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A Review on Drag Reduction and Stability Optimization Techniques for Small Satellite Launch Vehicles

Yaddala Somasekhar*

ORCID: 0009-0004-6389-7713

Dhanalakshmi Srinivasan College of Engineering and Technology, Mahabalipuram, Tamil Nadu

Abstract: Small satellite launch vehicles have become increasingly critical in the space industry, providing dedicated, cost-effective access to space for a variety of missions, including commercial, scientific, and defense applications. As the demand for small satellites continues to rise, there is a growing need to optimize the design of small launch vehicles, particularly in terms of aerodynamic performance. The aerodynamic forces acting on these vehicles, such as drag and stability, play a crucial role in determining their overall efficiency and ability to reach the desired orbit. Traditional approaches to stabilizing rockets have relied on the use of fins, which, while effective in maintaining stability, also introduce significant drag, thereby reducing fuel efficiency and overall vehicle performance. This paper explores innovative strategies to reduce aerodynamic drag while maintaining or enhancing stability in small launch vehicles. The focus is on refining fin designs and investigating alternative stabilization methods, such as perpendicular thrust, to achieve these goals. By addressing these aerodynamic challenges, the paper aims to contribute to the development of more efficient and effective small satellite launch vehicles, ultimately improving access to space. The study leverages both theoretical analysis and computational fluid dynamics (CFD) simulations to evaluate the proposed designs and methods. Initial results indicate that the strategic redesign of fins, coupled with the integration of perpendicular thrust mechanisms, can lead to a substantial reduction in drag without compromising stability. These findings suggest that the adoption of these innovations could pave the way for more advanced small launch vehicles capable of meeting the growing demands of the space industry.

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1. Introduction

Small satellite launch vehicles have emerged as pivotal instruments in the rapidly expanding space industry, particularly in the deployment of small payloads such as CubeSats and microsatellites. These launch vehicles are specifically designed to offer cost-effective, reliable access to space for commercial, scientific, and defence purposes. The increased demand for small satellites, driven by their applications in Earth observation, communications, and scientific research, has necessitated the development of dedicated small launch vehicles that can cater to the unique requirements of these missions. The design of small launch vehicles presents several engineering challenges, primarily due to the constraints of size, weight, and cost. Aerodynamic forces, including drag and stability, are critical factors that influence the performance of these vehicles. The drag force, which opposes the vehicle's motion through the atmosphere, is a significant concern as it directly impacts fuel efficiency and the vehicle's ability to reach orbit. On the other hand, maintaining stability is essential to ensure the vehicle's flight path remains controlled and aligned with its intended trajectory. Historically, the aerodynamic design of rockets has relied heavily on the use of fins to provide stability during flight. However, fins also contribute to increased drag, which can hinder the vehicle's performance. This paper aims to explore innovative methods for

*UG Research Scholar, Dhanalakshmi Srinivasan College of Engineering and Technology, Mahabalipuram, Tamil Nadu. **Corresponding Author: yaddalasomasekhar112@gmail.com.**
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reducing drag while maintaining stability, particularly through modifications to fin design and the introduction of novel concepts such as "perpendicular thrust" for stability control. By addressing these challenges, the goal is to enhance the efficiency and effectiveness of small launch vehicles, enabling them to achieve faster and more reliable access to space [1-2].

2. Overview of Small Satellite Launch Vehicles

Small launch vehicles are a crucial component of the modern space industry, tailored to meet the growing demand for launching small satellites into low Earth orbit (LEO) and beyond. These vehicles are typically characterized by their smaller size, reduced payload capacity, and lower launch costs compared to traditional heavy-lift launchers. The following is an overview of some notable small launch vehicles that have been developed and deployed over the years [1]:

- **Northrop Grumman Pegasus (XL):** First launched in 1990, the Pegasus is an air-launched rocket capable of delivering payloads of up to 443 kg to low Earth orbit. With 45 successful launches, it has established itself as a reliable platform for small satellite deployment.
- **MITT Start-1:** This Russian launch vehicle, first launched in 1993, has a payload capacity of 167 kg and has conducted seven launches. Although less prolific than others, it has contributed to the diversification of small satellite launch options.
- **SpaceX Falcon-1/Falcon-1e:** SpaceX's entry into the small satellite launch market, the Falcon-1, first launched in 2006, could carry payloads of up to 1000 kg. Despite a relatively low number of launches, it was a significant milestone in the development of commercial spaceflight.
- **Rocket Lab Electron:** Since its first launch in 2017, the Electron has become one of the most prominent small launch vehicles, with 48 launches to date. It offers a cost-effective solution with a payload capacity of 200 kg and is known for its rapid launch cadence.
- **ISRO SSLV:** The Indian Space Research Organisation (ISRO) developed the Small Satellite Launch Vehicle (SSLV) to cater to the growing demand for small satellite launches. First launched in 2022, the SSLV can carry payloads of up to 500 kg and is priced competitively at $4.2 million per launch.
- **Relativity Terran 1:** An innovative small launch vehicle developed by Relativity Space, the Terran 1, which debuted in 2023, features 3D-printed components and has a payload capacity of 900 kg. It represents a significant advancement in the use of additive manufacturing in rocketry.

These vehicles represent a diverse range of approaches to small satellite launch, each tailored to specific mission requirements and market segments. The development of these vehicles has been driven by the need for more flexible and affordable access to space, enabling a wide array of missions that were previously cost-prohibitive with traditional launch vehicles. However, despite the progress made in small launch vehicle development, challenges remain. The aerodynamic design of these vehicles, particularly in terms of drag and stability, continues to be a critical area of research and innovation. As the industry evolves, there is a growing need for solutions that can further reduce drag, improve fuel efficiency, and enhance the overall performance of small launch vehicles. This paper seeks to contribute to this ongoing effort by exploring novel ideas and methodologies for optimizing the design of small launch vehicles, with a focus on reducing drag and improving stability through innovative fin designs and alternative stabilization techniques [2].

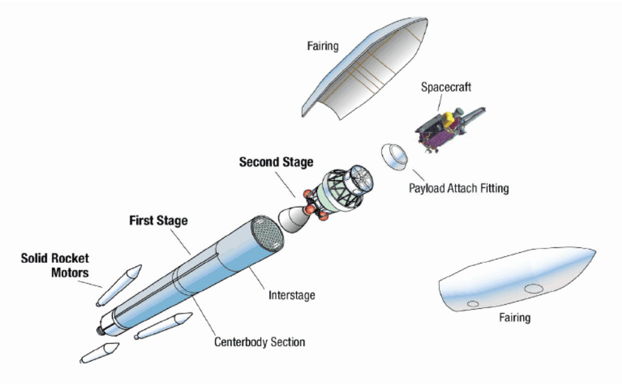

Figure-1 Components of a Launch Vehicle [Image Courtesy: Vajiraman.et.al.2024]

Table-1 Comparison of Small Satellite Lunch Vehicles of Global Space Agencies [1]

