

OPTIMIZING PASSIVE ATTITUDE CONTROL IN CUBESATS AN ANALYSIS OF SIZE VARIABILITY AND AERODYNAMIC DRAG FORCE EFFICIENCY

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Abstract

The challenge of achieving precise attitude control in CubeSats represents a significant obstacle for many CubeSat missions. An innovative approach to mitigate this issue involves leveraging the environmental disturbances encountered in orbit as a means of passive attitude stabilization. These disturbances, which include gravitational and magnetic forces, as well as aerodynamic drag, exert varying degrees of torque on the satellite based on its geometry, mass distribution, and material composition. Passive attitude control systems offer significant advantages over their active counterparts, notably in terms of reduced power consumption, mass, and lower overall mission costs. This research delves into the potential of passive attitude stabilization by focusing on the aerodynamic drag force prevalent in low Earth orbits (LEO) as a mechanism to control CubeSat orientation. The core of this study examines the impact of CubeSat size variations on the efficacy of passive attitude control systems. The investigation explores the relationship between CubeSat size and the deployment angles of solar panels, which are critical for shifting the centre of mass and enabling passive stabilization. Additionally, the study assesses the use of ferromagnetic materials to dampen angular rates, considering how different CubeSat sizes affect the rate of stabilization and the limitations of passive aerodynamic stabilization techniques within specific deviation error angles. The findings of this study will provide valuable insights into the design and operational strategies of CubeSats, enhancing their performance and reliability in future space missions.

Keywords: CubeSats, Passive Attitude Control, Drag Force, Size Variations, Passive Aerodynamic Stabilization

1. Introduction

CubeSats have revolutionized access to space by providing a compact, low-cost, and standardized platform for educational, scientific, and commercial missions. Despite their advantages, CubeSats face several engineering limitations due to their small size and constrained resources. One of the most critical among these is attitude control — the ability to orient the satellite in space to meet mission requirements such as Earth imaging, communications, or solar power generation.

Traditional attitude control systems, which rely on active components like reaction wheels or magnetorquers, are often power-wise and mass-wise costly for CubeSats due to their mass, power consumption cost. As a result, passive attitude control techniques have emerged as a viable alternative. These methods leverage natural environmental torques — such as gravity gradients, magnetic fields, and atmospheric drag — to stabilize a satellite's orientation without the need for active control or power input.

Among these techniques, aerodynamic drag stabilization is particularly promising for CubeSats operating in low Earth orbit (LEO). At these altitudes, residual atmospheric particles exert drag forces on the satellite's surfaces. By carefully designing the satellite's geometry and mass distribution, these drag forces can induce restoring torques that passively align the satellite along the velocity vector [1], [2], [3]. This approach is especially attractive for missions with low pointing accuracy requirements and limited power budgets.

This paper investigates how CubeSat size variations affect the efficiency of aerodynamic drag-based passive attitude stabilization. Using a MATLAB/Simulink simulation environment, various CubeSat sizes (ranging from 1U to 16U) are analysed with a symmetric two-panel configuration. The results show a nonlinear relationship between satellite size and stabilization performance, influenced by the trade-off between aerodynamic torque and moment of inertia. In addition to the simulation-based analysis, this study includes a brief literature review on the use of ferromagnetic materials, particularly hysteresis rods, as a passive means for angular rate damping. Although not simulated in this work, such materials have been shown to be effective in real missions for reducing residual rotation, and they complement aerodynamic drag in hybrid passive control systems. By analyzing the relationship between CubeSat size and passive control effectiveness, and by assessing the potential of ferromagnetic damping, this research provides valuable guidance for designing efficient, low-power attitude control systems suitable for resource-constrained space missions.

This paper is structured as follows: Section 2 outlines the related work. Section 3 details the methodology followed in this work. Section 4 presents the MATLAB/Simulink implementation. Section 5 provides the results and discussion of the simulation. Section 6 concludes with key findings and future work recommendations.

