CubeSat Aerodynamic Stability at ISS Altitude and Inclination

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ABSTRACT

At altitudes below 500km, satellites experience a significant amount of aerodynamic drag that can be utilized to stabilize satellites to align with the relative wind direction. Designing a spacecraft such that the center of pressure is behind the center of mass provides an aerodynamic restoring torque, that in combination with an oscillation damping system, provides stability and alignment with the spacecraft velocity vector. Passive aerodynamic stability and damping has been demonstrated on orbit by the Soviet Union on Cosmos-149 and Cosmos-320 and by NASA on the PAMS spacecraft which was deployed from STS-77. This paper discusses aerodynamic stability solutions for the CubeSat domain, where CubeSat form factors are significantly smaller and lighter than the previous flight demonstrations and they must fit inside a CubeSat launcher and only deploy aerodynamic elements post orbit-insertion. Completely passive solutions for 3U and 1U CubeSats are described where aerodynamic fins are deployed and magnetic hysteresis material is used for oscillation damping. Greater velocity vector alignment can be achieved using active rate damping, utilizing a magnetometer and magnetic torque coils running the B-dot control law to provide improved oscillation damping. Component selections are offered to create off-the-shelf aerodynamically stable CubeSat platforms. Aerodynamic stability is suitable for the altitude and inclination of upcoming CubeSat flight opportunities on ISS crew resupply missions.

INTRODUCTION

Passive attitude stabilization, in general, is an attractive attitude control solution for satellites where coarse pointing is required, especially when power, mass, and volume are constrained. By tuning and designing the spacecraft to specific geometric, mass, and magnetic properties, its attitude can be controlled passively without the need of any active sensors or actuators.

Magnetic, gravity gradient, and aerodynamic torques are the main sources of moments on Small Satellites in Low Earth Orbit (LEO). Solar pressure is also an important factor for satellites with significantly large surface areas. A satellite can be designed to amplify one of these forces to overcome the others to achieve stability. For example, several CubeSats employed passive magnetic stabilization, where permanent magnets align the satellite with Earth’s magnetic field, to provide antenna or sensor pointing [1,2]. CubeSats have also been designed to deploy gravity booms to create a gravity gradient bias and achieve nadir pointing [3]. Also, aerodynamic drag in low orbits can be used to achieve velocity-vector pointing; this is discussed in detail in this paper.

Angular rate damping must accompany these stabilization techniques [2]. While the environmental torques would provide restoring torques necessary for stability, a form of angular rate damping is necessary to reach a steady state. Angular rate damping can be achieved using active attitude control actuators such as reaction wheels and magnetic torque coils, at the cost of the added complexity. There are also simple passive solutions that require no power and processing capabilities (and have fewer failure modes) such as the inclusion of magnetic hysteresis material [2,4], particle dampers, and fluid dampers [5].

Passive aerodynamic stability has been successfully demonstrated on orbit by the Soviet Union and NASA, further discussed in the background section, on larger than the CubeSat class satellites. Also, aerodynamic stability with active damping has been demonstrated on a 3U CubeSat. This research studies the feasibility of completely passive solutions for 1U and 3U CubeSat designs that can be built with commercial off-the-shelf components. Active damping using magnetic torque coils is considered for improved steady state performance.

Aerodynamic stability has been shown to be feasible for altitudes below 500km. In conjunction with a passive
damping solution, it provides a simple and low cost pointing solution. Velocity vector alignment is convenient for spacecraft dipole antenna pointing or when a sensor requires its aperture to track the velocity vector, for example, for atmospheric plasma measurements or Earth horizon sensing. The design of the CubeSats in this work feature deployable drag fins (resembling a shuttlecock) that provide their attitude aerodynamic stability. The increased drag area caused by the fins reduces its orbital life time to be on the order of months for ISS altitudes, which is desirable in many cases to mitigate orbital debris concerns.

A significant amount of CubeSat launch opportunities are expected to become available on upcoming crew resupply missions to the ISS as expressed by SpaceX, each mission will carry up to four CubeSat deployers [6]. From an attitude control point of view, satellites at this relatively low altitude are dominated by aerodynamic torques as shown in Table 1. This will drive complexity and limit the feasibility of common attitude control schemes that are not designed to counter disturbance torques of that magnitude. The designs in this paper utilize the strong aerodynamics for passive stability, and are proposed to be simple and low cost alternatives that are suitable for short-term and reoccurring experimental missions on ISS crew resupply launches.