Organization	Launcher	First launch	Launches	Cost	Payload (kg)
Northrop Grumman	Pegasus (XL)	1990	45	$56M	443kg
MITT	Start-1	1993	7	-	167kg
Northrop Grumman	Minotuar c (taurus-11)	1994	12	$50M	1045kg
Lockheed Martian	Athena-1	1995	4	$17M	794kg
Lockheed Martian	Athena-2	1998	2	$65M	1165kg
Makeyev OKB	Shtil	1998	2	-	160kg
Northrup grumman	Minotar-1	2000	12	-	331kg
Casc	Kaituozhe-1(kT-1)	2002	2		100kg
Spacex	Falcon-1\Falcon-1e	2006	5	$11M	1000kg
Kari	Naro (KSLV-1)	2009	3	-	100kg
Aerojet Rocketdyne	Spark/ super strypi	2015	1	$15M	300KG
Calt	Longmarch 11 (CZ-11, SD-2)	2015	17	-	350KG
CASC	Long March -6	2015	11	-	1080kg
CASC	Kaituozhe-2 (KT-2)	2017	1	-	800kg
JAXA	SS-520-4	2017	2	$3.5M	4kg
ROCKET LAB	Electron	2017	48	$7.8M	200kg
ExPace /CASIC	Kuaizhou-1A	2017	26	$6M	300kg
LandSpace	ZQ-1	2018	1	-	200kg
China Rocket	Smart Dragon-1	2019	1	$6M	150kg
i-Space	Hyperbola-1	2019	6	$5M	300kg
One Space	OS-M	2019	1	$4.7M	112kg
Astra	Rocket - 3	2020	7	$2.5M	150kg
ExPace / CASIC	Kuaizhou-11 (KZ-11)	2020	3	$10M	1000kg
Galactic Energy	Ceres-1	2020	13	$4.5M	300kg
Virgin Orbit	LauncherOne	2020	6	$12M	300kg
Firefly	Alpha	2021	4	$15M	630kg
KARI	Nuri (KSLV-2)	2021	3	$30M	1500kg
CAS Space	Kinetica-1 (ZK-1, Zhongke-1, Lijian-1)	2022	3	-	1330Kg
China Rocket	Jielong-3 (Smart Dragon-3)	2022	3	-	150kg
ISRO	SSLV	2022	2	$4.2M	500kg
LandSpace	Zhuque-2 (ZQ-2)	2022	3	-	1500kg
Space Pioneer	Tianlong-2	2023	1	-	1500kg
ABL	RS1	2023	1	$12M	1000Kg
Relativity	Terran 1	2023	1	$12M	900Kg
Space One	KAIROS	2024	1	-	150Kg

3. Literature Review

The aerodynamic design of launch vehicles has been a subject of extensive research since the early days of rocketry. The fundamental principles governing the flight of rockets, such as drag, lift, and stability, have been well established, with various studies exploring ways to optimize these parameters for improved performance. In the context of small satellite launch vehicles, where size, weight, and cost are critical factors, the challenge of reducing aerodynamic drag while maintaining stability becomes even more pronounced [3-6].

3.1 Drag Reduction in Launch Vehicles

Drag, the resistive force experienced by a vehicle as it moves through the atmosphere, is a major concern for rocket designers. The reduction of drag is essential for improving the vehicle's fuel efficiency, enabling it to reach higher altitudes or carry larger payloads. Several strategies have been proposed and implemented over the years to minimize drag in launch vehicles:

- **Streamlined Body Shapes:** One of the most common methods of reducing drag is through the design of streamlined body shapes, which minimize the frontal area exposed to the airflow and reduce turbulent flow around the vehicle. Studies by *Anderson (1999)* and *Hoerner (1965)* highlight the importance of body shaping in reducing drag and enhancing overall vehicle performance.
- **Nose Cone Designs:** The shape of the nose cone plays a significant role in determining the drag experienced by a launch vehicle. *Nielsen et al. (2010)* conducted extensive research on various nose cone shapes, concluding that ogive and parabolic shapes are particularly effective in minimizing drag.
- **Boundary Layer Control:** Techniques such as boundary layer tripping and the use of vortex generators have been explored to reduce drag by delaying flow separation. *Smith and Moffatt (2002)* demonstrated that these techniques could lead to a marked reduction in drag, particularly at supersonic speeds.

However, while these strategies have proven effective in traditional rockets, their application to small launch vehicles presents unique challenges due to the different scale and operational environments. There is a need for more specialized research focused on drag reduction techniques tailored to small launch vehicles.

