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Aerodynamic Panel Shape Optimization for CubeSats to Reduce Chaotic Motion in Lower Earth Orbit

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Abstract: CubeSats are increasingly employed in various low-Earth orbit (LEO) missions. However, their stability is often compromised by chaotic motion induced by aerodynamic disturbances and the deployment of appendages, such as solar panels or fins. Addressing these challenges is critical to ensuring mission reliability and extending operational lifetimes. This study explores the aerodynamic performance and stability implications of deployable fin geometries for CubeSats, where two configurations of square-shaped and elliptical fins are chosen for analysis. Using computational fluid dynamics (CFD) simulations under identical boundary conditions, velocity fields, flow structures, and turbulence intensity around the CubeSat have been examined. The results reveal that elliptical fins produce smoother flow patterns with reduced velocity gradients, minimizing turbulence and enhancing stability. In contrast, square fins exhibit higher turbulence intensity, which could promote chaotic motion. By establishing the aerodynamic advantages of elliptical fin designs, this work not only provides actionable insights for stabilizing CubeSats in LEO but also offers a framework for optimizing fin geometries to mitigate chaotic behavior. These findings lay the foundation for future advancements in CubeSat design, enabling improved aerodynamic performance and stability in dynamic orbital environments.

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1. Introduction

The rapid growth in CubeSat deployments for space missions has transformed the landscape of satellite technology, offering cost-effective and versatile platforms for scientific research, communication, and Earth observation [1]. However, their compact design and reliance on deployable panels for functionalities such as solar power generation and thermal management introduce unique challenges. In the lower Earth orbit (LEO) environment, aerodynamic forces become significant due to interactions with residual atmospheric particles. These forces, combined with the asymmetric geometries of deployable panels, often lead to chaotic rotational motion, negatively impacting mission-critical operations [2] like imaging stability, precise communication alignment, and sensor accuracy, addressing this issue is vital for advancing CubeSats' reliability and operational efficiency in highly demanding LEO missions.

This study focuses on aerodynamic panel shape optimization as a strategic solution to mitigate chaotic motion and enhance CubeSat stability [3] This research aims to reduce disturbances caused by unbalanced forces by leveraging computational simulations to analyze and optimize the aerodynamic behavior of various panel shapes. The insights gained from this work have far-reaching implications, enabling CubeSats to maintain stable attitudes with reduced control system demands, conserving energy, and extending mission lifetimes. With CubeSats playing an increasingly prominent role in advancing space exploration and technology, this study contributes to a critical gap in design methodology, ensuring their effectiveness in dynamic and challenging orbital environments.

Murcia P J O et. al [3] investigated the impact of aerodynamic forces, particularly drag on CubeSat orbital lifetimes in low Earth orbit (LEO). Their study explored how rotational movements influence CubeSat attitude,

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altering the ballistic coefficient and decay rates. Using the panel method, they calculated drag coefficients for different flow incidence angles and spin rates, showing that controlled rotation significantly increases the mean drag coefficient. Through trajectory simulations, they demonstrated that initiating rotation could reduce orbital lifetimes by over 10%, offering a debris mitigation strategy for non-operational CubeSats. Notably, their results indicated that the reduction in orbital lifetime depends more on initiating rotation than on its angular velocity.

V.S. Aslanov [4] explores the chaotic behavior in CubeSats equipped with flexible stabilizing panels in low Earth orbit (LEO). The study demonstrates how flexible panels, instead of stabilizing the satellite, can induce oscillations that lead to chaotic attitude dynamics. By employing methods such as Poincaré sections and Lyapunov exponents, the research quantifies the chaos, showing that minor disturbances, like panel oscillations, can destabilize the satellite's motion. The results highlight that the degree of chaos is influenced by factors such as altitude and panel flexibility. These findings underscore the need to carefully consider the destabilizing effects of flexible components in CubeSat designs. Future studies could delve into three-dimensional chaotic motion, define chaotic boundaries in parameter spaces, and further analyze the dynamics of panel deployment.

S.A. Rawashdeh [5] discusses passive stabilization methods for CubeSats in low Earth orbit (LEO), particularly at altitudes near the International Space Station (ISS). The study focuses on utilizing aerodynamic drag and magnetic hysteresis damping to control attitude without relying on active systems like thrusters or reaction wheels. Deployable aerodynamic fins are designed to shift the center of pressure behind the center of mass, generating a restoring force that aligns the CubeSat with the velocity vector, akin to a shuttlecock. Using the Smart Nanosatellite Attitude Propagator (SNAP) tool, the authors evaluate the effects of varying panel angles and sizes, showing that a deployment angle of approximately 50 degrees can achieve effective stabilization. Magnetic hysteresis material is shown to provide sufficient damping to minimize oscillations caused by aerodynamic and gravity gradient forces, making this approach well-suited for short-duration missions where deorbiting is beneficial for debris mitigation. The paper highlights opportunities for future research, including optimizing hysteresis material placement and exploring active damping systems, such as magnetic torque coils, to enhance stability for longer missions or higher-altitude operations.