2. Related Work

The increasing complexity of CubeSat missions has intensified the need for reliable yet lightweight and power-efficient attitude control systems. Passive attitude control, leveraging environmental torques, has emerged as a promising alternative to conventional active systems that often exceed the size, mass, or power budgets of nanosatellites.

2.1 Passive Attitude Control via Aerodynamic Drag

Aerodynamic drag is one of the most accessible passive forces in low Earth orbit (LEO), especially below 600 km altitude. Riano-Rios et al. [1] introduced an adaptive controller that exploits drag and gravity gradient torques using a Drag Manoeuvring Device (DMD). Their simulations incorporated uncertainties in atmospheric density and centre of mass (CoM) location and demonstrated bounded attitude tracking errors using Lyapunov-based control. The DMD features four extendable surfaces mounted at 90° intervals and tilted 20° off the anti-ram direction. This configuration allows real-time modulation of drag and lift torques without actuators — an efficient approach for long-duration missions (as can be seen in Figure 1).

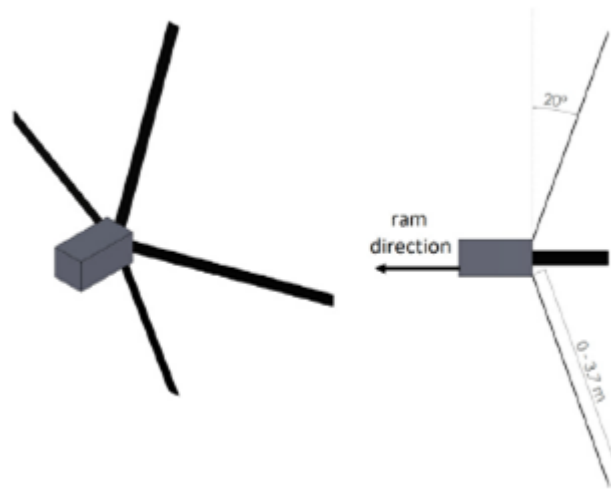


Fig. 1. Drag Manoeuvring Device Schematic by [1]

Omar and Wersinger [2] examined how differential drag can be utilized for both orbit and attitude control. Their simulations showed that small CubeSats (~1U–3U) can achieve significant trajectory separation (up to 143 km/day) with only minor drag surface area differences, validating the effectiveness of aerodynamic forces for passive control. Sabug Jr. et al. [3] proposed a co-design methodology integrating passive magnetic components and active reaction wheels, while modelling aerodynamic and hysteresis torques. Their findings demonstrate that integrating passive mechanisms significantly improves system robustness and energy efficiency. A black-box optimization algorithm helped determine the optimal balance between passive and active components, achieving better performance under power and pointing constraints. As can be seen in Table 1, these studies vary in CubeSat configurations, drag surface designs, and control objectives, but consistently demonstrate the feasibility of aerodynamic drag for passive stabilization.

Table 1. Comparison of aerodynamic passive control systems in some of the related work

Study	CubeSat Size	Aerodynamic Surface	Control Strategy	Simulation Duration	Performance Summary
Riano-Rios et al. (2021) [1]	3U	4 Drag Manoeuvring Device (DMD)	Adaptive control with CoM uncertainty	Full orbital cycles	Stabilized under environmental uncertainty; bounded

		panels (20° inclined)			quaternion tracking error Achieved 143 km/day separation using minor drag variations; proves feasibility of drag use Improved accuracy and energy efficiency by integrating passive magnetic and drag effects
Omar & Wersinger (2013) [2]	1U–3U (assumed)	Flat-panel extensions for drag area modulation	Differential drag-based separation	Several days (simulated)	
Sabug Jr. et al. (2023) [3]	3U	Implicit drag torque included in system model	Co-design of passive+active using BBO	Orbital scenario cycles	

