Orbital Class Nanosatellite
Launch Vehicle Spin Stabilization System

Richard Baptista, Spencer Fehlberg, Kristen Hawkins, Matthew Morse
Dr. Jonathan Jones
NASA Propulsion Academy – Nano Launch Vehicle
Let’s Make a Rocket Spin

Richard Baptista, Spencer Fehlberg, Kristen Hawkins, Matthew Morse
Dr. Jonathan Jones

NASA Propulsion Academy – Nano Launch Vehicle
Presentation Outline

Introduction
• Overview of Project
• Project Goals

System Design
• Motor Sizing
• Nozzle Design
• Case Design
• Ignition System

Testing and Development
• Computer Simulations
• Electrical System
• Test Article Design/Layout
Spyder Vehicle and Project Goals

• Spyder Launch Vehicle
• Collaboration with UP Aerospace
• Spin-Stabilization System
• Project Goals
  • Determine important design criteria
  • Design test layout for Spyder’s spin-stabilization system
  • Remain cost-effective with design criteria
Selecting a Motor

Total impulse required was calculated using the following expression:

\[ J = \frac{I_{\text{roll}} \Delta \omega}{rg} \]

Where:
- \( J \) = total impulse (N-s)
- \( I_{\text{roll}} \) = moment of inertia about the roll axis (N-m^2)
- \( \Delta \omega \) = angular velocity (Hz)
- \( r \) = distance from axis of rotation (m)
- \( g \) = acceleration due to gravity (9.81 m/s^2)

Impulses matched using data from thrustcurve.org
- Selected motor: AeroTech G339 - $25.67
- Space-grade propellant (ammonium perchlorate)
Nozzle Performance in Space

• Hobby rocket nozzles typically have expansion ratio around 5
  ▪ This optimizes exit pressure for sea level operation
• Spyder will operate at 90 km (space)
  ▪ Higher expansion ratio, higher performance
  ▪ Upper limit (due to mass constraints) of 70
• Excel® spreadsheet analytically estimates in-space performance for a fixed chamber pressure
  ▪ Predicts $I_{sp}$ increase as high as 26% for G339 motor with expansion ratio of 70
  ▪ Performance losses and geometric constraints not included in model
Optimizing the Case Design

Python script:

• Calculates the case thickness ($t_{cs}$) for several different materials
• Calculates the case mass using the material density
• Runs an optimizes on the mass
• Returns the case thickness, mass, and material

Result: A case thickness greater than 2mm is appropriate for design and all materials considered.

Governing equations (hoop stress):

\[ t_{cs} = \frac{P_{b}r_{cs}}{F_{tu}} \]

\[ P_{b} = SF \times MEOP \]

\[ MEOP = 1.03P_{max} \]

- $P_{b}$: pressure
- $r_{cs}$: case radius
- $F_{tu}$: ultimate tensile stress
- $SF$: safety factor
- $P_{max}$: maximum chamber pressure
A Robust Initiation System

Orbital ATK’s semi-conductor bridge (SCB) initiator features:

- Mass: 0.588 grams
- Bridgewire resistance: 1.0 ohms
- Maximum no-fire current: 1 amp (1 watt) for 5 minutes
- Demonstrated reliability: 0.9992 at 95% confidence
- Pyrotechnic material: Titanium subhydride potassium perchlorate
- Pressure output: 729 psi in a 10 cc volume (approximately MEOP)
A MATLAB simulation was developed to explore flight dynamics of Spyder.

Variables include:

- Radial lever arm for spin-up thrust vectors
- Vertical lever arm for spin-up thrust vectors
- Different thrust curves with mismatched impulses
- Motor firing mismatch
Computer Simulation Results

Refer to MATLAB for Demonstration
Computer Simulation Results

Refer to MATLAB for Demonstration
Computer Simulation Results

Maximum Nutation Angle for Specified Motor Ignition Mismatches

- Maximum Nutation Angle (°)
- Motor Ignition Mismatch (s)
Developing a Robust Ignition Circuit

- Modified Space Shuttle/SLS Booster ignition circuit (safe and reliable)
  - Several items removed or simplified to reduce cost and weight
- Main power supply is 22-28 V
- ARM and FIRE commands are 3-5 V signals from NI myRIO 1900
  - Signals are sent via Wi-Fi ensuring safe operation
  - Redundancy: ARM, FIRE 1, FIRE 2
- Firing charge comes from a 1,000 µF capacitor
- Testing showed capacitor is charged quickly and plenty of energy is supplied to igniters
Simultaneous Ignition Testing
Goal: Match Spyder’s moments of inertia for test article design

