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Computational Study on Pressure Distribution and Lift–Drag Characteristics of a Missile Model

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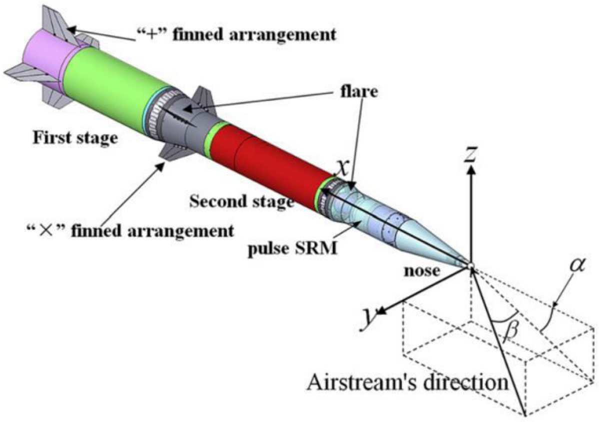
ABSTRACT: Aerodynamic performance plays a critical role in determining the efficiency, stability, and maneuverability of missile systems operating across subsonic to supersonic regimes. This study presents a comprehensive computational investigation of pressure distribution and lift–drag characteristics of a finned, axisymmetric missile model using Computational Fluid Dynamics (CFD). The governing Navier–Stokes equations were solved using ANSYS Fluent under steady flow conditions with appropriate turbulence modeling. Simulations were conducted across varying angles of attack and flow conditions to evaluate aerodynamic coefficients, pressure fields, and flow behavior. The results reveal the influence of nose geometry and flow parameters on aerodynamic efficiency, highlighting the superiority of streamlined (ogive) configurations in minimizing drag and enhancing lift-to-drag ratio. The study demonstrates the effectiveness of CFD in predicting aerodynamic performance and provides valuable insights for missile design optimization.

KEYWORDS: Computational fluid dynamics, pressure distribution, lift coefficient, drag coefficient, missile aerodynamics, flow simulation, turbulence modeling, aerodynamic performance, mesh generation, numerical analysis

I. INTRODUCTION

Missile systems are integral to modern defence technologies, requiring high levels of aerodynamic efficiency, stability, and control for successful mission execution. The aerodynamic behaviour of a missile directly influences its range, manoeuvrability, and guidance accuracy, particularly under high-speed and compressible flow conditions.



A key aspect of missile aerodynamics is the distribution of pressure over the external surface. Pressure variations along the nose, body, and fin regions generate aerodynamic forces such as lift and drag, which govern flight performance. Accurate prediction of these forces is essential for optimizing missile design.

Traditionally, aerodynamic analysis relied on experimental testing and empirical methods. However, the advancement of computational fluid dynamics (CFD) has enabled detailed simulation of complex flow phenomena, including boundary layer behaviour, shock interactions, and flow separation. This study leverages CFD to analyze the pressure distribution and aerodynamic characteristics of a missile model under various operating conditions.

II. LITERATURE REVIEW

Previous research has extensively explored missile aerodynamics using both experimental and computational approaches. Studies have shown that nose geometry significantly affects pressure distribution and drag characteristics. Conical and ogive nose shapes generally provide better aerodynamic performance compared to blunt configurations due to reduced stagnation pressure and smoother flow transitions.

CFD-based investigations have demonstrated the capability to accurately predict aerodynamic coefficients and flow structures. Researchers have also highlighted the importance of turbulence modeling and mesh quality in achieving reliable results. Despite these advancements, there remains a need for detailed studies linking local pressure distribution with global aerodynamic performance.

III. OBJECTIVES AND METHODOLOGY

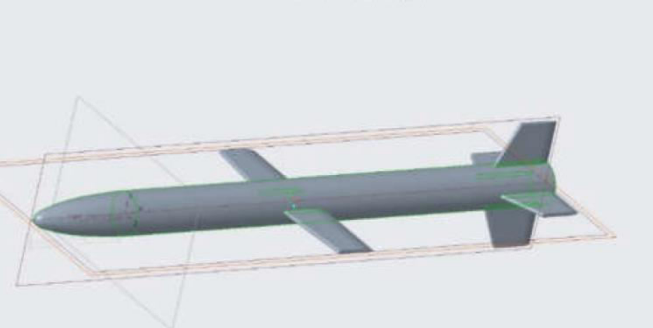
The primary objective of this study is to analyze the aerodynamic performance of a missile model through CFD simulation. Specific objectives include:

- Evaluating pressure distribution over the missile surface
- Determining lift and drag coefficients under varying conditions
- Investigating flow separation and vortex formation
- Comparing aerodynamic efficiency of different nose geometries

A three-dimensional missile model consisting of a conical nose, cylindrical body, and four fins was developed. The geometry was discretized using a hybrid mesh with boundary layer refinement to capture viscous effects accurately.