M. Taha [6] explores the development of a passive attitude stabilization system for CubeSats in Low Earth Orbit (LEO) to reduce dependence on power-intensive active control systems. The study investigates methods to achieve stabilization by optimizing CubeSat geometry, mass distribution, and accounting for environmental factors such as gravity gradient, magnetic fields, and aerodynamic drag. A passive magnetic stabilization approach is proposed, utilizing ALNICO-5 magnets and hysteresis materials to align CubeSat with Earth's magnetic field. The results show that stabilization is achieved within 50 minutes, with further refinement in alignment after 2.5 hours. The research highlights the potential of passive stabilization for efficient CubeSat operation and suggests exploring advanced materials or hybrid systems combining passive and low-power active controls for improved performance in future work.

Riano-Rios [7] developed an adaptive controller for CubeSat attitude control using environmental torques, such as aerodynamic and gravity gradient forces. The CubeSat utilizes a Drag Maneuvering Device (DMD) to modulate these forces by adjusting its drag surface's length and orientation. The controller compensates for uncertainties in atmospheric density, drag/lift coefficients, and the time-varying center of mass (CM), ensuring bounded attitude tracking errors. Lyapunov-based stability analysis demonstrates the controller's ability to maintain uniform, ultimately bounded tracking. Numerical simulations show their effectiveness in both fixed and time-varying maneuvers, with potential improvements in model inertia and DMD deployment. Future research could focus on advanced adaptive strategies and real-world testing.

CubeSats, miniature satellites with standardized modular designs, have revolutionized space exploration due to their cost-effectiveness and adaptability [8]. However, their small size and lightweight construction pose unique challenges in maintaining stability, particularly in lower Earth orbit (LEO). LEO, with altitudes ranging from 160 to 2,000 kilometers, presents a rarefied flow environment where aerodynamic forces play a significant role. Residual atmospheric particles at these altitudes interact with the CubeSat at high velocities, generating drag and aerodynamic torques that can induce chaotic rotational motion. This motion is further influenced by deployable components, such as solar panels, which alter the CubeSat's geometry and create asymmetric drag forces. These factors underscore the need for a comprehensive understanding of aerodynamic stability in the context of CubeSat design for LEO missions.

The aerodynamic behavior of CubeSats in LEO is governed by a delicate interplay of design parameters, including shape, surface roughness, and the relative positions of the center of pressure (CoP) and center of gravity (CG). For stability, the CoP - the point where aerodynamic forces act - should be aligned favorably with the CG to minimize restoring torques caused by drag asymmetry. Additionally, the panel shapes play a critical role in defining the aerodynamic profile. Square or sharp-edged panels may amplify turbulence and wake formation, leading to destabilizing torques, whereas streamlined shapes like ellipses or curved panels can reduce turbulent separation and ensure smoother flow interaction. Such design optimizations are critical in LEO, where the free molecular and transitional flow regimes dominate **[9–11]**. Here, aerodynamic forces arise predominantly from particle impacts rather than continuum fluid behavior, requiring tailored designs that consider the unique dynamics of this environment.

Aligning aerodynamic considerations with LEO-specific criteria is essential for achieving stable CubeSat designs. The high orbital velocity in LEO amplifies aerodynamic drag, making its control critical for mission success. Computational tools, such as CFD simulations, analyze flow fields around CubeSats under realistic LEO conditions, accounting for free-stream velocity, atmospheric density, and rarefied flow effects. Optimizing panel geometry and overall structure enables a stable aerodynamic configuration that minimizes chaotic motion. This work integrates aerodynamics and spacecraft design, addressing the unique challenges of LEO to develop robust and reliable CubeSat solutions.

Despite extensive research on CubeSat stability and performance in Low Earth Orbit (LEO), critical challenges persist in achieving precise control over chaotic attitude dynamics induced by aerodynamic and environmental forces. Previous studies have primarily focused on individual aspects such as the role of rotational dynamics, the effects of flexible appendages, or passive stabilization techniques using magnetic and aerodynamic forces. However, these approaches often overlook the intricate relationship between aerodynamic panel design and its impact on stability, drag, and overall orbital performance. Moreover, the nuanced influence of geometric properties and deployment configurations under varying orbital conditions remains underexplored.

This research addresses these gaps by investigating the aerodynamic behavior of CubeSats equipped with deployable panels, specifically designed to harmonize stability and drag control. By systematically analyzing the aerodynamic forces and their interaction with environmental factors in LEO, this study offers a deeper understanding of how panel geometry and deployment strategies influence CubeSat dynamics. The findings contribute to developing more efficient CubeSat designs capable of mitigating chaotic motion while optimizing performance, offering a critical advancement in the pursuit of reliable and sustainable satellite missions in LEO.