• Modeled the test article with crude geometries
• Matched Spyder’s moments about all three axes

Problems:
• The hemispherical air bearing had a maximum deflection angle of less than one degree
• The dimensions required to match were too large to construct a realistic, testable system
• Re-designed test article to match MOI about roll axis only
• Use AeroTech D21 for proof of concept
• I200 motors for full-scale tests
• Updated simulation variables based on test article design parameters for model verification
Conclusions

Based on the material presented, the following conclusions can be drawn:

• Standard hobby rocket motors are a cost effective, reliable option for small launch vehicle spin-stabilization

• To ensure flight stability during the spin-up stage, a motor firing mismatch of 20 ms or less is tolerable

• Simultaneous ignition of two solid rocket motors is achievable
Future Work

• Physical testing with D21/I200 motors
• Analysis of acquired data and determine model feasibility
• Material testing to determine new options for rocket motor casing such as nickel coated plastics
• A larger nozzle expansion ratio will increase performance in a near-vacuum environment, but geometric constraints still need to be determined
• Scarfed and canted nozzle analysis
• Mature design of spin-stabilization system
Acknowledgements

• Jonathan Jones
• Tim Kibbey
• Pat Lampton
• Ken House
• Brett Ables
• Zach Taylor
• David Lineberry
• The University of Alabama in Huntsville
• The Space Grant Consortiums that made this work possible
References


Questions?
SCB Initiator Specifications Sheet

Product Overview
Orbital ATK’s patented semiconductor bridge (SCB) initiator is a state-of-the-art squib device that utilizes an SCB chip in place of standard bridgewire to reduce function time and firing energy without the use of primary explosives.

Our unique squib design employs a patented SCB initiator to provide advantages over traditional hot-wire devices. Operation of the SCB chip produces a plasma output that enhances safety by allowing the initiation of insensitive materials (rather than primary explosives) in the squib. It achieves highly repeatable and fast function times (as low as 50 microseconds). The SCB initiator (with a Lexan® jacket) has been qualified to MIL-STD-1512 and serves as part of the human-rated U.S. Air Force Universal Water-Activated Release System (UWARS). The SCB takes only 10 percent of the energy required by a conventional bridgewire for initiation (requiring 1 to 3 millijoules versus 30 to 35 millijoules for conventional bridgewire devices), but can meet 1-watt/1-amp for 5 minutes minimum no-fire requirements. The SCB interface configuration and all-fire and no-fire levels can be tailored for individual mission requirements. The device currently meets both Department of Defense (DoD) and Department of Energy (DoE) military requirements for electrostatic discharge.

Application
The output of the squib and its mechanical interface can be tailored for specific applications. Our baseline initiator design serves as the core component for all of our new devices, including digitally and optically addressable units. Design modifications can be made as necessary to accommodate new requirements or to optimize high-volume production needs.

FACTS AT A GLANCE

Features and Benefits
- Contains no primary explosive material
- Includes same safety features as the MIL-STD-1316
- Qualified to MIL-STD-1512 (human-rated)
- Digital and optical addressable units available
- Customizable interface configuration
- All-fire and no-fire levels
- DoE approved for use in actuators of weapon systems
### Specifications

<table>
<thead>
<tr>
<th>Technical Data*</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>305 stainless steel</td>
<td></td>
</tr>
<tr>
<td>Hermetic seal</td>
<td>&lt;1 X 10^-6 STD cc/sec helium</td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>0.588 grams (0.0013 lb)</td>
<td></td>
</tr>
<tr>
<td>Function time</td>
<td>50 µsec typical at -10°F</td>
<td></td>
</tr>
<tr>
<td>Pressure output</td>
<td>729 psi in a 10 cc bomb</td>
<td></td>
</tr>
<tr>
<td>Pressure shock</td>
<td>15,000 psi</td>
<td></td>
</tr>
<tr>
<td>Calorific output</td>
<td>136 calories</td>
<td></td>
</tr>
<tr>
<td>Bridgewire resistance</td>
<td>1.0 ±0.1 ohms</td>
<td></td>
</tr>
<tr>
<td>Minimum firing current</td>
<td>3.5 amperes for 0.02 sec (max)</td>
<td></td>
</tr>
<tr>
<td>Maximum no-fire current</td>
<td>1-watt/1-amp at ambient for 5 mins</td>
<td></td>
</tr>
<tr>
<td>Demonstrated reliability</td>
<td>0.9992 at 95% confidence</td>
<td></td>
</tr>
<tr>
<td>Pyrotechnic material</td>
<td>Titanium subhydride potassium perchlorate</td>
<td></td>
</tr>
<tr>
<td>Monitor current</td>
<td>100 ma; 1008 hours; -40 to 194°F; 42 cycles</td>
<td></td>
</tr>
<tr>
<td>Recommended firing method</td>
<td>15 volts at the squib generated via 68-µF capacitor discharge</td>
<td></td>
</tr>
</tbody>
</table>