The attitude propagator described in this paper is used to observe the satellite’s dynamic response and steady-state behavior at ISS altitude and inclination due to aerodynamic torques while considering perturbing torques due to gravity gradient and magnetic effects. Stability characteristics and pointing errors are shown for two spacecraft designs based on off-the-shelf components.

<table>
<thead>
<tr>
<th>Regions of Influence</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>

**Figure 1: Cosmos 149 at the K.E. Tsiolkovsky State Museum of the History of Cosmonautics [11]**

Aerostabilization in LEO was also flight tested as an experiment on the shuttle Endeavour in 1996 [12]. The Passive Aerodynamically Stabilized Magnetically-damped Satellite (PAMS) experiment demonstrated the
feasibility of aerostabilization with magnetic hysteresis material for damping. The PAMS satellite was designed as a cylindrical “stove pipe” having a significantly thicker shell on one end to shift the center of mass of the satellite and produce an aerodynamically stable design for altitudes from 250 to 325 km [13,14,15]. The flight experiment was deemed a success after several rendezvous operations [16]. Figure 2 shows PAMS with the shuttle Endeavour in view.

![Figure 2. NASA photo of PAMS taken from Shuttle Endeavour](image)

### PREVIOUS WORK ON CUBESATS

The dimensions of PAMS are similar to those of CubeSats (see verification section); however the CubeSat Standard does not allow such an offset in the center of mass unless a shift is performed post-deployment. In the design studied here, a “shuttlecock” design is used as an effective way to shift the center of drag pressure behind the center of mass after orbit insertion while still conforming to the CubeSat standard that requires that the center of gravity lies within 2cm of the geometric center [17].

In previous work at the University of Kentucky Space Systems Laboratory, we investigated the conditions of stability of a 3U CubeSat with deployable side panels. One degree of freedom analysis was done to study the effect of varying panel lengths and deployment angles for the 3U form factor at varying altitudes in the presence of gravity gradient moments [18]. In other research, a 6 degree-of-freedom (6-DOF) orbit and attitude propagator was developed with models for aerodynamic, gravity gradient, permanent magnet, and magnetic hysteresis material torques [2]. The attitude propagator was mainly used to support KySat-1 (a 1U CubeSat manifested on NASA’s ElaNa-1 mission) in designing satellites with permanent magnet attitude stability systems with hysteresis material for angular rate damping. The propagator (SNAP: Smart Nanosatellite Attitude Propagator [19]), has been verified by simulating several spacecraft of known designs, including PAMS, and comparing the simulations with their on-orbit results [1]. In this paper, we improve on the aerodynamic modeling by increasing the fidelity of the geometric representation, as well as improving the magnetic hysteresis model to be a continuous and smooth mathematical model, and introduce a model for active magnetic control. Then we leverage the SNAP simulation tool and previous studies on general stability across altitudes and propose aerodynamically stable CubeSat designs for the ISS altitude using commercially available components, and use the propagator to simulate the satellites’ attitude response in all degrees of freedom.

The most recent development in CubeSats is by the US Naval Research Laboratory where two 3U CubeSats have been designed and operated that employed aerodynamic fins to provide correcting torques for velocity-vector pointing [20]. 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. The QbX spacecraft were based on the Pumpkin Inc. Colony-I CubeSat Bus where four deployables change the geometry to achieve an aerodynamic bias, as in Figure 3. The QbX “space darts” were launched in 2010 and successfully demonstrated the feasibility of aerodynamic stabilization for a 3U CubeSat at an altitude of 300km [21]. Future publications are expected to report on this success.

![Figure 3. Pumpkin Colony-1 Bus. Photo courtesy of Pumpkin, Inc.](image)
CubeSat with 25cm fins made of 1 inch wide tape measure.

SIMULATOR

The Smart Nano-satellite Attitude Propagator (SNAP) is a 6-DOF satellite attitude propagator implemented in MATLAB® and Simulink® that can be used to analyze the environmental torques affecting a satellite and to design and analyze passive attitude stabilization techniques, such as Passive Magnetic Stabilization, Gravity Gradient Stabilization, and Aerodynamic Stabilization. The propagator includes: a simple two-body gravitational model for orbit propagation, in addition to models for gravity gradient torque, magnetic torque due to permanent magnets, magnetic hysteresis torque and damping, aerodynamic torques, and Magnetic B-dot control. SNAP, with a subset of features, has been made publically available by the University of Kentucky Space Systems Laboratory [19]. This section describes portions of the attitude propagator implemented in Simulink that includes the attitude dynamics components that are relevant to the scope of this paper and are new for this research.

