CubeSat Aerodynamic Stability at ISS Altitude and Inclination

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Presentation Overview

- Overview and Motivation
- History of flight demonstrations
- Passive aerodynamic stability for CubeSats
- Simulation tool and design approach
- Design of aero-stable 3-Unit CubeSat
- Design of aero-stable 1-Unit CubeSat
Aerodynamic Stability

- Aero-stability feasible below 500 km
- Provides alignment with velocity-vector
- Damping required
- ISS at ~ 380km.

### Regions of Influence

<table>
<thead>
<tr>
<th>Region</th>
<th>Altitude Range</th>
<th>Environmental Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region I</td>
<td>Below 300 km</td>
<td>Aerodynamic torques dominate angular motion</td>
</tr>
<tr>
<td>Region II</td>
<td>300-650 km</td>
<td>Aerodynamic and Gravitational torques are comparable</td>
</tr>
<tr>
<td>Region III</td>
<td>650-1000 km</td>
<td>Aerodynamic, Gravitational and Solar torques are comparable</td>
</tr>
<tr>
<td>Region IV</td>
<td>Above 1000 km</td>
<td>Solar and Gravitational torques dominate angular motions.</td>
</tr>
</tbody>
</table>

Table 1: Environmental Torques Regions of Influence
Motivation

- ISS resupply missions to regularly deploy CubeSats
- Aerodynamic torque dominates at that altitude
- Utilize aerodynamics, not fight them.
- Orbit lifetime ~weeks
- Simple ADCS keeps cost down

View of the SpaceX Dragon spacecraft floating away from its trunk while orbiting the Earth during the COTS 1 mission. Rectangles highlight PPODs. 12/8/10
Cosmos 149 and 320

- First on-orbit demonstrations of passive aerodynamic stability
- Conducted by the Soviet Union in 1967 (Cosmos 149) and in 1970 (Cosmos 320).
- “Space Arrows” used extended aerodynamic skirt stabilizers.
- Damping was achieved using two gyroscopes connected to the satellite body through viscous-spring restraints that dissipate energy when satellite oscillations cause gyroscope precession.
- 375 kg, Orbit was 246-326 km, at 48.4°
NASA PAMS

- Demonstrated Aerostability with magnetic hysteresis material for damping.

- 35 kg Cylindrical “stove pipe” having a significantly thicker shell on one end to shift the center of mass
- Attitude response observed during several rendezvous operations.
- Orbit: 283.4 km, at 39°
Aerodynamically Stable CubeSats

- Deployable aerodynamic fins to provide correcting torques for velocity-vector pointing.
- Previous work by University of Kentucky – 2009, 2010
  - Study of design space; drag fin length, deployment angle, altitude, tracking accuracy.
- US Naval Research Laboratory QbX-1 and QbX-2
  - Angular rate damping achieved with a suite of active attitude control actuators (reaction wheels and torque coils) were used to augment the passive aerodynamic torques and provide angular rate damping.
  - Launched in 2010 and successfully demonstrated the feasibility of aerodynamic stabilization for a 3U CubeSat at an altitude of 300km.
Design Goals and Approach

- Completely passive solutions
  - Passive aerodynamic drag fins
  - Passive angular rate damping with magnetic hysteresis material
  - Requires no Attitude Determination
- Keep cost down for short mission life
- Minimize drag area to maximize orbit lifetime
- Minimize mechanical complexity

Approach:
- High fidelity simulation
- Spiral design: Model 1st concept and study resulting torques and required hysteresis material volumes, then improve.
SNAP: Smart Nanosatellite Attitude Propagator

Translational Forces

Earth's Gravity

Position ECI (X) Gravitational Force (N)

Fxyz (N) [ECI]

Velocity V (m/s) [ECI]

Attitude (DCM)

Mxyz (N.m) [Body-fixed]

DCMbe (Attitude) [ECI to Body]

Angular Moments

Angular Rate Damping Alternatives

Position

Velocity

Attitude

Position (X)

