Acceleron Aerospace Journal || AAJ.11.2106-2436
Volume 3, Issue 2, pp (419-426)
Review Paper
E-ISSN- 2583-9942 || DOI: 10.61359/11.2106-2436

Aerodynamic Optimization of Small Launch Vehicles: Challenges, Design Considerations, and Future Trends

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Abstract: This study explores the aerodynamics of small launch vehicles with the goal of enhancing efficiency and minimizing aerodynamic challenges. It delves into various lift and drag principles and the unique challenges faced by small vehicles tasked with carrying satellites into space. The research highlights optimization approaches that can be employed in aerodynamics, which are often difficult to implement due to conflicting design parameters. The findings emphasize the importance of maximizing aerodynamic efficiency to increase payload capacity, reduce launch costs, and improve mission success rates. Key discoveries include the impact of specific design choices on lift and drag forces, as well as maneuvers to address challenges such as shock absorption due to vibrations and preventing vehicle flipping, particularly during the first stage of flight. This research employs both computational fluid dynamics and theoretical analysis to evaluate different configurations and designs, providing valuable insights for aerospace engineers and scientists focused on the development of small launch vehicles. These findings are crucial for advancing innovation within the aerospace industry.

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1. Introduction

Small launch vehicles, often referred to as micro launchers or small satellite launchers, are rockets designed to carry payloads significantly lighter than those of traditional heavy-lift rockets like the Ariane 5 or Falcon 9. Typically, these vehicles are intended to transport loads to low Earth orbit (LEO) or sun-synchronous orbit (SSO) ranging from a few kilograms to several hundred kilograms. The growing demand for small satellites has led to the emergence of new companies offering reliable and cost-effective launch services. Advances in technology and materials have resulted in more specialized and efficient vehicles, providing satellite operators with increasingly affordable alternatives. Industry leaders in the small-scale rocket sector, such as Virgin Orbit, SpaceX, and Rocket Lab, continue to push the boundaries of delivering small satellites into space using their reusable technologies and models. Innovations in propulsion systems, materials science, and autonomous navigation are driving improvements in the performance and design of small launch vehicles. These advancements are enabling the development of smaller, more cost-effective launch vehicles capable of carrying heavier payloads into orbit. New entrants to the small launch vehicle market face challenges such as securing necessary licenses and permissions, adhering to international regulations, and ensuring compliance with global standards. However, collaboration with industry partners and government bodies can help overcome these hurdles. The future of the small launch vehicle industry appears promising, with increasing demand for small satellite deployment, growing investment from governments and public investors, and continued technological advancements. An expansion in the variety of

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** Received: 04-August-2024 || Revised: 22-August-2024 || Accepted: 26-August-2024 || Published Online: 30-August-2024.

launch services and options is crucial for the democratization of space, and this can only be achieved through increased competition in the industry [1-5].

2. Aerodynamic Analysis Methods (CFD, Wind Tunnel Testing.)

The movement of an object through a fluid, such as an airplane or car moving through air, causes the fluid to move as well, generating forces that push or pull on the object. These forces are central to the field of aerodynamics. Aerodynamic analysis focuses on understanding how these forces are generated and their effects on the object. This is a critical aspect of aerospace engineering, as predicting and mitigating potential aerodynamic instabilities is key to improving safety. A crucial part of this analysis is examining the flow of forces, particularly through drag analysis, which involves quantifying the drag force acting on the object. Drag analysis also identifies where design changes can be made to minimize drag or reduce its impact on surfaces or objects. This often involves optimizing aerodynamic features to reduce the resistance that slows down motion. The analysis also aims to predict how design adjustments, such as refining wing shapes, adjusting angles of attack, or configuring parts for optimal performance, can enhance lift. By stabilizing these elements during motion, operators can better manage the craft, ensuring efficient and safe operation [5-9].