2.2 Ferromagnetic Materials for Passive Angular Rate Damping

In addition to drag-based mechanisms, ferromagnetic hysteresis rods are widely used to passively damp rotational motion. These materials absorb angular momentum through magnetic hysteresis, allowing the CubeSat to gradually detumble and stabilize without active components. Gerhardt and Palo [4] implemented a hybrid passive magnetic system on the CSSWE CubeSat, consisting of a bar magnet for restoring torque and HyMu-80 rods for angular rate damping. The system achieved attitude stabilization within $\pm 10^\circ$ in approximately 6.5 days, using a total rod mass of just 8.6 grams — all without consuming power. Rawashdeh [5] evaluated a similar system on KySat-1 and emphasized the axis-limited nature of passive magnetic control, which can effectively align a CubeSat to the magnetic field but may leave one degree of freedom under-constrained. However, this trade-off is acceptable for missions with loose pointing requirements, such as beacon transmission or basic nadir pointing. OUFTI-1’s ADCS study [6] conducted detailed comparisons between HyMu-80 and Permenorm 5000 H2. They found Permenorm delivered up to 7× higher damping energy due to its broader hysteresis loop. Rod volume and placement strongly influenced the damping time and final pointing error — for instance, with two rods of 0.2 cm³ each, stabilization time dropped below 9 hours, with final angular errors ranging from 15° to 31° depending on configuration. These performance trends are visualized in Table 2, which shows stabilization time vs. rod volume for both materials. Table 3 summarizes key features and performance metrics of passive magnetic attitude control systems using ferromagnetic hysteresis materials from references [4], [5], and [6].

Table 2. Simulations of OUFTI-1 attitude with an initial rotation rate of (2; 3,5; 0,75) rad/s [6]

Permanent Magnet	Hysteretic Bars	Stabilization Time	Residual Rotation	System Resolution
AlNiCo-5 1cm ³	Hy-Mu-80 (2 × 0.4cm ³)	11h	5 (°/s)	26°
AlNiCo-5 1cm ³	Permenorm (2 × 0.2cm ³)	5h	16 (°/s)	31°
AlNiCo-5 2cm ³	Hy-Mu-80 (2 × 0.4cm ³)	9h	2 (°/s)	15°
AlNiCo-5 2cm ³	Permenorm (2 × 0.2cm ³)	4h	8 (°/s)	24°

Table 3. Comparison of passive magnetic control systems using ferromagnetic materials

Study	CubeSat	Material Used	Rod Volume	Stabilization Time	Final Pointing Error	Notes
Gerhardt & Palo (2010) [4]	CSSWE (3U)	HyMu-80	Not specified	~6.5 days	±10° (total)	Passive bar magnet + hysteresis

						rods; total system mass ~8.6 g One axis remains uncontrolled; suitable for coarse pointing missions Higher performance with Permenorm; depends on rod length and placement
Rawashdeh (2011) [5]	KySat-1 (1U)	HyMu-80	~1–2 cm ³ (est.)	~10–20 hours (sim.)	~10–20° (simulated)	
Aerts (OUFTI-1, 2012) [6]	OUFTI-1 (1U)	HyMu-80 vs. Permenorm	0.05–0.3 cm ³	9–28 hrs (HyMu-80), 3.5–14 hrs (Permenorm)	15°–31° (varies by config)	

3. Methodology

This study investigates the effect of CubeSat size on passive aerodynamic attitude stabilization using a standardized configuration featuring two flat deployable panel. The methodology followed a multi-step process combining geometric modelling, physical property extraction, and dynamic simulation.

Initially, detailed CAD models were developed for a range of CubeSat sizes, including 1U, 2U, 3U, 6U, 12U, and 16U configurations. Each model included two deployable panel attached to both sides of the satellite, implemented in a flat, wing-like configuration. Figure 2 presents a sample image of a 3U CubeSat for illustration purposes [7]. These models were used to ensure consistent geometry and deployment across all cases while scaling physical dimensions and mass appropriately with satellite volume.



Fig. 2. Sample image of a 3U CubeSat for illustration purposes

From the CAD environment, key physical parameters were extracted for each configuration. This included the moment of inertia (MOI) tensor, the projected aerodynamic drag area in the flight direction, and the vector from the centre of mass to the centre of pressure (lever arm). These parameters were calculated using the mass properties and

surface tools provided within the CAD software, ensuring realistic estimates based on accurate geometry and assumed mass distributions.