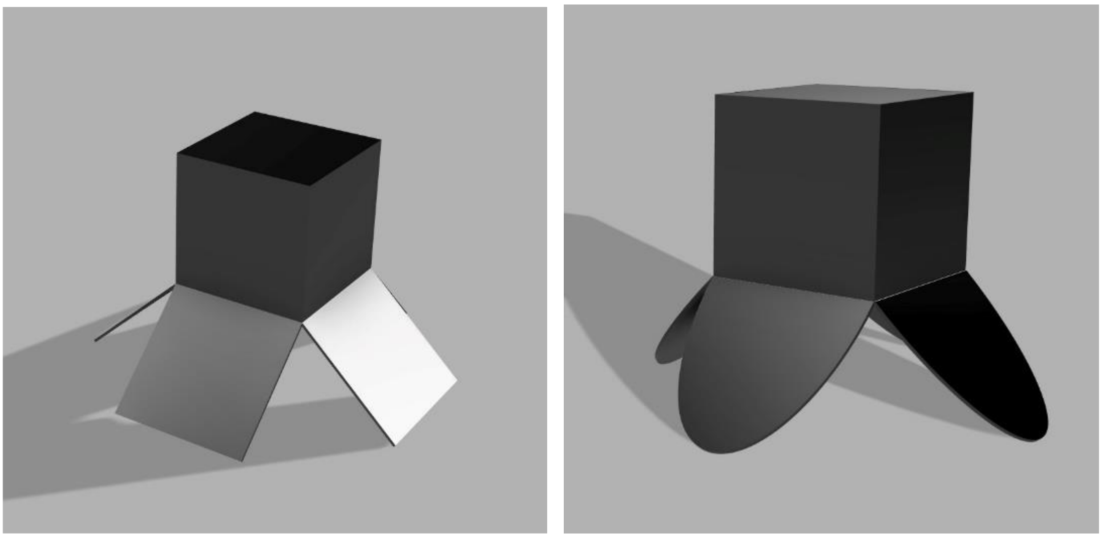

Figure-1 CAD representation for (left) reference model (right) optimized model

2. Methodology

The numerical simulation of the flow field around the CubeSat model with deployable fins has been conducted using a finite volume-based solver. Two configurations are considered for the study, one with square-shaped fins and the other with elliptical fins. An unstructured mesh approach is used for greater accuracy and efficiency in resolving the flow features. The computational domain is extended to 15 times the CubeSat's characteristic length to ensure no interference from boundary effects, with velocity inlet and pressure outlet boundary conditions applied. A no-slip wall boundary condition is imposed on all CubeSat surfaces. The simulations are performed at a free-stream velocity of 20m/s, 50m/s, 80m/s, and 100m/s corresponding to a Reynolds number of approximately 2.5×10^5. Fig. 2 represents the geometry design of the 1U CubeSat model with an elliptical fin configuration (left) and the geometry of the fluid domain around it (right). Fig. 3 shows the unstructured mesh distribution around the CubeSat model and its fluid domain for analysis. However, Fig. 4 demonstrates the boundary conditions applied for the simulations in the present study.

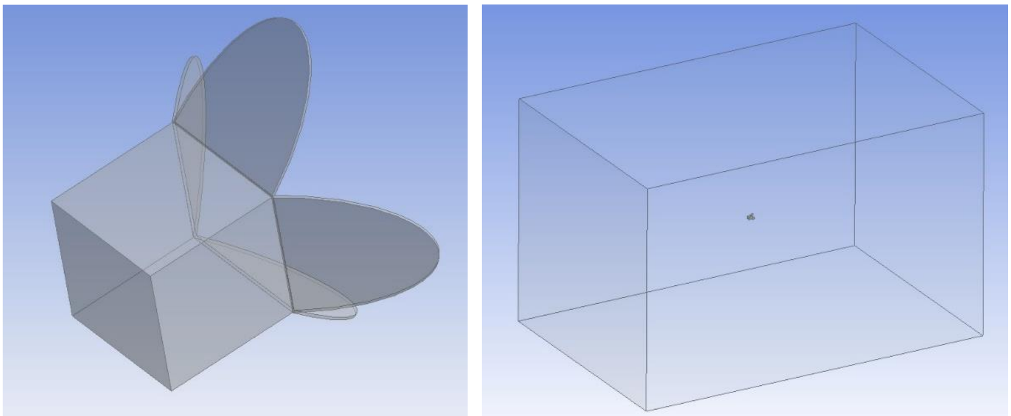

Figure-2 Geometry of (left) the optimized model (right) fluid domain around the optimized model

The flow field has been computed numerically by employing the finite volume method to solve the steady-state, two-dimensional Reynolds-averaged Navier-Stokes (RANS) equations. Pressure-velocity coupling is handled using the SIMPLEC (Semi-Implicit Method for Pressure-Linked Equations—Consistent) approach introduced by Van Doormaal and Raithby (1984). To model turbulence effects, the Shear Stress Transport (SST) $k-\omega$ model (Menter, 1993, 1994) is utilized, as it effectively captures near-wall flow behavior, particularly in the viscous sublayer. This model performs well in scenarios involving adverse pressure gradients and flow separation. However, it tends to predict excessive turbulence in regions with significant normal strain, such as stagnation points and areas experiencing strong acceleration. This tendency is quite less pronounced than in the $k-\omega$ model, though in the SST $k-\ \omega$ model, $k\ =\ TKE$ and $\omega\ =\ \varepsilon/k$ are the specific dissipation rate and ε = pseudo dissipation rate. The complete set of governing equations are:

$$\frac{\partial\bar{u}i}{\partial xi} = 0 \qquad (1)$$

$$\rho.\ \bar{u_j}\frac{\partial\bar{u}i}{\partial xj} = \frac{\partial}{\partial\bar{x}j}[-\bar{p}.\ \delta_{ij} + \mu(\frac{\partial\bar{u}i}{\partial\bar{x}j} + \frac{\partial\bar{u}j}{\partial\bar{x}i}) - \rho\overline{u_i'u_j'}] \qquad (2)$$