Computational Fluid Dynamics (CFD) Analysis

CFD simulations play a crucial role in the design of small launch vehicles, allowing engineers to accurately predict how these vehicles will perform under various atmospheric conditions. By studying airflow around the vehicle, engineers can make informed decisions about its shape and design to achieve optimal performance and efficiency. This research paper explores various methods of aerodynamic analysis within the small launch vehicle industry, focusing particularly on how CFD simulations can enhance vehicle design. Understanding the need for aerodynamic analysis and how to achieve it will keep companies at the forefront of space exploration, driving innovation in the industry. By running CFD simulations, engineers can accurately predict how air will flow around the vehicle at different speeds and altitudes, allowing for adjustments that minimize drag and maximize lift. This results in better fuel efficiency and higher overall performance for the launch vehicle. Companies that leverage advancements in aerodynamic analysis methods are well-positioned to develop next-generation technologies, shaping the future of space exploration. Leading in aerodynamics not only advances companies into deep space with safer and more reliable spacecraft but also reduces the environmental impact of space travel. Continuous innovation in space exploration brings endless possibilities, set to revolutionize our understanding of the universe.

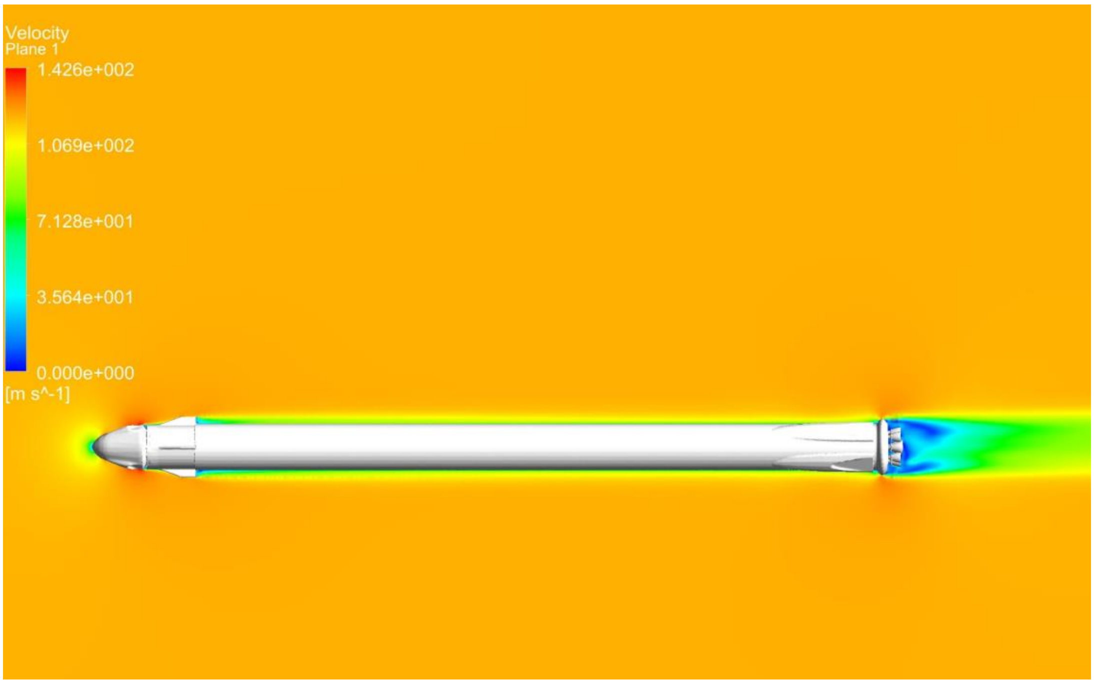


Figure-1 CFD of Falcon 9 Rocket [Image Courtesy: Fetch CFD]

Wind Tunnel Testing

Wind tunnel testing is another critical aspect of aerospace engineering, enabling firms to fine-tune and shape spacecraft for their intended missions and ensure they are prepared for the harsh conditions of space. Engineers run models through different speeds and pressures in a wind tunnel to gather data on vehicle performance under various conditions. This hands-on approach, combined with advanced computer simulations, allows companies to thoroughly understand their spacecraft's capabilities and limitations. As a result, space travel has a bright future. The data collected from wind tunnel testing helps engineers identify potential weaknesses in spacecraft design that could be critical before launch. The more refined and well-developed these models are, the safer and more reliable the vehicle will be, increasing the likelihood of successful missions. With rapid technological advancements, the scope of space exploration and discovery continues to expand. For example, testing a new spacecraft may reveal that some components are not strong enough to withstand the extreme temperatures of outer space. Early identification of these issues allows engineers to redesign and reinforce those parts, ensuring the spacecraft's ultimate safety. This iterative process in design development leads to more successful and reliable missions, pushing the boundaries of space exploration.