Figure 4 shows the high-level view of the Simulink implementation of SNAP with the relevant force and moment models for this work. The satellite’s 6-DOF states and body dynamics are implemented in the center block, which has translational forces and rotational moments as inputs. The translational force is found using a two-body gravitational model to simulate orbital motion. Rotational moments are a sum of the environmental effects, namely gravity gradient, aerodynamics, and magnetic effects (either magnetic hysteresis material or active magnetic B-dot control, depending on the method of damping). Feedback elements for the orbital position, velocity, and the attitude can be observed in the Figure 4. The value of the forces and moments at each time step is a function of the satellite’s position in orbit and its attitude at the previous time step. Simulink’s solvers propagate the satellite’s state with time, given the description of the dynamics.

The total external torque is found as the combination of the Gravity Gradient, Aerodynamic, Magnetic Coil, and Magnetic Hysteresis moments:

\[ M_{total} = M_{gg} + M_{aero} + M_{coils} + M_{hysteresis} \]

These models calculate the torque components due to the respective environmental effects at a certain point in orbit as a function of the satellite mass and magnetic properties, the attitude at that point, the position in orbit, and the velocity in orbit. The individual torques are discussed in detail next.

Gravity Gradient Torque

As shown in Table 1, Gravity Gradient torque is the main source of disturbance moments for aerodynamically stabilized satellites in LEO. This is also evident in the literature where other sources of disturbances are considered to be minute and are ignored [7,8,10,14]. The gravity gradient torque for an Earth orbiting satellite is caused by differences in the distance to Earth across the satellite body; mass that is closer to Earth experiences higher gravitational attraction. An asymmetric body in a gravitational field will experience a torque tending to align the axis of least inertia with the field direction [23].

The mass distribution of the satellite is adequately described in the inertia matrix. The torque due to the Gravity Gradient effect is modeled in the Attitude Propagator as [24,25]:

\[ M_{gg} = \frac{3\mu}{R_0^3} \mathbf{u} \times \mathbf{u} \times \mathbf{e} \]

Where \( M_{gg} \) is the gravity gradient torque, \( \mathbf{u} \) is the unit vector towards nadir, \( R_0 \) is the distance from the center of Earth to the satellite, \( J \) is the inertia matrix, \( \mu \) is the geocentric gravitational constant.

This equation is modeled in Simulink to calculate the gravity gradient torque at each time step, given the position in orbit which defines the distance \( R_0 \), and the current attitude, which is used to find the nadir vector \( \mathbf{u} \), expressed in body-frame coordinates.

Aerodynamic Torque

The amount of aerodynamic torque a satellite experiences is a function of atmospheric density, the orientation relative to the wind vector (velocity vector), the forward facing area, and the satellite geometry where shadowing must be considered. The aerodynamic torque, in rarefied atmospheric conditions, for a certain area element can be calculated by [26,24]:

\[ M_{aero} = \frac{1}{2} \rho V^2 C_d A (\mathbf{u}_v \times \mathbf{s}_{cp}) \]

Where \( M_{aero} \) is the aerodynamic torque, \( \mathbf{u}_v \) is the unit velocity vector, \( s_{cp} \) is the vector from the center of pressure to the center of mass, \( \rho \) is the atmospheric density, \( V \) is the satellite velocity, \( C_d \) is the drag coefficient, and \( A \) is the affected area.
The aerodynamic torque for a certain attitude is a function of the area facing the velocity vector that is not shadowed by any other parts of the spacecraft body. Taking torque due to aerodynamics into account requires a method of representing the spacecraft geometry. Then an algorithm is needed to calculate the torque the spacecraft experiences given the geometric representation, and the attitude of the satellite relative to the wind vector (negative velocity vector).