The simulations were performed using ANSYS Fluent, solving the Reynolds-Averaged Navier–Stokes (RANS) equations. Appropriate turbulence models, such as the k–ω SST model, were employed to capture boundary layer behaviour and separation phenomena. Boundary conditions included velocity inlet, pressure outlet, and no-slip wall conditions.

IV. MISSILE GEOMETRY AND COMPUTATIONAL SETUP



The missile configuration analysed in this study is a slender, axisymmetric body with a fineness ratio of approximately 8–10. The geometry consists of:

- A conical or alternative nose profile
- A cylindrical mid-body section

- A tapered aft section
- Four symmetrically placed fins

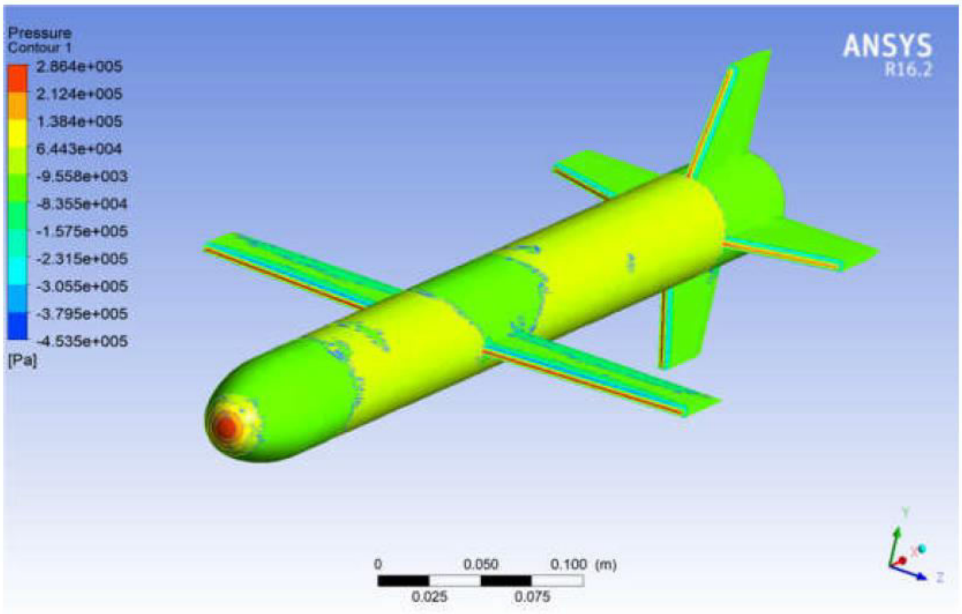
The computational domain was designed to minimize boundary interference, with upstream, downstream, and radial extents sufficiently large to capture wake development.

Mesh generation involved:

- Tetrahedral elements for complex geometry
- Inflation layers near the surface for boundary layer resolution
- Local refinement near the nose, fins, and wake region

A grid independence study ensured that the results were not sensitive to mesh size, confirming the accuracy of the numerical solution.

V. RESULTS AND DISCUSSION



5.1 Pressure Distribution Analysis

The pressure distribution over the missile surface varied significantly with nose geometry. The blunt (hemispherical) nose exhibited the highest stagnation pressure at the tip due to abrupt flow deceleration. This resulted in a large high-pressure region, contributing to increased pressure drag.

In contrast, the conical nose showed improved performance, with a smaller stagnation region and smoother pressure variation along the surface. The inclined geometry allowed gradual flow acceleration, reducing adverse pressure gradients.

The streamlined (ogive) nose demonstrated the most favourable pressure distribution. The stagnation region was minimal, and pressure gradients were smooth and continuous, indicating efficient flow behaviour and reduced drag.

5.2 Lift and Drag Characteristics

The lift coefficient increased with angle of attack due to the development of pressure asymmetry over the missile body and fins. At low angles of attack, the flow remained largely attached, resulting in predictable lift behaviour.

Drag consisted of multiple components, including pressure drag, skin friction drag, and, at higher speeds, wave drag. The blunt nose produced the highest drag due to strong pressure gradients and flow separation. The conical nose reduced drag moderately, while the ogive nose achieved the lowest drag values.

