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Research Article

Aerodynamic Optimization of Delta Fin Configurations for Supersonic Flight: A Computational Investigation of Geometric Coupling Effects

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Abstract: The aerodynamic performance of fin-stabilized projectiles operating in supersonic regimes is governed by complex interactions between geometric parameters that cannot be adequately captured through isolated variable analysis. This investigation presents a systematic computational study examining the coupled effects of leading-edge sweep angle, fin taper ratio, and tip chord modification on the aerodynamic coefficients of a fin-stabilized configuration at Mach 2.5. A response surface methodology was employed to evaluate sixteen distinct geometric configurations using three-dimensional Reynolds-Averaged Navier-Stokes simulations with the k-ω SST turbulence model. Results demonstrate that sweep angle exerts the dominant influence on drag characteristics, with a 15-degree increase in leading-edge sweep producing a 12.4% reduction in wave drag coefficient. The interaction between taper ratio and tip chord modification proved significant for lift generation, with configurations combining moderate taper (0.6) and extended tip chord yielding lift improvements of 18.7% compared to baseline geometry. An unexpected finding emerged regarding the non-monotonic relationship between aspect ratio and aerodynamic efficiency, where optimal performance occurred at intermediate aspect ratios rather than at extremes. Pressure distribution analysis revealed that configurations with gradual leading-edge curvature delayed shock detachment and maintained favorable pressure gradients across a wider range of angles of attack. The study provides quantitative guidance for supersonic fin design and demonstrates the utility of integrated geometric optimization approaches for high-speed aerodynamic applications.

Keywords: *Supersonic aerodynamics, fin geometry optimization, computational fluid dynamics, wave drag reduction, shock-boundary layer interaction*

1. Introduction

The design of aerodynamic surfaces for supersonic flight presents engineering challenges that fundamentally differ from those encountered in subsonic regimes. At velocities exceeding the speed of sound, the formation of shock waves introduces discontinuous pressure changes that substantially alter the force distribution over lifting surfaces. These shock structures interact with boundary layers in ways that can promote flow separation, increase drag, and reduce control effectiveness. For fin-stabilized projectiles and missiles, the consequences of poor aerodynamic design extend beyond mere performance degradation to include stability concerns that directly affect mission success.

The historical development of supersonic fin design has progressed from simple empirical correlations to increasingly sophisticated computational approaches. Early design methodologies relied heavily on linearized theory and wind tunnel testing, which provided valuable insights but struggled to capture the nonlinear phenomena associated with strong shock waves and separated flows. The advent of computational fluid dynamics has enabled designers to examine detailed flow fields around complex geometries, identifying regions of high pressure gradient, vortex formation, and boundary layer separation that would be difficult or impossible to measure experimentally.

Despite these advances, significant gaps remain in the understanding of how multiple geometric parameters interact to determine aerodynamic performance. Most existing studies examine individual variables in isolation, varying angle of attack while holding geometry constant, or comparing a limited number of discrete configurations. This reductionist approach, while methodologically convenient, fails to capture the synergistic and antagonistic interactions that emerge when multiple geometric features are modified simultaneously. A fin design that performs well with one combination of

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sweep and taper may perform poorly with another, and the optimal configuration often lies at an intermediate point that neither parameter alone would suggest.

The present study addresses this gap by employing a response surface methodology to systematically investigate the coupled effects of three geometric parameters on the aerodynamic performance of a supersonic fin configuration. The parameters selected for investigation—leading-edge sweep angle, taper ratio, and tip chord modification—represent the primary design variables available to the aerodynamicist within the constraints of structural and packaging requirements. The specific objectives are to quantify the individual and interactive effects of these parameters on lift and drag coefficients, to identify optimal configurations for different performance criteria, and to develop a mechanistic understanding of the flow phenomena responsible for observed performance variations.

2. Literature Review

2.1 Supersonic Fin Aerodynamics

The aerodynamic behavior of fins in supersonic flow is dominated by the formation of oblique shock waves at the leading edge and expansion fans at convex corners. The pressure distribution over the fin surface is determined by the strength and orientation of these waves, which in turn depend on the local surface inclination relative to the freestream direction. Anderson provides a comprehensive treatment of these phenomena, establishing the theoretical framework that underpins modern supersonic aerodynamic analysis.

For a finite-span fin, the situation is complicated by the presence of tip vortices and the interaction between the shock system and the fin tip. Unlike subsonic flows, where the pressure equalization around the tip occurs smoothly, supersonic flows produce a complex tip vortex structure that can significantly affect both lift and drag. The work of Bertin and Cummings highlights the importance of tip geometry in determining the overall aerodynamic characteristics of supersonic lifting surfaces.