3.2 Stability and Control

Stability is a critical aspect of launch vehicle design, ensuring that the vehicle follows its intended flight path without excessive deviation. Fins have traditionally been used to provide aerodynamic stability, particularly during the early stages of flight when the vehicle is still within the atmosphere:

- **Traditional Fin Designs:** The use of fins to stabilize rockets dates back to the early days of rocketry. Research by *Barrowman (1966)* established the mathematical foundation for predicting the stability of rockets using fin parameters such as size, shape, and placement. The Barrowman equations remain a cornerstone in the design of fin-stabilized rockets.
- **Canard Configurations:** Some launch vehicles use canard configurations, where smaller fins are placed near the nose of the vehicle, to improve maneuverability and control. Studies by *Blair and Wagner (2007)* have shown that canard designs can enhance stability, though they also tend to increase drag.
- **Active Control Systems:** In modern launch vehicles, active control systems, such as gimballed engines and reaction control thrusters, are often used in conjunction with or instead of fins to provide stability and control. *Ward (2011)* discussed the evolution of these systems, highlighting their increasing importance in maintaining stability without the drag penalties associated with large fins.

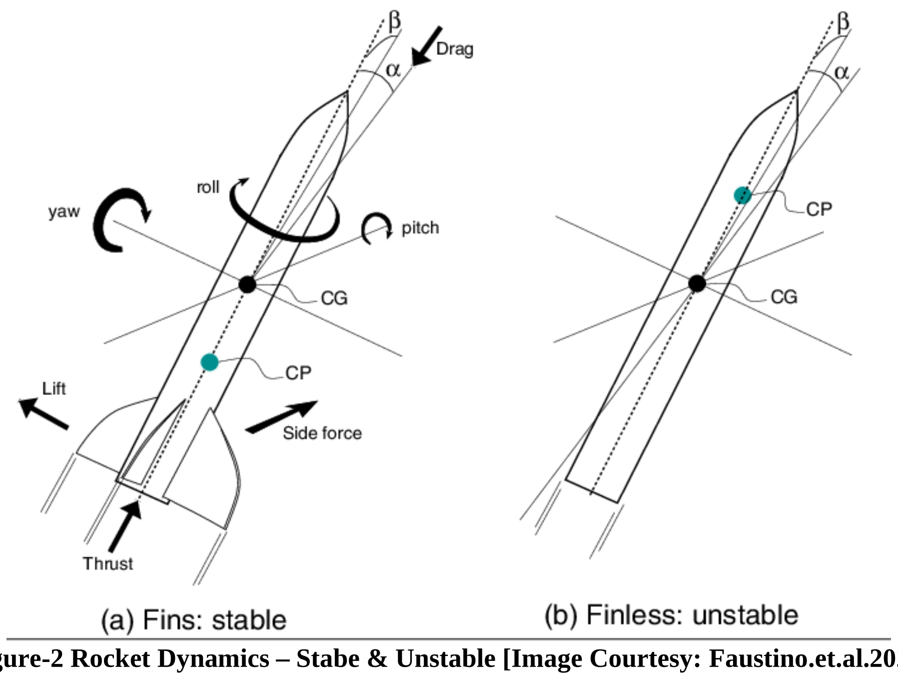

Figure-2 Rocket Dynamics – Stabe & Unstable [Image Courtesy: Faustino.et.al.2022]

3.3 Emerging Techniques in Small Launch Vehicles

The advent of small satellite missions has driven innovation in the design of launch vehicles specifically tailored for these payloads. Given the constraints of size and cost, there has been significant interest in exploring new methods for reducing drag and improving stability without resorting to traditional large fin designs:

- **Perpendicular Thrust for Stability:** One emerging concept is the use of perpendicular thrust mechanisms, where small thrusters are used to control the vehicle's attitude and maintain stability. *Jin et al. (2015)* explored this concept in the context of spaceplanes, showing that it can provide effective stabilization with minimal impact on drag.
- **Innovative Fin Designs:** Advances in materials and computational modeling have enabled the exploration of non-traditional fin designs, such as adaptive fins that can change shape in response to flight conditions. *Larsen and Schmidt (2018)* investigated the potential of such designs to reduce drag while providing adequate stability, with promising results.
- **Drag Reduction via Aerospike Nozzles:** Aerospike nozzles, known for their ability to maintain efficiency at varying altitudes, have been studied as a potential means of reducing base drag in small launch vehicles. *Rockwell and Kratz (2019)* demonstrated that aerospike nozzles could significantly reduce drag compared to traditional bell nozzles, particularly during the transonic and supersonic phases of flight.