Using the extracted physical parameters, a passive attitude dynamics model was developed in MATLAB/Simulink. The simulation environment incorporated aerodynamic drag as the primary external disturbance torque and modelled the satellite as a rigid body. The attitude kinematics were expressed using quaternion representation, and the attitude dynamics were governed by Euler’s rotational equations. A MATLAB script was used to vary the input parameters for each CubeSat configuration and automatically run the simulations. The simulation outputs included two key performance metrics: stabilization time and pointing accuracy. These results were then analysed across CubeSat sizes to assess the influence of satellite geometry on passive stabilization behaviour. Figure 3 shows a flowchart of the methodology followed in this work.

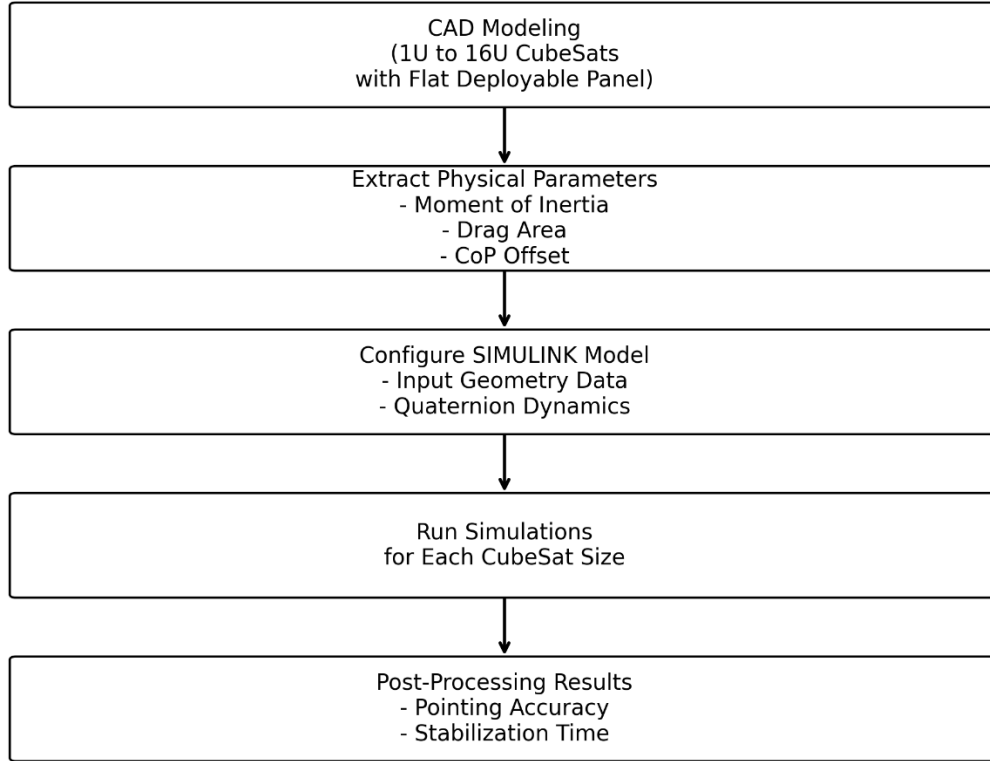


Fig. 3. The methodology followed in this work

4. MATLAB Implementation

To model the passive attitude stabilization of CubeSats under aerodynamic drag, a custom MATLAB/Simulink environment was developed. The Simulink model simulates the rotational dynamics of a CubeSat in Low Earth Orbit (LEO) based on rigid body kinematics, using extracted physical parameters. The simulation was implemented using two primary modules. The first is the Attitude Dynamics Block, which implements Euler’s rotational dynamics using Equation 1 [8].