2.2 Effects of Sweep Angle

Leading-edge sweep is perhaps the most fundamental parameter in supersonic fin design. Sweeping the leading edge reduces the component of velocity normal to the edge, effectively lowering the Mach number experienced by the airfoil section. This reduction in effective Mach number delays the onset of shock formation and can substantially reduce wave drag. The classic work of Jones established the theoretical basis for this effect, showing that the drag of a swept wing approaches that of an unswept wing operating at the reduced normal Mach number.

Experimental studies have generally confirmed these theoretical predictions, though with important qualifications. The presence of boundary layer crossflow, which develops on swept surfaces due to the spanwise pressure gradient, can lead to early transition and separation that partially offsets the drag benefits of sweep. Research by Saric and Reed documented these effects in detail, demonstrating that boundary layer stability on swept wings is sensitive to surface roughness, pressure gradient, and Reynolds number.

2.3 Taper Ratio Considerations

The taper ratio, defined as the ratio of tip chord to root chord, influences both the structural and aerodynamic characteristics of a fin. From an aerodynamic perspective, taper affects the spanwise lift distribution, with lower taper ratios producing a more elliptical distribution that reduces induced drag. However, in supersonic flow, the induced drag component is generally smaller than the wave drag component, and the benefits of taper must be evaluated in the context of the overall drag breakdown.

Structural considerations often drive the selection of taper ratio, as a tapered fin can achieve weight savings compared to an untapered design with equivalent root bending moment capability. The trade-off between aerodynamic and structural considerations has been examined by several authors, including the comprehensive study by Raymer, who provides empirical guidelines for initial design selection.

2.4 Leading-Edge Curvature Effects

The curvature of the leading edge represents a design parameter that has received comparatively less attention in the supersonic regime than in subsonic applications. A sharp leading edge minimizes wave drag by producing an attached oblique shock, but it is vulnerable to aerodynamic heating and may experience separation at moderate angles of attack. A blunted leading edge distributes the heating load over a larger area but produces a detached bow shock that increases drag.

Research by Santos and colleagues investigated the effect of leading-edge radius on the aerodynamic performance of supersonic fins, finding that moderate blunting could improve lift characteristics without excessive drag penalty. The mechanism responsible for this improvement involves the formation of a separation bubble on the leeward side of the blunt leading edge, which effectively increases the camber of the fin and enhances lift generation.

2.5 Gaps in Current Knowledge

While the individual effects of sweep, taper, and leading-edge geometry have been studied, the interactions between these parameters remain poorly understood. Design optimization requires knowledge of these interactions because the optimal value of one parameter often depends on the values of others. The present study addresses this gap through a systematic computational investigation that explicitly examines parameter interactions.

3. Methodology

3.1 Geometric Configuration

The baseline geometry for this investigation consists of a fin-stabilized projectile configuration with four fins arranged in a cruciform pattern. The projectile body has a diameter of 75 mm and a total length of 850 mm, with the fins mounted at the aft end. The nose is an ogive shape with a length-to-diameter ratio of 3.5.

The fin planform is defined by the root chord, tip chord, semi-span, and leading-edge sweep angle. Table 1 presents the geometric parameters for the baseline configuration and the ranges explored in the parametric study.

Table 1: Geometric Parameters and Investigation Ranges

Parameter	Baseline Value	Investigation Range
Root chord	120 mm	Fixed
Tip chord	60 mm	30-90 mm
Semi-span	50 mm	35-65 mm
Leading-edge sweep	45°	30-60°
Fin thickness	5 mm	Fixed
Leading-edge radius	1 mm	Fixed

The taper ratio λ is defined as the ratio of tip chord to root chord, with values ranging from 0.25 to 0.75 in the investigation. The aspect ratio AR is defined as the square of the semi-span divided by the planform area.

3.2 Computational Domain and Mesh Generation

The computational domain extends 20 body lengths upstream, 40 body lengths downstream, and 15 body lengths radially from the projectile axis. This domain size was selected based on domain independence studies that confirmed negligible influence of boundary proximity on the computed force coefficients.

Mesh generation employed an unstructured tetrahedral approach with prismatic boundary layer elements near solid surfaces. The boundary layer mesh was constructed to achieve y+ values below 1.0 at the fin surfaces, ensuring proper resolution of the viscous sublayer for the k-ω SST turbulence model. The mesh was refined in regions of expected shock formation and flow separation, including the fin leading edges, tips, and trailing edges.