Geometry Gradient Model

Velocity (V)

Gravity Gradient (N.m)

Aero. Torque (N.m)

6DOF Dynamics

Euler Angles

Stability Measure

Scope

velocity Cone angle

Angle to velocity vector

Aerodynamic Model

Position (X)

Gravity Gradient Model

Position (X)

Attitude (DCM)

Hysteresis Material

Hysteresis Torque (N.m)

Troque Coils (B-dot)
Satellite shapes represented as a point cloud and torque factors are calculated for all orientations

Magnetic Hysteresis curve represented using a numerical model
Aero-stable CubeSat Design

3U

Can be realized using Pumpkin Colony-1 Bus

1U

- Fins can be realized using 1-inch tape measure.
- 25 cm long fins do not completely wrap around

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## 3U CubeSat Results

<table>
<thead>
<tr>
<th>3U CubeSat, 10cm x 30cm fins deployed at 20°</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Type</strong></td>
</tr>
<tr>
<td>Passive Damping Solution</td>
</tr>
<tr>
<td><strong>Mass, Inertia (I_{xx}, I_{yy}, I_{zz})</strong></td>
</tr>
<tr>
<td>5 kg, (0.0109, 0.0664, 0.0664) kg.m^2</td>
</tr>
<tr>
<td>0.020261 m^2</td>
</tr>
<tr>
<td><strong>Drag Area</strong></td>
</tr>
<tr>
<td><strong>Angular Rate Damping</strong></td>
</tr>
<tr>
<td>Hysteresis: HyMu80</td>
</tr>
<tr>
<td>10.5 cm^3 (3.5 cm^3 per axis)</td>
</tr>
<tr>
<td><strong>Simulation Parameters</strong></td>
</tr>
<tr>
<td>10 °/second initial rate</td>
</tr>
<tr>
<td><strong>Results</strong></td>
</tr>
<tr>
<td><strong>Detumbling Time</strong></td>
</tr>
<tr>
<td>5 hours</td>
</tr>
<tr>
<td><strong>Steady State</strong></td>
</tr>
<tr>
<td>15-20°</td>
</tr>
<tr>
<td><strong>Orbit Lifetime</strong></td>
</tr>
<tr>
<td>9-33 months</td>
</tr>
</tbody>
</table>

![Graph](image)

*Note: Image shows an attitude response graph with time (hours) on the x-axis and angle to velocity vector (°) on the y-axis.*

*Figure*:
### 1U CubeSat Results

1U CubeSat, 2.5cm x 25cm fins deployed at 50°

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Passive Damping Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, Inertia ( I_{xx}, I_{yy}, I_{zz} )</td>
<td>1.33 kg, ( (0.00281, 0.003, 0.003) ) kg.m² ( 0.014788 ) m²</td>
</tr>
<tr>
<td>Drag Area</td>
<td></td>
</tr>
<tr>
<td>Angular Rate Damping</td>
<td>Hysteresis: HyMu80 0.9 cm³ (0.3 cm³ per axis)</td>
</tr>
<tr>
<td>Simulation Parameters</td>
<td>10 °/second initial rate</td>
</tr>
</tbody>
</table>

#### Results

<table>
<thead>
<tr>
<th>Detumbling Time</th>
<th>5 hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady State</td>
<td>10-20°</td>
</tr>
<tr>
<td>Orbit Lifetime</td>
<td>3 – 14 months</td>
</tr>
</tbody>
</table>

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Conclusion

- Analysis and history of aerodynamic stability proves feasibility
- CubeSats are a unique challenge: requires deployables after orbit insertion, small area and volume
- CubeSat designs with magnetic hysteresis damping show tracking accuracy $10^\circ \sim 20^\circ$
- Active damping using magnetic B-dot control shows “perfect” tracking with ideal magnetometer and torque coils
- CubeSats designs proposed for ISS Altitude
- Low complexity and cost for short orbit lifetime
Thank You

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