### Electrical Characteristics

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Bridge Resistance, ohms</th>
<th>No-Fire Current, amperes (MIL-DTL-23659)</th>
<th>All-Fire Current, amperes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.0</td>
<td>0.7</td>
<td>1.2</td>
</tr>
<tr>
<td>B</td>
<td>1.0</td>
<td>1.0</td>
<td>3.5</td>
</tr>
<tr>
<td>C</td>
<td>1.0</td>
<td>0.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Derivation of Impulse Required

\[ L = I_{\text{roll}} \omega \]

\[ \sum M = I_{\text{roll}} \alpha \]

\[ \int M(t) \, dt = I_{\text{roll}} \]

\[ I_{\text{total}} r = I_{\text{roll}} \Delta \omega = Fr \Delta t \]

\[ I_{\text{total}} = \int F(t) \, dt = I_{\text{roll}} \Delta \omega / r \]
Moment of Inertia Derivation

\[
\vec{L} = \vec{r} \times \vec{\omega}
\]
\[
\vec{L} = \sum m_i \vec{r}_i \times (\vec{\omega} \times \vec{r}_i)
\]
\[
\vec{r} = (x, y, z)
\]
\[
\vec{\omega} = (\omega_x, \omega_y, \omega_z)
\]
\[
\omega \times \vec{r} = \begin{vmatrix}
\hat{i} & \hat{j} & \hat{k} \\
\omega_x & \omega_y & \omega_z \\
x & y & z
\end{vmatrix} = (z\omega_y - y\omega_z) \hat{i} - (z\omega_x - x\omega_z) \hat{j} + (y\omega_x - x\omega_y) \hat{k}
\]
\[
mr \times (\omega \times r) = \begin{vmatrix}
\hat{i} & \hat{j} & \hat{k} \\
x & y & z \\
x\omega_y - y\omega_z & y\omega_x - z\omega_z & z\omega_x - x\omega_y
\end{vmatrix}
\]
\[
\vec{L} = m \left\{ [y(\omega_x - x\omega_y) - z(-z\omega_x + x\omega_z)] \hat{i} - [x(y\omega_x - x\omega_y) - z(z\omega_y - y\omega_z)] \hat{j} \\
\quad + [x(-z\omega_x + x\omega_y) - y(z\omega_y - y\omega_z)] \hat{k} \right\}
\]
\[
L_x = m( [y^2 + z^2] \omega_x - xy\omega_y - xz\omega_z )
\]
\[
L_y = m( [x^2 + z^2] \omega_y - xy\omega_x - yz\omega_z )
\]
\[
L_z = m( [x^2 + y^2] \omega_z - xz\omega_x - yz\omega_y )
\]

\[ \vec{L} = \vec{I} \vec{\omega} \]

\[ \vec{L} = \sum \alpha \vec{l}_\alpha \times (\vec{\omega} \times \vec{r}_\alpha) \]

\[ \vec{r} = (x, y, z) \]

\[ \vec{\omega} = (\omega_x, \omega_y, \omega_z) \]

\[ l_{xx} = m_\alpha \Sigma (y_\alpha^2 + z_\alpha^2) \]

\[ l_{xy} = -m_\alpha \Sigma x_\alpha y_\alpha \]

\[ l_{yy} = m_\alpha \Sigma (x_\alpha^2 + z_\alpha^2) \]

\[ l_{yz} = -m_\alpha \Sigma y_\alpha z_\alpha \]

\[ l_{zz} = m_\alpha \Sigma (x_\alpha^2 + y_\alpha^2) \]

\[ l_{xz} = -m_\alpha \Sigma x_\alpha z_\alpha \]

\[ \vec{l} = \begin{vmatrix} l_{xx} & l_{xy} & l_{xz} \\ l_{xy} & l_{yy} & l_{yz} \\ l_{xz} & l_{yz} & l_{zz} \end{vmatrix} \]

\[ l_{xy} = l_{xz} = l_{yz} = 0 \]

If rotation is about principle axes, then the non-diagonal moment of inertia components are zero.

\[ l_{xy} \]

- Angular momentum (L) component

\[ x \]

- Angular velocity (\( \vec{\omega} \)) component

\[ y \]
Did you find Waldo?