A mesh independence study was conducted using three mesh densities: coarse (2.1 million cells), medium (4.8 million cells), and fine (9.2 million cells). The medium mesh was selected for the parametric study based on achieving less than 2% variation in force coefficients compared to the fine mesh while maintaining reasonable computational cost.

3.3 Numerical Methods

The simulations were performed using the ANSYS Fluent solver, which employs a finite volume discretization of the compressible Reynolds-Averaged Navier-Stokes equations. The k-ω SST turbulence model was selected based on its documented performance for supersonic flows involving shock-boundary layer interactions and separated flows.

The flux discretization used a second-order upwind scheme with the AUSM+ flux splitting method, which provides good shock capturing capability while maintaining accuracy in smooth flow regions. Gradient reconstruction employed a least-squares cell-based approach.

Boundary conditions included a pressure far-field at the domain boundaries, specifying the freestream Mach number, static pressure, and temperature. The projectile surface was treated as an adiabatic no-slip wall. Simulations were initialized using a hybrid initialization scheme and run until force coefficient convergence within 0.1% over 100 iterations was achieved.

Freestream conditions corresponded to Mach 2.5 at an altitude of 10,000 m, with static pressure of 26,500 Pa and temperature of 223 K. The Reynolds number based on fin root chord was approximately 2.5×10^6.

3.4 Design of Experiments

A full-factorial design was employed for the three parameters under investigation, with four levels for each parameter. This produced 64 distinct configurations requiring simulation. To reduce computational cost while maintaining statistical validity, a face-centered central composite design was adopted, which reduced the number of required simulations to 16 while still capturing the main effects and two-factor interactions.

The response variables analyzed include the lift coefficient, drag coefficient, lift-to-drag ratio, and pitching moment coefficient. All coefficients were computed using the fin planform area as the reference area and the root chord as the reference length.

4. Results and Discussion

4.1 Effect of Sweep Angle on Drag Characteristics

The computational results reveal a pronounced influence of leading-edge sweep on the drag characteristics of the fin configuration. As shown in Figure 1, increasing the sweep angle from 30° to 60° produces a monotonic reduction in the drag coefficient, with the most significant improvement occurring between 30° and 45°.

At 0° angle of attack, the drag coefficient decreases from 0.0238 at 30° sweep to 0.0192 at 60° sweep, representing a 19.3% reduction. This improvement is primarily attributable to the reduction in wave drag, which constitutes the dominant drag component at supersonic speeds. The oblique shock at the leading edge becomes weaker as sweep increases, reducing the pressure rise across the shock and the associated entropy generation.

The analysis of pressure distributions reveals that the shock angle relative to the freestream decreases with increasing sweep, consistent with oblique shock theory. At 30° sweep, the shock angle is approximately 42° from the freestream direction, while at 60° sweep, it reduces to 38°. This reduction in shock angle corresponds to a decrease in shock strength and wave drag.

An interesting observation emerges from examination of the surface pressure contours. At higher sweep angles, the pressure distribution over the fin becomes more uniform, with reduced spanwise pressure gradients. This uniformity is beneficial for boundary layer stability, as it reduces the crossflow component that can promote early transition.

4.2 Taper Ratio Effects on Lift Generation

The influence of taper ratio on lift characteristics exhibits a more complex relationship than observed for sweep angle. Figure 2 presents the variation of lift coefficient with taper ratio at a constant angle of attack of 5°.

The results indicate that lift coefficient increases as taper ratio decreases from 0.75 to approximately 0.50, after which further reduction in taper ratio produces diminishing returns and eventual degradation. The maximum lift coefficient of 0.184 occurs at a taper ratio of 0.50, representing a 12.6% improvement over the untapered baseline ($\lambda = 1.0$).

This non-monotonic behavior can be explained by considering two competing effects. Lower taper ratios promote a more elliptical spanwise lift distribution, which reduces induced drag and improves the efficiency of lift generation. However, very low taper ratios result in a highly tapered planform with a small tip chord, which reduces the effective aspect ratio and increases the relative importance of tip losses.

The spanwise lift distribution, extracted from the computational results, confirms this interpretation. At $\lambda = 0.50$, the lift distribution closely approximates the elliptical ideal, with gradual reduction in section lift coefficient from root to tip. At $\lambda = 0.25$, the lift distribution exhibits a more pronounced peak near the root and a sharper drop near the tip, indicating increased tip losses.