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k\, ui)}{\partial xi} = \frac{\partial}{\partial xj}[\Gamma_k\frac{\partial k}{\partial xj} + G_k - Y_k + S_k] \qquad (3)$$

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho\omega\, uj)}{\partial xj} = \frac{\partial}{\partial xj}[\Gamma\omega\frac{\partial\omega}{\partial xj}] + G_\omega - Y_\omega + D_\omega + S_\omega \qquad (4)$$

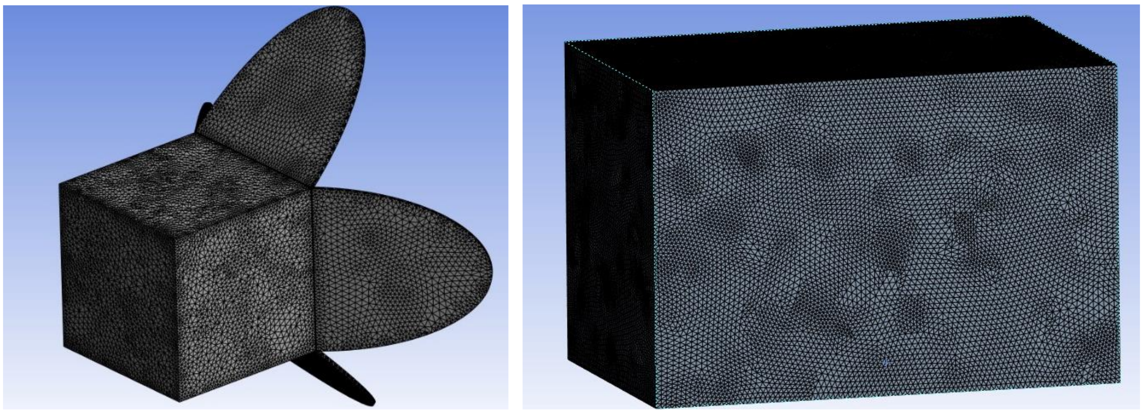

Figure-3 Unstructured grid distribution of (left) the CubeSat model (right) fluid domain

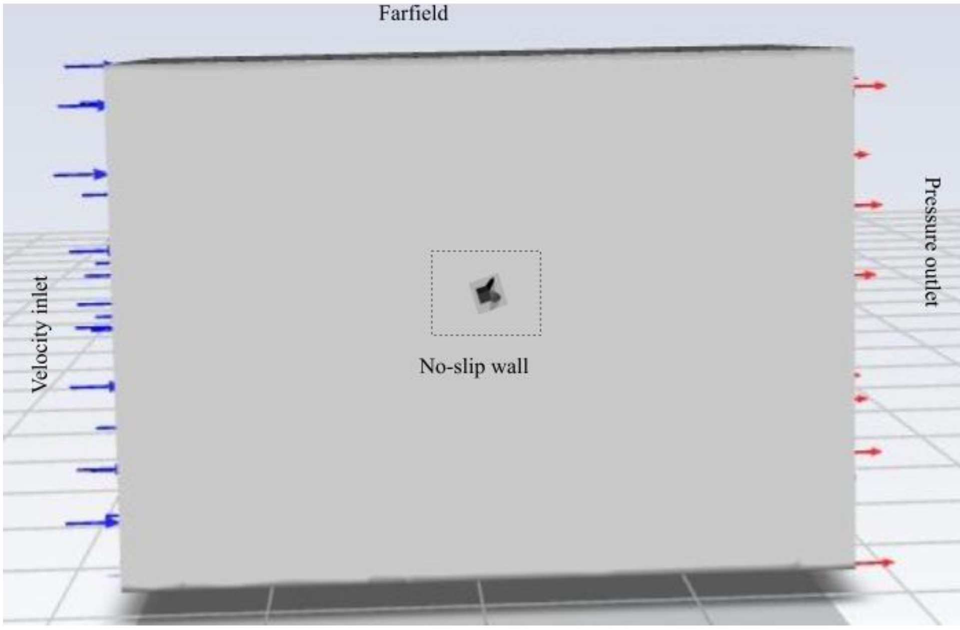

Figure-4 Boundary condition for the computation

3. Results and Discussion

A numerical simulation based on computational fluid dynamics (CFD) is conducted for a 1U CubeSat with two different fin-shape configurations. As a reference model, a square-shaped deployable fin configuration is considered. On the other hand, an elliptical-shaped fin configuration is proposed as an optimized model to achieve better aerodynamic efficiency and stability. The study investigates key aerodynamic parameters, including the drag coefficient and pressure coefficient distribution, under identical boundary conditions. This comparative analysis aims to identify the fin design that enhances CubeSat performance during lower-earth orbital (LEO) operations.