Importance of Aerodynamic Analysis in Optimizing Performance and Efficiency

Aerodynamic analysis is a vital tool for improving the performance and efficiency of vehicles, structures, and even sports equipment. Reducing drag enhances fuel efficiency and overall performance while also reducing noise, thus reinforcing stability and safety. Increased velocity leads to improved fuel economy, as aerodynamic shapes reduce drag forces. By significantly decreasing air resistance, aerodynamic designs help lower fuel consumption, particularly in industries like aviation and automotive. Additionally, effective aerodynamic design provides greater stability in poor weather conditions. Enhancing aerodynamics often results in reduced emissions, making it essential for environmental preservation and sustainability goals. Aerodynamic analysis drives product design innovation, resulting in sleek, more efficient shapes. Long-term financial savings can be realized through lower fuel consumption, reduced maintenance costs, and improved operational efficiency, all thanks to superior aerodynamic design. Aerodynamics forms the foundation of modern engineering, shaping the design of vehicles, sports gear, and buildings while promoting innovation and sustainability across various sectors.

3. Literature Review

Rogers et al. (2015) conducted CFD simulations focused on the ascent aerodynamics and booster separation of the Space Launch System (SLS). Their study provided valuable insights into the aerodynamic forces and flow patterns encountered by the SLS during ascent, as well as the dynamics involved in booster separation. The findings significantly enhanced our understanding of the aeroenergetic behaviors during the SLS's ascent phase and the subsequent booster separation process.

Kiris et al. (2016), in their research published in Aerospace Science and Technology, presented a comprehensive computational framework for launch, ascent, and vehicle aerodynamics. The authors emphasized the critical importance of developing high-fidelity computational methods to accurately simulate the complex aerodynamic behavior of aerospace vehicles during the launch and ascent stages. Their work offers valuable insights into the opportunities and challenges associated with Launch, Ascent, and Vehicle Aerodynamics (LAVA) simulations.

Takizawa et al. (2012) explored bio-inspired flapping-wing aerodynamics for small aerial vehicles using space-time computational analysis. Their findings contribute to the broader understanding of aerodynamic principles and provide guidance for developing computational frameworks applicable to LAVA. The study’s combination of bio-inspired design and aerodynamic phenomena offers valuable insights for advancing novel computational methods for simulating aerospace vehicles during ascent and launch.

4. Comparison of Small Launch Vehicles (Launchers)

Company	Rocket	Est. Cost	1st Launch	LEO (200 km)
Rocket Lab	Electron	$7M	Jan 2018	~300 kg
Virgin Orbit	LauncherOne	$10-12M	Early 2021	500 kg
FireFly	Alpha	$15M	Early 2021	1000 kg
Relativity	Terran 1	$10M	2021+	1250 kg
ABL Space	RS1	$12M	2021+	1350 kg

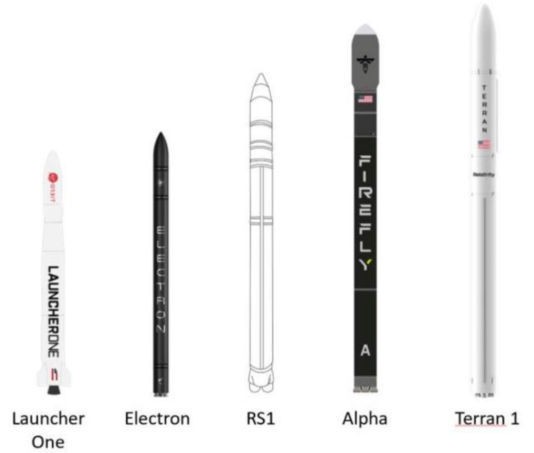


Figure-2 Comparison of Small Lift Launch Vehicle [Image Courtesy: Ryan C.Woolley, 2021]