The geometry of the satellite is discretized into volumetric elements, as shown in Figure 8 in the analysis section, at a dot per 0.125 cm³. A look-up table is generated that maps the attitude relative to the velocity vector to the amount of torque satellite experiences at that orientation. This torque profile is generated before the simulation runtime to reduce the amount of computations and minimize the simulation duration. At runtime, the satellite’s angle to the velocity vector (the incoming wind) is computed from the current attitude and orbit model. The look-up table returns the torque associated with that deflection angle. The mapping table is generated across a full range of satellite rotations, by considering elements directly facing the wind vector that are not shadowed by other satellite components. A form of numerical integration is performed by summing up the torque contributions of all the satellite elements to find the total torque affecting the satellite at a given attitude. Although shadowing is often ignored in literature when the main body of the satellite is small relative to the dimensions of the fins, this assumption cannot be made for the designs that will follow, where shadowing is an important factor to consider for CubeSat solutions. This geometric representation is a very convenient tool for solving this type of problem.

The look-up table is used at runtime to obtain a torque factor given the current satellite attitude. That value is then scaled by the atmospheric density at that altitude using another look-up table, and the satellite’s orbital velocity computed from the orbit propagator to find the final torque affecting the satellite at that time step.

**Magnetic Torque Coils**

Next we develop the model for magnetic torque coils, which are used here as an alternative to provide angular rate damping for improved tracking accuracy. A magnetic dipole in a magnetic field experiences an angular moment that aligns the dipole with the magnetic field lines, like a compass needle pointing north. The torque affecting a satellite due to a magnetic dipole interacting with the Earth’s magnetic field is modeled as [23]:

\[ \mathbf{M}_{\text{ coils}} = \mathbf{m} \times \mathbf{B}_{\text{earth}} \]

Where \( \mathbf{M}_{\text{ coils}} \) is the magnetic torque vector in body-frame, \( \mathbf{m} \) is the magnetic dipole moment vector in A·m² in body-frame, \( \mathbf{B}_{\text{earth}} \) is the Earth magnetic flux density vector in body-frame.

In this paper, the magnetic dipole moment \( \mathbf{m} \) is generated using magnetic torque coils based on the popular B-dot control law [27]:

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Figure 4: Simulink Model of SNAP, the Smart Nanosatellite Attitude Propagator, with the models relevant to this work. The Hysteresis Material and Torque Coils models are alternatives for passive and active damping.
\[ \mathbf{m} = -K \cdot \mathbf{B} = -K \cdot \frac{d}{dt} \mathbf{B} \]

Where \( \mathbf{m} \) is the magnetic dipole moment vector, \( K \) is a tunable gain factor, and \( \mathbf{B} \) is the Earth magnetic flux density vector in body frame. The B-dot control law actuates the torque coils to counter any changes of the observed magnetic field. From the satellite perspective, variations in the magnetic field caused by the satellite travel through orbit and the Earth’s rotation are slower than the observed magnetic field variations caused by the satellites angular motion, therefore the change in the observed magnetic field is an approximation of the satellite angular rates. The B-dot control law in effect acts to resist angular motion and is an effective detumbling and damping solution.

The Earth’s magnetic field is modeled as a dipole (L-Shell Model) [26]. Given the position in orbit at a given simulation step, the local magnetic field from the Earth can be found using the dipole model, and rotated to body-frame coordinates given the attitude of the satellite. At runtime, given the Earth’s magnetic field, and the satellite’s orientation, the magnetic torque due to the magnetic dipole is found.

The active magnetic damping solution requires a set of magnetic torque coils, typically three that are installed orthogonally. It also requires knowledge of the magnetic field which can be measured using a magnetometer. In this paper, active damping is only presented as a proof of concept; perfect knowledge of the magnetic field is assumed. An upper limit for the magnetic dipole per coil of 0.04 A-m² is set, which is a conservative number that can be achieved with air-core coils embedded in solar boards as traces across multiple layers. Solar boards with embedded torque coils and magnetometers are commercially available [28].

**Magnetic Hysteresis Damping**

Magnetic hysteresis material is a completely passive solution for angular rate damping, it is however non-trivial to study and predict, motivating the implementation of a simulation environment. Magnetically “soft” material of low coercivity can be magnetized by the Earth’s magnetic field and follows hysteresis patterns as it cycles in a magnetic field. This makes it suitable as a means for angular rate damping for small-satellites in orbits with a significant magnetic field. The lag (or “Hysteresis”) in tracking the externally applied magnetic field caused by the coercivity and remanence of the material results in energy lost as heat in the material. The phenomenon can be thought of as the magnetic dipoles having “friction” when their orientation is forced to change.