Fig. 5 shows that the drag coefficient decreases with an increase in freestream velocity for both cases driven by the reduction in pressure drag due to delayed flow separation and the effect of higher Reynolds numbers, which promote more efficient aerodynamic behavior. However, even if the trend is the same for both models, there is a significant drag difference which depicts the elliptical-shaped fin's noticeable aerodynamic efficiency. Cd increases slightly at lower free stream velocity due to lower Reynolds numbers, as flow separation becomes more prominent, especially for the square fins. For both fin shapes, at higher free stream velocity Cd decreases slightly as the flow stabilizes and separation points shift, especially for the elliptical fins.

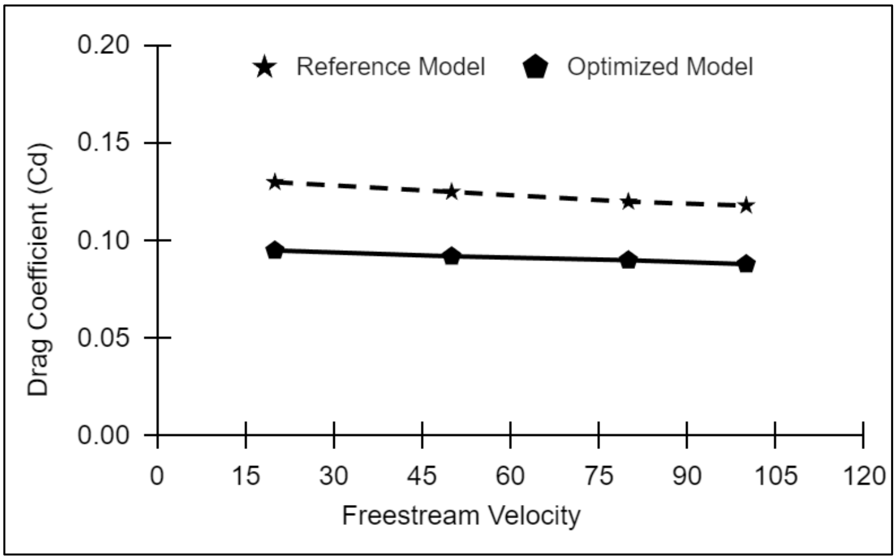

Figure-5 Comparison of drag coefficients for two different configurations

Fig. 6 shows the pressure coefficient distribution along the position axis for the CubeSat with square fins (top) and elliptical fins (bottom). Both graphs show a significant dip in the pressure coefficient, especially corresponding to a region where airflow accelerates or detaches around the fins. However, the square fins show a deeper and broader pressure drop than the elliptical fins. In addition, higher positive pressure on the leading side of the fins is observed for the square fin-shaped CubeSat. Greater negative pressure in the region where flow detaches or accelerates, possibly due to sharp edges that enhance flow separation. There is less pronounced positive pressure on the leading side of the elliptical fin-shaped CubeSat. A shallower and narrower pressure dip indicates smoother flow behavior and reduced separation. The square fins exhibit a more turbulent flow, leading to higher drag and greater instability. On the other hand, the elliptical fins show smoother and more stable flow behavior, reducing drag and improving aerodynamic efficiency.

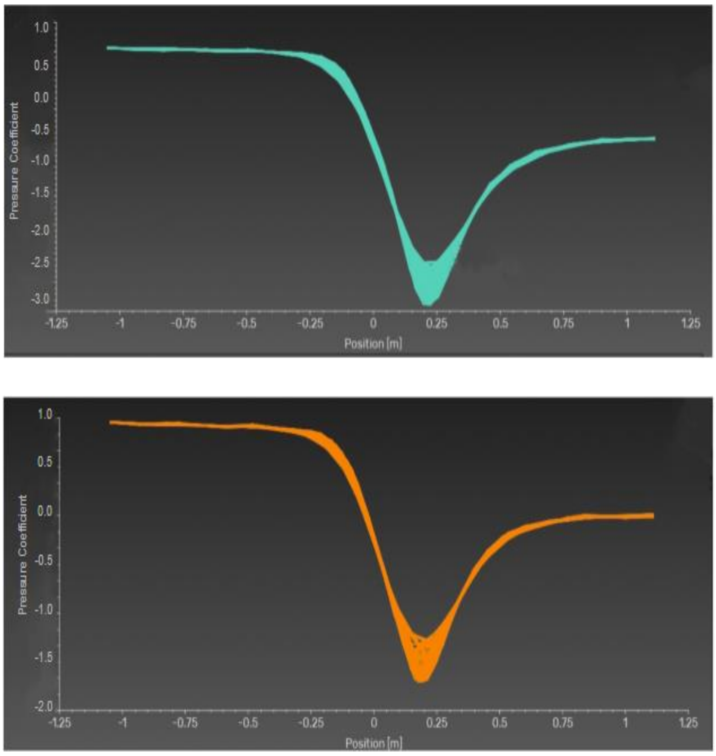

Figure-6 Pressure coefficient plot for (top) reference model (bottom) optimized model

