base updated
  – SFDT-2 great agreement with pitching moment coefficient and base pressures

Conclusions

– Highly under expanded plume-air interactions can be significant
  • Observed similar plume induced environment issues with separation motors
  • Changes in altitude and angle of attack angle change the plume, affects degree of entrainment, base pressure distribution

– Modeling base flow fields with single plume-air interaction with CFD
  • Match nozzle total enthalpy and nozzle boundary layer flow characteristics- low momentum gases interacting with freestream
  • Adequate grid resolution to capture:
    – Reverse jet impingement and recirculation eddies
    – Base features affecting recirculation eddies