![B-H Hysteresis Curve Trace](image)

**Figure 5. Trace of the hysteresis loop model of HyMu80.**

Figure 5 shows a sample magnetization curve generated using the mathematical model of the hysteresis material used in this study [29]. The mathematical recipe was developed to simulate the NASA PAMS satellite, and is a set of first order differential relationships that we implemented and introduced to the propagator for this work. The model is an improvement on previous parallelogram approximations [2] as the continuous non-switching nature of the curve adds fidelity to the simulations.

Quantifying the amount of hysteresis material to include in a satellite design is challenging. The amount of damping caused by hysteresis material is not a fixed or calculated amount, it is a result of the behavior of the hysteresis material interacting and cycling through the Earth’s magnetic field. Modeling and simulation are a convenient and effective way to study hysteresis material [4].

Several inexpensive alternatives are available commercially, most commonly as electric shielding material. For example, HyMu80, Carpenter 49, Permalloy 80, and Mumetal are high permeability alloys that are suitable as magnetic hysteresis material for spacecraft rotation damping. For the proposed designs in this paper, HyMu80 is used. HyMu80 has a Coercivity of 1.59 A/m, Remanence of 0.35 Tesla, and Saturation of 0.73 Tesla.

**NASA PAMS - SIMULATOR VERIFICATION**

The Passive Aerodynamically Stabilized Magnetically-damped Satellite (PAMS), discussed in the background
section, demonstrated aerodynamic stabilization with magnetic hysteresis material for damping as an experiment on the shuttle Endeavour in 1996. Here we use PAMS as a case study to verify the accuracy of the simulation environment that has been developed. Based on available information in publications and in NASA web archives on orbit injection and satellite design, Table 2 summarizes the simulation parameters. Figure 6 shows the representation of the satellite in SNAP and the computed torque profile, which shows the amount of torque PAMS experiences as a function of its deflection from the velocity vector. A characteristic of an aerodynamic stable configuration is a steep negative sloped zero-crossing, where positive error angles produce negative torques, and vice versa, causing the satellite to oscillate around the zero-crossing.

<table>
<thead>
<tr>
<th>Orbit</th>
<th>283.4 km, 39° inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>~12.4 kg, Center of Gravity 15 cm from leading end.</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Cylindrical: 45 cm long, 23.8 cm radius</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>Three rods 1/75th the volume of rods on TRANSIT 1B satellite [13]</td>
</tr>
<tr>
<td>Inertia ($I_{xx}$, $I_{yy}$, $I_{zz}$)</td>
<td>(0.11, 0.0815, 0.0815) kg.m²</td>
</tr>
</tbody>
</table>

Figure 6. PAMS geometric representation and resulting torque profile. The torque profile shows the amount of correcting torque the satellite experiences vs. the error angle.

Figure 7. PAMS simulated attitude response. The plot shows the cone angle relative to the velocity vector.

Simulations Results. The simulation response for the PAMS parameters in SNAP, which is described in this paper, is shown in Figure 7. The response shows the satellite settling to a cone angle just below 20° after 18 orbits, with some variability across different simulations depending on the initial attitude and around which axis the initial tumble is applied. Generally speaking, the simulations show similar damping effect and velocity vector tracking given that configuration. The steady state oscillatory behavior with a cone angle smaller than 20 degrees matches the simulations and observations performed by NASA [16].

3U CUBESAT WITH DEPLOYABLE SIDE PANELS

The design requirements for aerostabilized CubeSats include conforming to the CubeSat mass limit (1.33 kg per 1U CubeSat), and the center of gravity restriction where the center of gravity is required to be within 2 cm from the geometric center before deployment [17]. This excludes the PAMS and Cosmos solutions, where the satellite is designed with a center of mass shift to create the aerodynamic bias, and any CubeSat solution

On-orbit observations. PAMS was launched in 1996 and observed to have a 0.5 degrees/second initial tumble. The shuttle Endeavor performed several rendezvous operations to observe its attitude. PAMS was declared to have achieved velocity vector tracking stability under 20 degrees and to be a successful experiment in the STS-77 mission report [12].
would require that the separation between the center of pressure and center of gravity be achieved after orbit insertion. The objective of the attitude solutions presented in this paper is to recover from the initial tumble after launch then achieve and maintain velocity vector alignment in steady-state.