Fig. 7 shows the static pressure distribution around two CubeSat designs with deployable square fins (left) and elliptical fins (right). The static pressure shows higher peaks near the stagnation points (front surfaces of the fins) and more pronounced low-pressure regions near the wake zones. There are distinct areas with large pressure gradients along the edges, indicating stronger flow disturbances and potential flow separation. The static pressure is more uniformly distributed for the elliptical fin model, with lower maximum pressure regions. This streamlined design contributes to lower drag, as the lower drag coefficient indicates. The uniform pressure distribution on the elliptical fin enhances aerodynamic efficiency. It potentially stabilizes the CubeSat during deployment whereas the uniform pressure distribution on the elliptical fin enhances aerodynamic efficiency and potentially stabilizes the CubeSat during deployment.

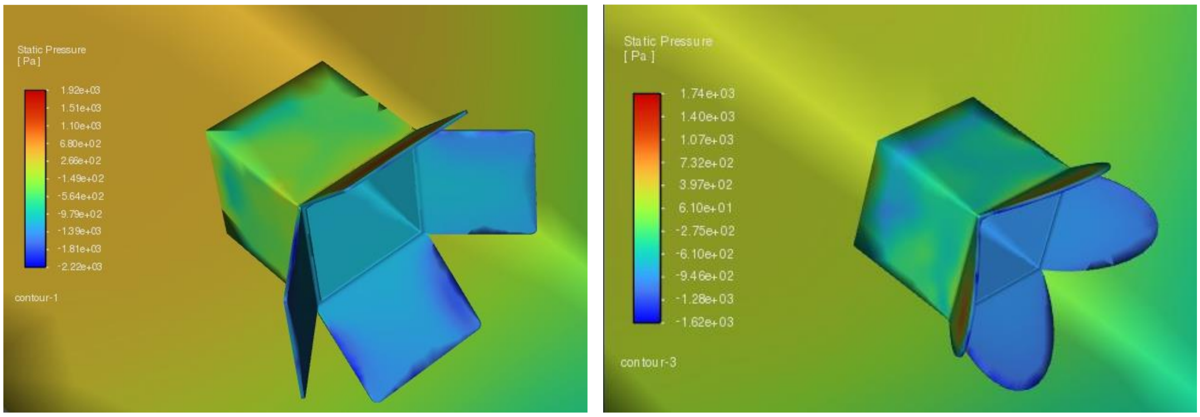

Figure-7 Comparison of static pressure contour for (left) reference model (right) optimized model

Fig. 8 shows the wall shear stress distribution around two CubeSat designs with deployable elliptical fins (right) and square fins (left). For the reference model, the wall shear stress is higher, with regions reaching up to 18.4 Pa. Sharp corners and edges create localized areas of high stress, particularly at the intersections of the fins and the CubeSat body. Higher wall shear stress indicates increased resistance to flow around sharp edges, contributing to a higher drag coefficient. For the optimized model, the wall shear stress is relatively lower, with maximum values around 10.3 Pa. Smooth, curved surfaces facilitate gradual flow separation and reduce high-stress zones compared to the square fin model. The absence of sharp corners leads to more streamlined interactions between the fins and the incoming flow. The absence of sharp corners leads to more streamlined interactions between the fins and the incoming flow.

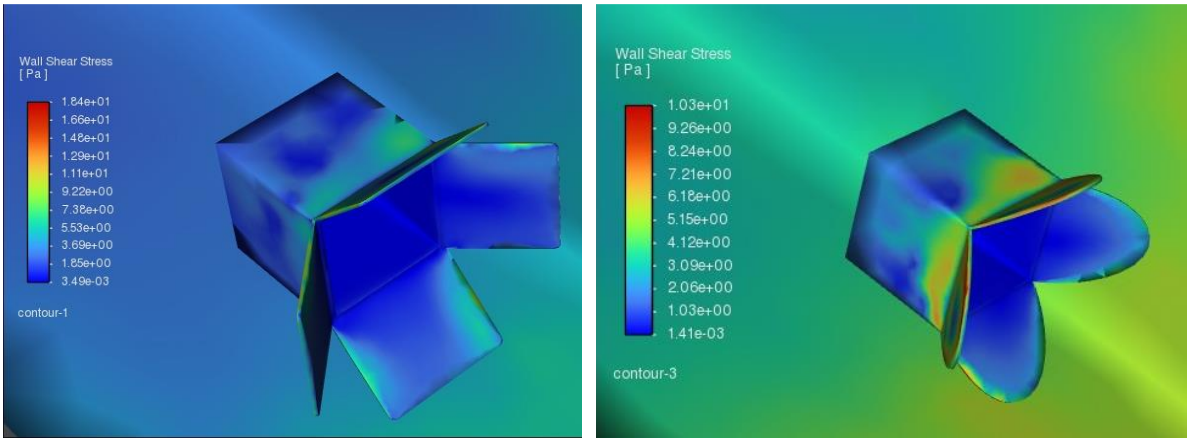

Figure-8 Comparison of wall shear stress for (left) reference model (right) optimized model