Table-1 Comparison of Various Small Launch Vehicles

S.No	Name	Launcher Mass (kg)	Payload Delivering Capability (kg)	Projected Orbit	Stages	Fuel	Thrust (kN)
01	Electron	300	200	LEO, SSO	4	Liquid	260kN
02.	SSLV	500	300	LEO, SSO	2	Solid/Liquid	396 kN
03.	Start-1	532	350	LEO, SSO	5	Liquid	550 kN
04.	Long March 6	103000	1080	LEO, SSO	3	Liquid	1374 kN
06.	Long March 11	700	350	LEO, SSP	4	Solid	1200 kN

5. Aerodynamic Challenges of Small Launch Vehicles

Different aerodynamic limitations faced by small launch vehicles (SLVs) stem from their size and operational features. These challenges significantly impact the performance and success of these vehicles **[10-11]**.

High Angle of Attack (AoA)

Small launch vehicles, due to their size, often experience higher angles of attack compared to larger rockets. This is influenced by atmospheric conditions, trajectory requirements, and vehicle dynamics. The issues arising from high AoA include:

- **Increased Drag**: At higher AoA, the airflow impact on the vehicle's front increases, leading to a rise in drag forces. This reduces the vehicle's propulsion efficiency, necessitating more fuel to achieve mission objectives.
- **Ineffectiveness of Control Surfaces**: The effectiveness of control surfaces such as fins or canards diminishes as AoA increases, which reduces the vehicle's ability to stabilize or maintain the desired flight attitude.
- **Lateral Forces and Moments**: High AoA induces significant lateral forces and moments on the vehicle, affecting stability and control during the ascent phase. Managing these forces is critical to ensuring the vehicle follows its intended trajectory.

Transonic Flow

Transonic flow refers to the transition of a vehicle's speed from below to above the speed of sound, which presents several aerodynamic challenges:

- **Buffeting**: Buffeting is the rapid, unsteady force acting against the flow direction, leading to vibrations and motion responses in the vehicle. This can result in structural failures and complicate boundary layer management.
- **Shock Wave Formation and Boundary Layer Separation**: At transonic speeds, shock waves form, inducing additional drag and dynamic loads on the structure. This can cause boundary layer separation, where airflow detaches from the vehicle's surface, increasing drag and reducing aerodynamic efficiency.

Reynolds Number Effects

The Reynolds number is a nondimensional value expressing the ratio of inertial forces to viscous forces in fluid flow. SLVs, due to their smaller size, generate lower Reynolds numbers compared to larger rockets. This poses several aerodynamic challenges:

- **Reduction in Lift Generation Efficiency**: At lower Reynolds numbers, the airfoil or wing sections of SLVs suffer from reduced lift generation efficiency, affecting the ability to achieve the desired ascent trajectory.
- **Increase in Flow Separation and Turbulence**: Lower Reynolds numbers can trigger early flow separation from the vehicle's surfaces, increasing turbulence and drag, which directly impacts overall aerodynamic performance.

6. Optimizing Aerodynamics and Its Benefits for SLVs

Aerodynamic optimization for small launch vehicles offers several benefits directly related to vehicle performance and capabilities:

- **Reduced Drag**: Drag reduction minimizes opposition as the vehicle travels through the atmosphere, improving fuel efficiency. This allows the vehicle to achieve higher velocities or altitudes without significantly increasing fuel consumption. Reduced drag also increases payload capacity by reducing the amount of fuel required.
- **Reduced Buffet Loads**: Optimized aerodynamic design can reduce buffet loads—oscillatory aerodynamic forces that can affect the vehicle's structural integrity. By reducing these loads, the structure's durability and the accuracy of onboard guidance systems are enhanced.
- **Aerodynamic Control Surfaces**: Effective aerodynamic control surfaces enable precise maneuvering during different flight phases, particularly useful for reusable vehicles. These surfaces aid in optimizing vehicle attitude during ascent and descent, contributing to mission success.