The first proposed design is based on the Pumpkin Colony-1 bus (shown in Figure 3). Using the attitude propagator described thus far, several design configurations were tested and simulated. The panels of the 3U CubeSat are designed to be deployed at 20 degrees. This deployment angle minimized forward facing area (directly affecting orbit lifetime) without sacrificing steady state tracking accuracy. Figure 8 describes the satellite dimensions and location of the center of mass, and shows the point cloud representation of this geometry. Figure 9 shows the torque profile for this configuration, it provides a restoration torque comparable in magnitude to the PAMS design.

Table 3 summarizes the design parameters and simulation results. For the passive solution, several simulations have been run with varying amounts of hysteresis material, the best performing amount was chosen. Given an initial rate of 10 °/second, the simulation shows that hysteresis losses successfully detumble the satellite and a worst case steady state of 20° between the forward leading face and the velocity vector is achieved. The attitude response for the passive solution is shown in Figure 10. The steady state behavior is an artifact of several counteracting torques. The aerodynamic torques work to correct for pointing errors, counteracting gravity gradient disturbance torques (that are significant for 3U solutions) and hysteresis material torques.

Figure 8: Design diagram of the 3U CubeSat, panels deployed at 20°, and the discretized representation for torque calculation.

![Figure 8](image)

![Table 3](image)

![Figure 9](image)

![Figure 10](image)
18000, this results in an average total magnetic dipole of 0.000675 A/m, with a maximum dipole of 0.002 A/m for any of the three coils in steady state.

We note that a deployment angle of 20° results in a forward facing area of 0.020261 m². The orbit lifetime associated with this drag area at ISS altitudes is on the order of 9 to 33 months, as found by the NASA Debris Assessment Software (DAS 2.0) as worst-case and best-case scenarios depending on solar activity [30]. This lifetime may be considered desirable for short duration missions and for debris mitigation reasons.

Next we investigate the feasibility for a 1U CubeSat solution. The 1U CubeSat is the most frequent form factor and usually has the lowest launch cost. We present an aerodynamically stable design that is feasibly under the weight and volume limitations of the 1U form factor. The main design requirement was simplicity and manufacturability; especially because no off-the-shelf frame can be bought (at the time of the writing) to readily achieve aerodynamic stability on a 1U CubeSat. Dimensions and deployment of the drag fins were considered, as well as the volume required for hysteresis material, and placement of the magnetic coils in the case of the active damping solution.

Figure 12 shows the 1U CubeSat design that employs four 25cm long and 2.5cm wide drag fins. The fins can be realized using 1-inch wide flexible tape measure spring steel. The fins can be wrapped around the

Table 4: Design parameters and simulation results for 1U CubeSat with fins deployed at 50°

<table>
<thead>
<tr>
<th>Design Type</th>
<th>Passive Damping Solution</th>
<th>Active Damping Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>380 km circular, 51.6° inclination</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>1.33 kg</td>
<td></td>
</tr>
<tr>
<td>Inertia (I_{xx}, I_{yy}, I_{zz})</td>
<td>(0.00281, 0.003, 0.003) kg.m²</td>
<td></td>
</tr>
<tr>
<td>Drag Area</td>
<td>0.014788 m²</td>
<td></td>
</tr>
<tr>
<td>Angular Rate Damping</td>
<td>Hysteresis: HyMu80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.9 cm³ (0.3 cm³ per axis)</td>
<td></td>
</tr>
<tr>
<td>Simulation Parameters</td>
<td>10 °/second initial rate</td>
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</tr>
<tr>
<td>Results</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detumbling Time</td>
<td>5 hours</td>
<td></td>
</tr>
<tr>
<td>Steady State Tracking Accuracy</td>
<td>10-20°</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Below 1°</td>
<td></td>
</tr>
</tbody>
</table>

Figure 10: Simulated time response of aerostabilized 3U CubeSat with 30cm panels deployed at 20° and HyMu80 hysteresis damping.

Figure 11: Simulated time response of aerostabilized 3U CubeSat with 30cm panels deployed at 20° and magnetic B-dot damping.

1U CUBESAT WITH TAPE-MEASURE FINS

Next we investigate the feasibility for a 1U CubeSat solution. The 1U CubeSat is the most frequent form factor and usually has the lowest launch cost. We present an aerodynamically stable design that is feasibly under the weight and volume limitations of the 1U form factor. The main design requirement was simplicity and manufacturability; especially because no off-the-shelf frame can be bought (at the time of the
satellite and tied down before deployment, similar to the antenna deployment mechanism on KySat-1 [31]. Once released, the fins unravel and snap to their final intended positions.