Fig. 9 depicts the turbulent kinetic energy (TKE) distribution around two CubeSat designs with deployable elliptical fins and square fins. TKE values are higher, with significant energy concentrations near the sharp edges of the square fins. Maximum TKE is higher (~286 m^2/s^2), indicating stronger turbulence generation. The sharp corners and edges of the square fins cause more flow separation and vortex shedding, contributing to increased turbulence. The sharp edges cause earlier flow separation, resulting in larger turbulent regions behind the fins. These turbulent regions can lead to increased drag and instability. For elliptical fin configuration, the TKE values are more uniformly distributed across the flow field, with lower energy concentrations around the CubeSat. Maximum TKE is slightly lower (~244 m^2/s^2) than the square fin configuration (~286 m^2/s^2). The smoother, rounded design of elliptical fins minimizes abrupt flow separation, leading to a reduction in turbulent energy production. The flow remains relatively attached to the fins for a longer distance, as indicated by smoother gradients in TKE. Reduced flow disturbances are beneficial for maintaining stability and lowering aerodynamic drag.

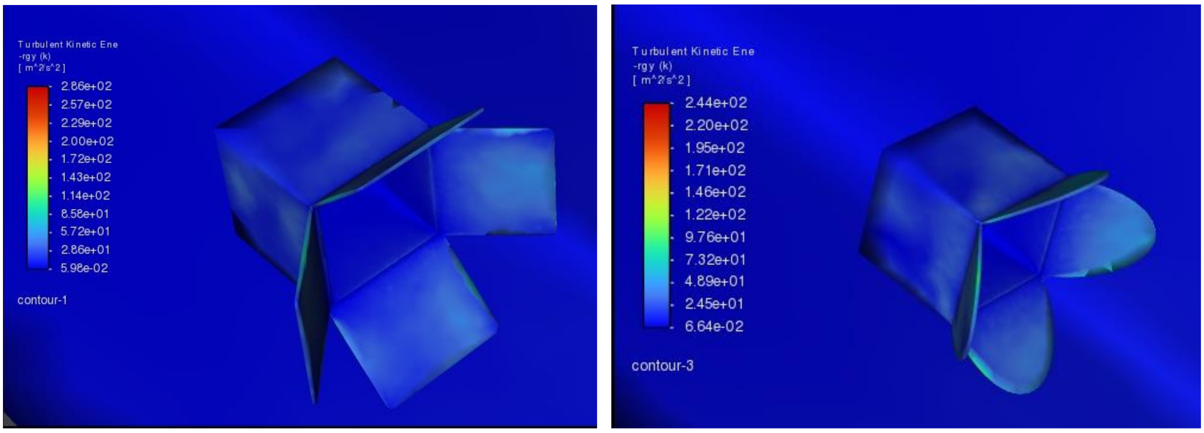

Figure-9 Comparison of turbulent kinetic energy for (left) reference model (right) optimized model

Fig. 10 (left) displays more intricate flow structures, potentially with higher turbulence or vortex formation whereas the other plot (right) shows a more elongated and smoother flow field, indicating reduced flow separation. The blunt geometry of the square fins causes increased drag and wake turbulence, lowering aerodynamic efficiency. However, the elliptical fins end to minimize drag due to their streamlined shape, resulting in better aerodynamic efficiency. The smoother flow distribution of the elliptical fins suggests better stability, as reduced turbulence would likely minimize oscillations and chaotic motion whereas in square-shaped fin configuration, higher turbulence and complex wake patterns might destabilize the CubeSat during deployment or operation.

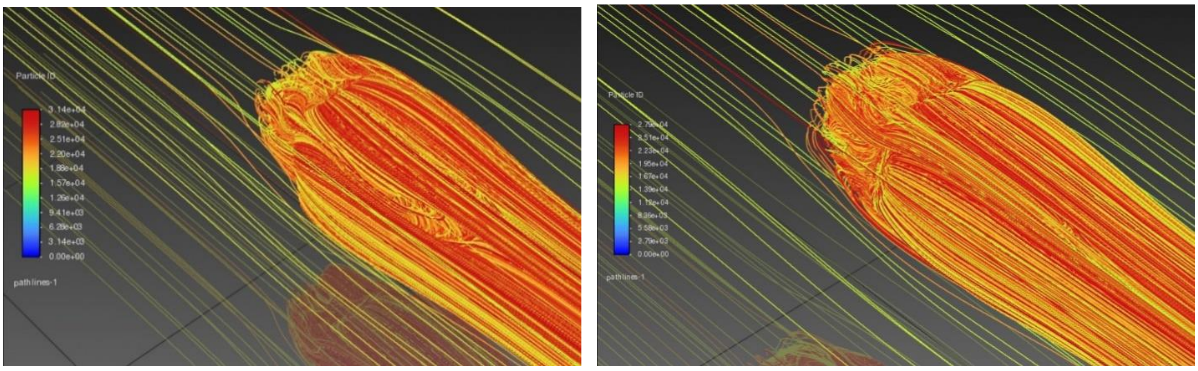

Figure-10 Comparison of flow pattern for (left) reference model (right) optimized model