7. Design Considerations for Mitigating Aerodynamic Effects

7.1. Fin Design and Placement for Stability and Control

Aircraft and vehicle fins have many factors to consider in their design. Fin sizes and shapes are crucial, and their optimal dimensions can be determined through simulations using computational fluid dynamics (CFD). The efficiency of a fin is also influenced by its aspect ratio, as higher ratios generally reduce induced drag but may increase structural weight. Fins should be strategically positioned, taking into account the vehicle's center of gravity (CG), aerodynamic center, and intended flight conditions. Vertical and horizontal stabilizers should be placed at the rear of an aircraft or vehicle to stabilize yaw motion during flight. Achieving sufficient yaw stability, pitch stability, and roll control requires appropriately sized fins. The interaction between fins and wings is important, as wing-mounted fins can help reduce induced drag. The tail configuration also contributes to the aerodynamic balance of a vehicle. The center of gravity (CG) impacts both stability and handling characteristics, and through advanced simulations and experimental testing, engineers can obtain the best possible stability and control characteristics. **[13-14]**.

7.2. Center of Gravity Location for Vehicle Stability and Handling

Vehicle design heavily relies on the center of gravity (CG), which significantly influences stability and handling characteristics. Therefore, the CG should be located in a position that minimizes pitching moments caused by aerodynamic forces. Additionally, it must be positioned far enough forward to ensure stability during flight or movement, but not so far forward that it causes excessive nose-down tendencies. The vertical position of the CG also plays a crucial role in both lateral and longitudinal stabilities. The lateral CG position affects the ability to maintain level flight or travel and influences roll stability. Vehicles can benefit from adjustable CG mechanisms, especially when there are changes in payload, fuel, or cargo weight. For example, aircraft use fuel tanks to adjust the CG during cruising to maintain stability. High-performance cars often allow adjustments to ride height and CG position through adjustable chassis systems, optimizing handling on different tracks. CG position determines stability, handling characteristics, and safety. Proper CG positioning is essential for safer operations, reducing the risk of instability, particularly during critical maneuvers or unexpected situations in aircraft, racing cars, and boats. **[14]**.

7.3. Fuselage Shape Optimization for Drag Reduction and Aerodynamic Efficiency

The purpose of fuselage shape optimization is to minimize drag by ensuring smooth airflow around the vehicle. Computational Fluid Dynamics (CFD) simulations are crucial for analyzing various fuselage shapes and their impact on drag forces. Factors such as nose shape, body profiles, and tail designs are important in this process. Additionally, fairings and fillets are employed to create smooth transitions between different fuselage components, wings, and other structures, reducing drag caused by flow separation and vortices. This includes well-designed fairings at wing-fuselage junctions and fillets at connection points between the fuselage and vertical stabilizer. Wing design should complement the fuselage shape to minimize interference drag and optimize lift distribution. This coordinated design between the fuselage and horizontal stabilizers ensures effective aerodynamic balance and stability. Overall, a streamlined fuselage results in less air disturbance, thereby enhancing stability and efficiency in an aircraft. Applications include airplanes, high-speed trains, and racing cars. With advanced design tools like CFD simulations and the use of smooth fairings or fillets, engineers can achieve significant drag reduction and enhanced aerodynamic performance in various vehicles and structures. **[14]**.