This literature review highlights the extensive research that has been conducted on the aerodynamic design of launch vehicles, with a particular focus on drag reduction and stability. While traditional methods have proven effective for larger rockets, the unique challenges of small launch vehicles necessitate further innovation. This paper seeks to build on the existing body of knowledge by exploring new approaches to reducing drag and enhancing stability in small launch vehicles, with the goal of improving their overall performance and accessibility.

4. Aerodynamic Analysis

Aerodynamic analysis is a critical component in the design and optimization of small satellite launch vehicles. This analysis focuses on understanding the forces and moments acting on the vehicle as it travels through the atmosphere, which directly impacts performance, stability, and fuel efficiency **[4]**.

4.1 Drag Force Components

The drag force experienced by a launch vehicle is composed of several components, each influenced by different aspects of the vehicle's geometry and flight conditions **[5-7]**:

- **Skin Friction Drag:** This is caused by the friction of air molecules sliding over the surface of the vehicle. Skin friction drag is directly proportional to the surface area exposed to airflow and the smoothness of the surface. Even minor surface imperfections can contribute to significant drag, making surface treatment and material selection crucial in minimizing this force.

- **Pressure Drag:** Also known as form drag, pressure drag results from the differential pressure between the front and rear of the vehicle as it moves through the atmosphere. Streamlining the body and using aerodynamically optimized shapes, such as pointed nose cones and tapered bodies, can reduce pressure drag significantly.

- **Wave Drag:** At supersonic speeds, the formation of shock waves around the vehicle leads to wave drag. This type of drag is especially relevant for launch vehicles, which must pass through various speed regimes as they ascend. The design of nose cones, body shapes, and fin configurations must account for wave drag to avoid excessive fuel consumption and potential instability during high-speed flight.

- **Base Drag:** This occurs due to the low-pressure wake that forms behind the vehicle, particularly in the region aft of the main propulsion system. The design of the rear section, including the nozzle and any base features, is critical in mitigating base drag. Aerospike nozzles and boat-tailing are among the methods explored to reduce this component of drag.

4.2 Stability Considerations

In addition to minimizing drag, ensuring the stability of the vehicle throughout its flight trajectory is essential. Aerodynamic stability is primarily concerned with the vehicle's ability to maintain or return to a desired flight path without excessive oscillations or deviations:

- **Static Stability:** This refers to the vehicle's natural tendency to return to its original flight path after a small disturbance. Static stability is influenced by the placement of the center of pressure (CP) relative to the center of gravity (CG). For a launch vehicle to be statically stable, the CP should be located behind the CG. Fin placement and size play a significant role in achieving the desired static stability.

- **Dynamic Stability:** Dynamic stability involves the vehicle's response over time to disturbances, considering factors such as damping and oscillation frequency. The aerodynamic design must ensure that any oscillations are quickly damped, preventing resonance or uncontrollable movements. Computational simulations are often employed to analyze dynamic stability, providing insights into how design changes affect the vehicle's behavior under various flight conditions.

4.3 Computational Fluid Dynamics (CFD) Analysis

To thoroughly understand and optimize the aerodynamic performance of small launch vehicles, this study employs Computational Fluid Dynamics (CFD) as a primary analytical tool. CFD allows for detailed simulations of airflow around the vehicle, capturing the effects of various design elements on drag, lift, and stability **[8-14]**:

- **Meshing and Grid Generation:** High-quality meshing is essential for accurate CFD results. The study uses a combination of structured and unstructured grids to model the complex geometries of the vehicle, including the nose cone, fins, and propulsion system. Fine meshing is applied in regions where high gradients in pressure and velocity are expected, such as near the shock waves and boundary layers.

- **Turbulence Modeling:** Given the importance of accurately predicting drag and stability, turbulence models such as the k-ε or k-ω models are utilized to simulate the turbulent flow conditions experienced by the vehicle. These models help in predicting the onset of flow separation and the formation of vortices, which are critical for understanding drag forces.