$$\frac{d\omega}{dt} = I^{-1} (T_{drag} - \omega \times I\omega) \quad (1)$$

where ω is the angular velocity vector [rad/s], I is the satellite’s inertia matrix [$kg \cdot m^2$], and T_{drag} is the external torque due to atmospheric drag. The second module is the Quaternion Kinematics Block. Satellite orientation is represented using quaternions to avoid singularities associated with Euler angles. The quaternion differential equation is shown in Equation 2 [8].

$$\frac{dq}{dt} = \frac{1}{2} \Omega(\omega)q \quad (2)$$

where q is the unit quaternion and $\Omega(\omega)$ is the quaternion multiplication matrix defined as shown in Equation 3 [8]. Moreover, the aerodynamic drag torque was computed using Equation 4 with the drag force approximated in Equation 5 [8].

$$\Omega(\omega) = \begin{bmatrix} 0 & -\omega_x & -\omega_y & -\omega_z \\ \omega_x & 0 & \omega_z & -\omega_y \\ \omega_y & -\omega_z & 0 & \omega_x \\ \omega_z & \omega_y & -\omega_x & 0 \end{bmatrix} \quad (3)$$

$$T_{drag} = (r_{cp} - r_{cm}) \times F_{drag} \quad (4)$$

$$F_{drag} = -\frac{1}{2} \rho V^2 C_D A \cdot \hat{v} \quad (5)$$

where ρ is the atmospheric density, V is the orbital velocity, C_D is the drag coefficient, A is the projected area facing the flow, and \hat{v} is the unit velocity vector in the body frame. The drag direction was derived from orbital velocity vectors converted from Keplerian orbital elements using standard orbital mechanics transformations [9].

Each simulation began with an initial attitude represented by a non-identity quaternion (e.g., [0.5;0.5;0.5;0.5]) [10]. The Simulink model integrated the dynamics over time using the Runge-Kutta solver (ode45). The quaternion error was post-processed in MATLAB to compute two key metrics: Stabilization Time, defined as the time after which the CubeSat reached stabilization; and Pointing Accuracy, defined as the average error when pointing towards Nadir.

5. Results and Discussion

After running the implemented model in MATLAB/Simulink, a plot shown in Figure 4 was generated to compare the different CubeSat sizes used in the simulation in terms of stabilization time and pointing accuracy.