7.4. Passive and Active Control Systems for Aerodynamic Management

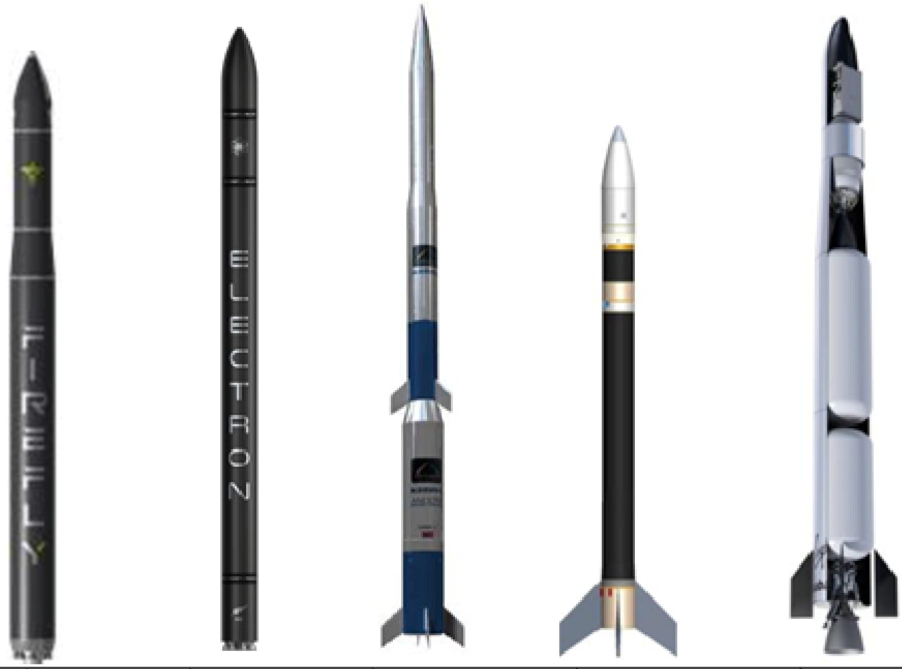
An aircraft's passive systems include vortex generators, which control airflow and prevent boundary layer separation, and boundary layer control systems that help maintain laminar flow over wings and fuselages. These systems contribute to the stability and control of the airplane at low speeds or high angles of attack. Dynamic flow control utilizes actuators to manipulate airflow over surfaces. These systems can adaptively alter their behavior in response to varying flight conditions or operational requirements, thereby enhancing efficiency and stability. Trim tabs and control surfaces are traditionally managed by pilots or automated systems to maintain desired flight characteristics. These systems are crucial for controlling pitch, roll, yaw, and lift during flight operations. In modern aircraft, automatic mechanisms often adjust these surfaces based on real-time aerodynamic data and pilot inputs. The combination of both passive and active control mechanisms creates a synergy that enhances adaptability and safety in vehicle design. Improved management of aerodynamic forces results in better handling and a reduced risk of aerodynamic instabilities. The integration of passive and active control systems could lead to significant technological advancements in aerodynamic efficiency and ground stability. **[14]**.

7.5. General Design Principles for Aerodynamic Optimization

The underpinning integrated design approach ensures that vehicle components function together to achieve optimal aerodynamic performance. This holistic approach involves collaboration among engineers from multiple disciplines to focus on functionality and integration, avoiding any negative impact on the overall functionality or safety of the vehicle. This iterative design process refines aerodynamic designs through cycles of CFD simulations, wind-tunnel testing, and optimization, with continuous feedback loops. The use of materials and construction techniques that minimize weight and surface roughness is crucial. Smooth surfaces enhance laminar airflow, while lightweight materials—such as advanced composites and aluminum alloys—are finished to reduce skin friction drag. However, weight reduction must be carefully balanced with structural integrity to ensure safety and durability under operational loads. Proper design implementation enhances performance, efficiency, safety, and reliability. By following these design principles, engineers can achieve optimized aerodynamic performance across various vehicles and structures, resulting in efficiency gains, improved performance, safety, and operational capabilities even in challenging environments [14].

8. Conclusion and Future Application

Understanding the interaction between airflow and vehicle design is a critical aspect of SLV aerodynamics. By addressing challenges such as high AoA, transonic flow, and Reynolds number effects, engineers can optimize vehicle design to maximize performance. As technology advances, SLVs will continue to improve in efficiency and capability, playing a crucial role in the future of space exploration. Future research in SLV aerodynamics will focus on innovative mitigation strategies, AI and machine learning integration, and advanced CFD simulations. Hypersonic SLVs present new challenges and opportunities in aerodynamics, thermal management, propulsion systems, and structural integrity. Interdisciplinary approaches, experimental validation, sustainability, and autonomous systems will be key in advancing SLV technology for safer, more efficient, and capable systems. This ongoing evolution in aerospace engineering will pave the way for future victories in space exploration.



Launch Vehicle	Firefly	Electron	North Star	Super Strypi	LauncherOne
Manufacturer	Firefly	Rocket Lab	NAMMO	U. of Hawai	Virgin Orbit
Payload (kg)	200	150	10-50	200	300
Altitude (km)	500	500	350	500	500
Propulsion	LOX/RP-1	LOX/RP-1	Hybrid	Solid	LOX/RP-1
1st flight	Cancelled	2017	2020	2016/Failed	2019

Figure-2 Comparison of New Small Lift Launch Vehicles [12]

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10. Conflict of Interest

The author declares no competing conflict of interest.

11. Funding

No funding was received to support this study.