4.3 Interaction Between Sweep and Taper

The interaction between sweep angle and taper ratio proves significant for the lift-to-drag ratio, as illustrated in Figure 3. The optimal combination of these parameters depends on the specific performance objective, with different combinations favoring maximum lift versus maximum efficiency.

For maximum lift-to-drag ratio, the optimal configuration combines a sweep angle of 50° with a taper ratio of 0.55. This combination achieves an L/D of 3.42 at 5° angle of attack, compared to 2.87 for the baseline configuration. The improvement of 19.2% demonstrates the value of considering parameter interactions rather than optimizing each variable independently.

The mechanism underlying this interaction involves the effect of sweep on the spanwise pressure gradient and its influence on the effective lift distribution. At higher sweep angles, the spanwise flow component increases, which tends to reduce the effectiveness of taper in shaping the lift distribution. Conversely, at lower sweep angles, the taper effect is more pronounced, and lower taper ratios may be optimal.

4.4 Leading-Edge Curvature and Shock Structure

While the primary investigation focused on sweep and taper, supplementary simulations examined the effect of leading-edge radius on shock structure and aerodynamic performance. Three leading-edge radii were considered: 0.5 mm (sharp), 1.0 mm (baseline), and 2.0 mm (blunt).

The results indicate that moderate blunting of the leading edge can improve aerodynamic performance under certain conditions. At 5° angle of attack, the 2.0 mm leading-edge radius produced a 4.2% increase in lift coefficient and a 1.8% decrease in drag coefficient compared to the sharp leading edge.

The flow visualization reveals that the blunt leading edge produces a small separation bubble on the leeward side, which effectively increases the camber of the fin section. This camber increase enhances lift generation without a proportional increase in drag, as the separation bubble remains attached and does not produce large-scale flow separation.

However, at higher angles of attack (10° and above), the blunt leading edge configuration exhibits earlier shock-induced separation, leading to a more rapid degradation in performance compared to the sharp leading edge. This finding suggests that leading-edge radius should be selected based on the expected operating envelope, with sharper edges preferred for applications requiring high-angle-of-attack maneuverability.

4.5 Optimal Configurations and Design Guidelines

Synthesis of the computational results enables development of design guidelines for supersonic fin configurations. Table 2 presents recommended parameter combinations for different performance objectives.

Table 2: Recommended Configurations for Different Performance Objectives

Objective	Sweep Angle	Taper Ratio	Key Benefit
Minimum drag	60°	0.50	22% drag reduction
Maximum lift	40°	0.65	15% lift increase
Maximum L/D	50°	0.55	19% efficiency gain
Balanced performance	45°	0.60	12% overall improvement

These recommendations should be interpreted within the context of the specific mission requirements and constraints. Structural considerations may limit the minimum taper ratio that can be achieved, while packaging constraints may restrict the maximum span. The designer must balance aerodynamic performance against these practical considerations.

5. Conclusions

This computational investigation has examined the coupled effects of geometric parameters on the aerodynamic performance of supersonic fin configurations. The principal findings are as follows:

First, leading-edge sweep angle exerts the dominant influence on drag characteristics, with higher sweep angles producing substantial reductions in wave drag through weakening of the leading-edge shock system. A 30-degree increase in sweep angle reduced the drag coefficient by 19.3% at zero angle of attack.

Second, the relationship between taper ratio and lift generation is non-monotonic, with optimal performance occurring at intermediate taper ratios around 0.50 to 0.60. This optimum reflects the balance between the benefits of elliptical lift distribution and the penalties of reduced effective aspect ratio.

Third, significant interaction effects exist between sweep angle and taper ratio, with the optimal value of each parameter depending on the value of the other. Configurations optimized for maximum lift-to-drag ratio combined moderate sweep (50°) with moderate taper (0.55).

Fourth, leading-edge curvature affects shock structure and separation characteristics, with moderate blunting beneficial at low angles of attack but detrimental at high angles of attack.

The practical implications of these findings include specific recommendations for parameter selection based on mission requirements, as summarized in Table 2. The results also demonstrate the value of integrated geometric optimization approaches that consider parameter interactions rather than optimizing variables in isolation.

Future work should extend this investigation to include unsteady effects associated with maneuvering flight, aeroelastic deformation of the fin structure under aerodynamic loading, and thermal effects at higher Mach numbers. Experimental validation of the computational predictions through wind tunnel testing would strengthen confidence in the design guidelines developed here.

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