- **Simulation Scenarios:** The CFD simulations cover a range of flight conditions, including subsonic, transonic, and supersonic speeds. By analyzing the vehicle's aerodynamic performance across these regimes, the study identifies design modifications that can optimize drag reduction and stability throughout the entire flight profile.

5. Methodology

The methodology of this study is designed to systematically evaluate and optimize the aerodynamic performance of small satellite launch vehicles. The approach integrates theoretical analysis, computational modeling, and experimental validation to achieve comprehensive results.

5.1 Conceptual Design and Initial Analysis

The first step in the methodology involves the conceptual design of the launch vehicle, focusing on the overall geometry, including the shape of the body, nose cone, and fins. The initial design is informed by existing literature and established aerodynamic principles, ensuring a balance between drag reduction and stability.

- **Preliminary Calculations:** Theoretical calculations are performed to estimate key aerodynamic parameters, such as drag coefficients and stability margins, based on the initial design. These calculations provide a baseline understanding of the vehicle's performance and guide the subsequent CFD analysis.
- **Material Selection:** The choice of materials plays a significant role in both the aerodynamic performance and structural integrity of the vehicle. The study considers lightweight, high-strength materials that offer smooth surface finishes to minimize skin friction drag.

5.2 CFD Simulation Process

Following the initial analysis, the design is subjected to detailed CFD simulations. This phase of the methodology is crucial for identifying potential areas of improvement in the vehicle's design:

- **Modeling and Meshing:** The vehicle's geometry is modeled in a CFD environment, with careful attention to meshing quality. The study employs advanced meshing techniques to capture intricate details of the design, particularly around the fins and propulsion system.
- **Boundary Conditions and Solver Settings:** Appropriate boundary conditions are applied to simulate the atmospheric environment through which the vehicle will travel. Solver settings are chosen based on the expected flow regime, with particular focus on ensuring accurate turbulence modeling and shock wave capture.
- **Parametric Studies:** The CFD simulations include parametric studies where various design variables, such as fin shape, size, and placement, are systematically varied. These studies help identify configurations that minimize drag while maintaining or enhancing stability.

5.3 Experimental Validation

To validate the CFD results and ensure their accuracy, experimental testing is conducted using wind tunnel facilities:

- **Scale Model Testing:** A scaled-down model of the launch vehicle is fabricated using rapid prototyping techniques. The model is tested in a wind tunnel across a range of Mach numbers to replicate the conditions experienced during flight.
- **Data Acquisition:** Measurements of drag force, lift force, and moments are taken during the wind tunnel tests. These data are compared with the CFD predictions to assess the accuracy of the simulations and refine the computational models as necessary.
- **Flow Visualization:** Flow visualization techniques, such as smoke trails or laser-based methods, are used to observe the airflow patterns around the vehicle. This provides qualitative insights into phenomena like flow separation and vortex formation, which are critical for understanding the vehicle's aerodynamic behavior

6. Innovations and Advancing Ideas

The innovative ideas explored in this study focus on pushing the boundaries of traditional aerodynamic design to create more efficient and effective small satellite launch vehicles. These innovations are aimed at reducing drag, enhancing stability, and ultimately improving the overall performance of the vehicle **[16-18]**.

6.1 Adaptive Fin Designs

One of the key innovations explored is the concept of adaptive fins. Unlike traditional fixed fins, adaptive fins can change their shape or orientation in response to different flight conditions:

- **Morphing Fins:** These fins are designed to alter their shape based on aerodynamic loads. For instance, during low-speed flight, the fins might extend to provide maximum stability, while at higher speeds, they could retract or change angle to reduce drag. This adaptability allows the vehicle to maintain optimal performance throughout its ascent.
- **Smart Materials:** The use of smart materials, such as shape-memory alloys or piezoelectric materials, enables the fins to morph in real-time. These materials respond to external stimuli, such as temperature changes or electrical signals, allowing for precise control over fin shape and orientation.
- **Control Systems Integration:** Adaptive fins are integrated with the vehicle's control systems, enabling real-time adjustments based on sensor feedback. This integration ensures that the vehicle remains stable and efficient, even in the presence of unexpected disturbances or changing atmospheric conditions.