Figure 13: Torque profile at a selected roll angle, normalized to atmospheric density and velocity, of 1U CubeSat with deployable fins at 50°.

A short enough fin length was chosen were the fins would not wrap around completely and interfere with other fins when stowed. A deployment angle of 50° was chosen to maximize restoration torque, several simulations were run to find the most effective volume of hysteresis material. Figure 13 shows the torque profile for this design. This configuration has a significantly smaller magnitude of restoration torque compared to the 3U solution presented earlier. However, gravity gradient torques, that are a function of the mass distribution of the satellite, are minimal for this design. The 1U form factor, being more symmetric, has an advantage over the 3U shape and is less affected by gravity gradient disturbance torques. This allows the presented 1U design with relatively low fin area to be sufficient for aerodynamic stability.

Table 4 describes the simulation parameters and results for the 1U CubeSat solution. Figure 14 shows the satellite response for the completely passive solution that utilizes magnetic hysteresis material for damping. We note that the attitude response shows improvement over the 3U CubeSat response plot, this is because of the smaller gravity gradient disturbance torques the 1U satellite experiences in comparison.

Figure 14: Simulated time response of aerostabilized 1U CubeSat with 2.5x25cm drag fins deployed at 50° and HyMu80 hysteresis damping.

For improved pointing accuracy, active rate damping can be employed. Using the same air core magnetic coils presented earlier driven by the B-dot control law, the attitude response of the active damping alternative is presented in Figure 15. Velocity vector tracking below 1 degree is achieved. The B-dot control gain was chosen to be K = 9000, this results in an average total magnetic dipole of 0.00031 A/m, with a maximum dipole of 0.001 A/m for any of the three coils in steady state.

Figure 15: Simulated time response of aerostabilized 1U CubeSat with 2.5x25cm drag fins deployed at 50° and magnetic B-dot damping.

This design has an expected orbit lifetime of 3 – 14 months. The Area-to-mass ratio of this design, which is key for orbit lifetime calculations, is higher than the previous 3U design and has therefore the shortest expected lifetime.

DISCUSSION

Effect of Altitude on Passive Solutions

The discussion so far was specific to the ISS orbit altitude and inclination (380km at 51.6°). Running the 3U CubeSat design with the same simulation parameters only increasing the orbit altitude showed reduced tracking accuracy. Specifically, errors to the velocity vector were up to 50° at 500km, and 120° at
Aerodynamic stabilization can provide velocity vector pointing for small satellites. Aerodynamic stabilization with passive damping has been demonstrated by the Cosmos-147, Cosmos-320, and NASA PAMS spacecraft. This paper surveys the previous work and discusses the alternatives to stabilize CubeSats aerodynamically.

An attitude propagator that incorporates an orbit propagator, gravity gradient torques, aerodynamic torques, magnetic hysteresis torques, and the B-dot control law was developed. The simulator was verified using flight results of several passively stabilized satellites, including the NASA PAMS data and mission results, and is used to propose designs for aerodynamically stable CubeSats that conform to the CubeSat standard.

The first design is based on the Pumpkin Colony-1 bus by Pumpkin Inc. The 3U CubeSat has side panels that deploy to trail the satellite pushing the center of aerodynamic pressure behind the center of gravity. The second design proposes an aerodynamically stable configuration for a 1U CubeSat. The design incorporates drag fins based on flexible spring steel used in tape measure. The design is feasible with reasonable amount of hysteresis material.

The proposed designs can be assembled with off-the-shelf components and provide a simple and low cost stable platform at the ISS orbit. Aerodynamic torques dominate attitude behavior at that altitude, driving the complexity and cost of other attitude control schemes. These designs are proposed as convenient platforms for short duration and repeatable experiments on upcoming ISS crew resupply missions.

REFERENCES

1. S. A. Rawashdeh, J. E. Lumpp, Jr., Nano-Satellite Passive Attitude Stabilization Systems Design by Orbital Environment Modeling and Simulation. In Infotech@Aerospace Conference (Atlanta 2010), AIAA.
6. Bjelde, Brian. SpaceX Keynote Address. (San Louis Obispo, CA April, 2011), CubeSat
Developers' Workshop.