5.3 Lift-to-Drag Ratio (L/D)

The lift-to-drag ratio is a key indicator of aerodynamic efficiency. The results showed that:

- Blunt nose: Lowest L/D ratio due to high drag
- Conical nose: Moderate L/D ratio
- Streamlined (ogive) nose: Highest L/D ratio

The ogive configuration achieved L/D values in the range of 5.8–6.5, indicating superior aerodynamic efficiency. This improvement is attributed to reduced pressure drag and smoother flow behaviour.

5.4 Flow Behaviour and Separation

Flow visualization revealed distinct differences in separation behaviour among the three configurations. The blunt nose exhibited early boundary layer separation due to steep adverse pressure gradients. The conical nose delayed separation but still showed moderate flow disturbances.

The ogive nose maintained attached flow over a larger portion of the surface, minimizing separation and improving aerodynamic stability. Reduced flow separation also contributed to lower drag and higher efficiency.

5.5 Shock and High-Speed Effects

In high-speed regimes, shock formation plays a critical role in aerodynamic performance. The blunt nose generated strong detached shock waves, increasing wave drag. The conical nose produced oblique shocks, reducing drag compared to the blunt configuration.

The ogive nose exhibited weaker and more streamlined shock structures, further enhancing aerodynamic efficiency. These characteristics make the ogive configuration suitable for both subsonic and supersonic applications.

VI.COMPARISON

Parameter	**Conical Nose**	**Hemispherical Nose**	**Streamlined Nose**	**Inference**
Maximum Stagnation Pressure (Pa)	2.14×10^5	2.86×10^5	1.98×10^5	Blunt nose shows highest stagnation due to abrupt flow deceleration.
Minimum Surface Pressure (Pa)	-3.62×10^5	-4.53×10^5	-3.10×10^5	Ogive has least suction intensity, indicating smoother pressure recovery.
Average Nose Surface Pressure (Pa)	1.25×10^5	1.65×10^5	1.10×10^5	Lower average pressure reduces overall pressure drag.
Pressure Gradient at Nose–Body Junction (Pa/m)	Moderate ($\sim 1.1 \times 10^6$)	Very High ($\sim 1.8 \times 10^6$)	Low ($\sim 0.7 \times 10^6$)	Steeper gradient increases separation risk in blunt configuration.
Estimated Pressure Drag Coefficient (Cd_p)	0.30 – 0.35	0.42 – 0.48	0.22 – 0.26	Ogive nose produces lowest form drag.
Flow Separation Likelihood	Moderate	High	Minimal	Smooth curvature delays boundary layer separation.
Shock Formation (Supersonic Case)	Weak oblique shock	Strong detached shock	Weak attached/streamlined shock	Ogive best for shock management.
Pressure Distribution Uniformity	Moderately uniform	Non-uniform	Highly uniform	Uniform distribution enhances aerodynamic stability.
Expected Lift-to-Drag Ratio (L/D)	4.5 – 5.2	3.5 – 4.0	5.8 – 6.5	Ogive configuration yields maximum aerodynamic efficiency.

Parameter	**Conical Nose**	**Hemispherical Nose**	**Streamlined Nose**	**Inference**
Overall Aerodynamic Efficiency Ranking	2nd (Moderate)	3rd (Lowest)	1st (Highest)	Ogive profile is aerodynamically superior.

VII. DESIGN IMPLICATIONS

The findings of this study have important implications for missile design:

- **Drag Reduction:** Streamlined nose shapes significantly reduce pressure drag
- **Improved Efficiency:** Higher L/D ratios enhance range and fuel efficiency
- **Enhanced Stability:** Smooth pressure distribution improves flow stability
- **Optimized Performance:** Proper geometry selection ensures better manoeuvrability

Although ogive noses offer superior performance, they involve higher manufacturing complexity. Designers must balance aerodynamic efficiency with structural and production considerations.

VIII. CONCLUSION

This study presents a detailed computational analysis of pressure distribution and lift–drag characteristics of a missile model using CFD techniques. The results demonstrate that nose geometry plays a crucial role in determining aerodynamic performance.

The blunt nose configuration exhibits high stagnation pressure and drag, resulting in poor efficiency. The conical nose provides moderate improvement, while the streamlined (ogive) nose achieves the best aerodynamic performance with minimal drag and maximum lift-to-drag ratio.

The study confirms that CFD is a powerful tool for analyzing complex aerodynamic phenomena and optimizing missile designs. The insights gained from this work can be applied to the development of high-performance missile systems with improved efficiency, stability, and operational effectiveness.

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