Fig. 11 shows the velocity vector field distribution around two CubeSat designs with deployable square fins (left) and elliptical fins (right). For square fins, the velocity field indicates more prominent velocity gradients, especially at the fin edges. The abrupt geometric transitions of the square fins create more flow separation and localized turbulence, leading to higher drag. The wake region behind the CubeSat is more chaotic and broader due to increased flow separation at the sharp corners of the square fins. For elliptical fins, the velocity field shows smoother transitions around the fins, with less abrupt changes in velocity magnitudes. This suggests a more streamlined flow around the elliptical geometry, reducing flow disturbances and drag. The flow remains attached for a longer distance along the fins, and the wake region appears less turbulent and narrower, which is beneficial for aerodynamic performance. Both models have velocity peaks around the leading edges, but the elliptical fins manage the flow more effectively, maintaining higher velocities near the surfaces compared to the square fins, which experience more deceleration due to separation effects. The elliptical fins exhibit superior aerodynamic performance by reducing drag and turbulence intensity compared to the square fins.

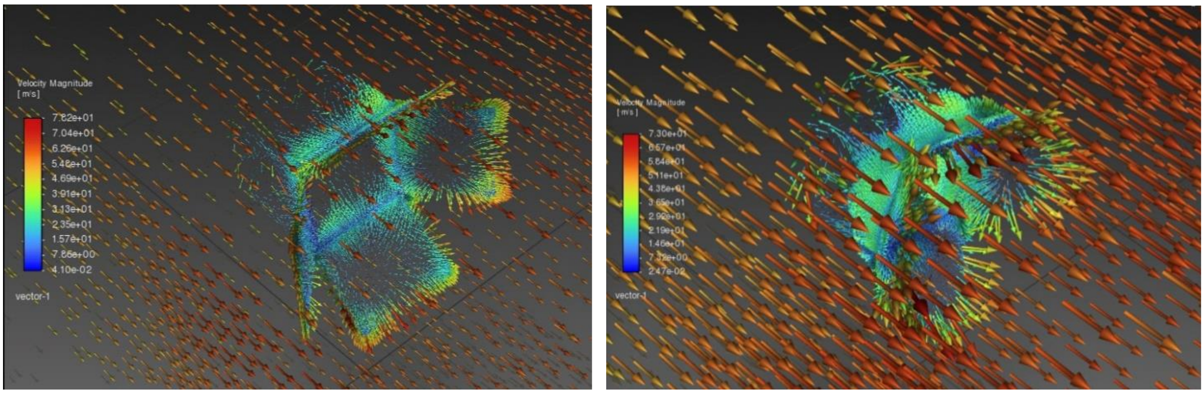

Figure-11 Comparison of velocity vector field for (left) reference model (right) optimized model

4. Gimballing Spacecraft Thruster

This study employed numerical analysis utilizing computational fluid dynamics (CFD) simulations to analyze the aerodynamic performance of a 1U CubeSat equipped with deployable fins. Two distinct fin geometries, square and elliptical, were modeled and evaluated under identical boundary conditions to ensure an insightful comparison. The simulations captured detailed flow dynamics, including velocity fields, pressure distributions, and wake characteristics, to assess how each design interacts with the surrounding airflow. Particular attention was given to calculating drag coefficients (C_d) and observing pressure coefficient (C_p) variations across the fin surfaces to provide a comprehensive understanding of the aerodynamic behavior of both configurations.

The results reveal that the elliptical fin design significantly outperformed the square fins in terms of aerodynamic efficiency. The elliptical fins achieved a 26% reduction in drag coefficient (C_d), highlighting their ability to minimize resistance and streamline the airflow around the CubeSat. The pressure coefficient distribution further underscored the advantages of elliptical geometry, with smoother flow patterns and reduced flow separation compared to the square fins. This streamlined performance not only enhances CubeSat stability but also contributes to improved orbital lifespan and reduced chaotic motion, making the elliptical fin design a superior choice for applications requiring optimal aerodynamic performance.

While this study effectively highlights the aerodynamic advantages of elliptical fins over square fins for a 1U CubeSat, certain limitations present opportunities for further research. The analysis was performed under steady-state flow conditions and did not account for the influence of transient effects, such as variable atmospheric densities or dynamic CubeSat orientations during orbital maneuvers. Additionally, material properties and structural considerations of the fins were not included, which could affect their deployment efficiency and overall performance. Future work could explore these aspects, incorporating transient simulations, structural analysis, and thermal loads to provide a more comprehensive understanding of the design's viability in real-world orbital conditions. Investigating additional fin geometries or hybrid designs, as well as optimizing fin size and deployment mechanisms, could further enhance CubeSat stability and drag reduction. Experimental validation through wind tunnel testing or suborbital flight tests would also strengthen the reliability of these computational findings, paving the way for more robust CubeSat designs.

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6. Conflict of Interest

The author declares no competing conflict of interest.