6.2 Perpendicular Thrust Mechanisms

To further reduce reliance on traditional fins for stability, the study investigates the use of perpendicular thrust mechanisms. These systems employ small thrusters strategically placed around the vehicle to provide stability and control:

- **Reaction Control Thrusters (RCTs):** RCTs are commonly used in spacecraft for attitude control, but their application in launch vehicles is relatively novel. By firing short bursts of thrust in directions perpendicular to the main axis, these thrusters can correct any deviations from the intended flight path without the need for large aerodynamic surfaces.
- **Integration with Main Propulsion:** The perpendicular thrust system is integrated with the main propulsion system, allowing for coordinated control of the vehicle's trajectory. This integration is particularly beneficial during the transonic and supersonic phases of flight, where traditional fins may be less effective or introduce excessive drag.
- **Fuel Efficiency Considerations:** While the use of RCTs adds complexity to the vehicle design, the potential drag reduction and increased stability may offset the additional fuel required for these thrusters. The study examines the trade-offs involved and explores optimization strategies to maximize overall efficiency.

6.3 Advanced Nose Cone Designs

The design of the nose cone is critical for minimizing drag and improving the aerodynamic performance of the vehicle. This study explores advanced nose cone designs that go beyond traditional shapes:

- **Aerospike Nose Cones:** Drawing inspiration from aerospike nozzles, aerospike nose cones are designed to maintain aerodynamic efficiency across a wide range of speeds and altitudes. These designs help reduce wave drag by minimizing shock wave formation, particularly during the supersonic phase of flight.
- **Variable Geometry Nose Cones:** Similar to adaptive fins, variable geometry nose cones can change shape during flight to optimize aerodynamic performance. For instance, the nose cone could elongate at higher speeds to reduce drag or blunt during re-entry to improve thermal protection.
- **Laminar Flow Enhancement:** The study explores methods to enhance laminar flow over the nose cone, such as using riblets or surface coatings that reduce turbulent flow. Maintaining laminar flow reduces skin friction drag and improves overall aerodynamic efficiency.

6.4 Base Drag Reduction Techniques

Addressing base drag is another area of innovation in this study. The rear section of the vehicle, particularly around the nozzle, is a major contributor to base drag:

- **Boat-Tailing:** The study explores the use of boat-tailing, where the rear of the vehicle tapers inward, reducing the wake size and thus base drag. This design is optimized through CFD simulations to ensure minimal impact on the vehicle's stability and propulsion efficiency.
- **Aerospike Nozzles:** As mentioned in the aerodynamic analysis, aerospike nozzles are known for their ability to maintain efficiency across varying altitudes. Their use in small launch vehicles could significantly reduce base drag, particularly during the critical transonic phase.
- **Base Bleed:** Base bleed involves ejecting a small amount of gas at the base of the vehicle to fill the low-pressure wake, thereby reducing base drag. This technique, often used in artillery shells, is adapted for use in launch vehicles to enhance aerodynamic performance.

7. Conclusion

Developing small satellite launch vehicles is a complex but crucial task in aerospace engineering. This study focused on optimizing the aerodynamic performance of these vehicles to improve efficiency, stability, and mission success. We identified key drag contributors—skin friction, pressure drag, wave drag, and base drag—and explored methods to reduce them. Emphasizing the importance of static and dynamic stability, we examined center of pressure placement and advanced fin designs. Our approach included theoretical analysis, CFD simulations, and experimental validation, providing a solid framework for refining vehicle design. High-fidelity CFD models and wind tunnel testing enabled precise aerodynamic predictions. Innovative concepts like adaptive fins, perpendicular thrust mechanisms, and advanced nose cones were proposed to reduce drag and enhance stability. The study suggests practical solutions and innovations for future designs, potentially improving the cost-effectiveness and reliability of small satellite launch vehicles. Continued research and collaboration will be key to further refining these innovations for next-generation launch vehicles.

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9. Conflict of Interest

The author declares no competing conflict of interest.

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