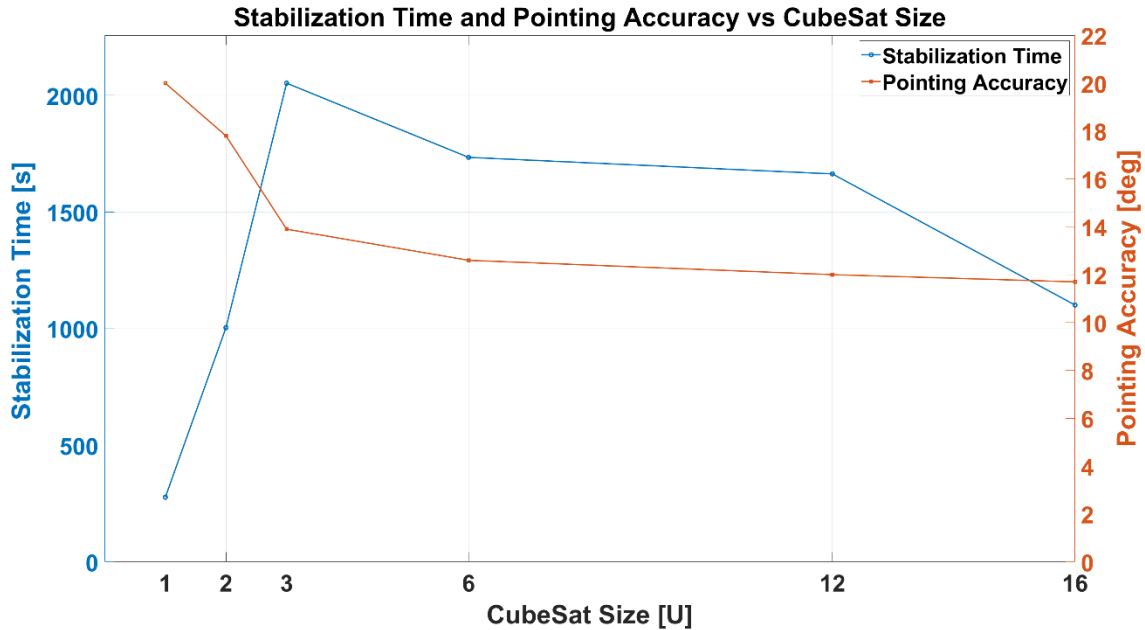


Fig. 4. Results of running the MATLAB/Simulink implementation for different CubeSat sizes

The simulation results demonstrate a clear relationship between CubeSat size and passive aerodynamic attitude stabilization performance when two flat-panel configuration is used across all unit sizes. Specifically, as CubeSat volume increases from 1U to 16U, the time to reach a nearly stable orientation initially increases, peaking at 3U (2052 seconds), and then gradually decreases, reaching 1101 seconds for the 16U case. Concurrently, the final pointing accuracy improves consistently, with angular error decreasing from 20° (1U) to 11.7° (16U).

This behaviour is justified by the interplay between two opposing factors: drag torque and MOI. Larger satellites naturally exhibit higher MOI, which tends to resist rotational acceleration and slow down convergence. However, they also present larger surface areas and longer moment arms for aerodynamic torques, enhancing the net torque available for passive alignment. In smaller units like 1U or 2U, the aerodynamic torque is often insufficient to overcome initial momentum quickly, leading to faster but less accurate stabilization. In contrast, medium to larger platforms (6U–16U) benefit from increased drag leverage, resulting in improved damping and tighter convergence to the desired orientation.

Interestingly, the peak stabilization time at 3U suggests a transitional zone where the increasing MOI briefly dominates before aerodynamic effects take over in larger structures. The improved final pointing accuracy in 12U and 16U confirms the benefit of higher drag-induced restoring torques in larger volumes, even in a symmetric flat-panel configuration. These findings suggest that, in the absence of active control, CubeSat geometry and deployment strategy must be co-optimized to achieve acceptable stabilization performance in passive aerodynamic systems.

6. Conclusions

This study investigated the role of CubeSat size in enhancing the performance of passive attitude control systems based on aerodynamic drag. Through a MATLAB/Simulink simulation framework, CubeSats ranging from 1U to 16U were analyzed using a consistent flat-panel configuration to isolate the effects of geometry and moment of inertia (MOI) on stabilization behavior.

The results revealed a nonlinear relationship between CubeSat volume and passive stabilization performance. Specifically, smaller CubeSats (e.g., 1U–2U) stabilized quickly but with higher residual pointing errors due to limited surface area and drag torque. Mid-sized platforms (around 3U) showed a temporary increase in stabilization time due to MOI dominance, while larger units (6U–16U) benefitted from greater aerodynamic leverage, achieving both improved damping and better final pointing accuracy — with the 16U CubeSat reaching a stable orientation in 1101 seconds and an angular deviation of just 11.7°.

The analysis confirms that CubeSat geometry and deployment strategy must be co-optimized to balance aerodynamic torque generation against rotational inertia. The findings suggest that for missions where active control is not feasible, CubeSat size and panel configuration play a crucial role in ensuring acceptable stabilization.

In addition, the paper reviewed existing work on the use of ferromagnetic materials for passive angular rate damping. Although not simulated directly, previous studies confirmed the practicality of incorporating hysteresis rods for detumbling, particularly for missions with relaxed pointing requirements. Materials like Permenorm 5000 H2 demonstrated faster damping than traditional HyMu-80 rods, albeit with higher residual rotation rates.

Together, the simulation results and literature review reinforce the value of passive control strategies for CubeSats operating in LEO. These methods offer mission designers a low-power, mass-efficient approach to attitude control, with tunable performance through the careful selection of size, structure, and material configuration.

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