A Review of Modern Missile Design

Tinghe Bai
University of Southampton, Southampton, Hampshire, United Kingdom, SO17 1BJ
baitinghe05@163.com

Abstract. This study examines the aerodynamic layout design of air-to-air missiles, focusing on the trade-offs between range, maneuverability, and combat effectiveness in short-range infrared (IR) and medium-range radar-guided missiles. The research analyzes historical case studies such as AIM-9 Sidewinder, AIM-120 AMRAAM, and R-77 Viper) to reveal the trade-off logic of different aerodynamic layout strategies. The study employs comparative analysis of missile configurations and performance metrics, integrating archival data on aerodynamic design principles. Key findings highlight that short-range missiles prioritize agility through unconventional layouts, while medium-range designs emphasize fuel efficiency and guidance accuracy. The research further identifies emerging trends, such as composite materials and hybrid propulsion systems, which aim to address thermal stress and extended operational ranges. The conclusions emphasize that missile design represents a dynamic equilibrium between conflicting requirements, and future advancements will depend on interdisciplinary innovations in materials science, avionics, and propulsion technology to enhance survivability and lethality in contested airspace.

Keywords: air-to-air missile, avionics, materials, airspace

1. Introduction

Humankind has always harbored the dream of soaring through the skies. It is undeniable that the most significant advancements in aviation technology have been driven by competition, especially in the context of war and confrontations. In the modern era, the air forces of major nations are actively developing various types of missiles to safeguard their airspace. This paper will categorizes air-to-air missiles carried by aircraft into infrared short-range missiles and radar-guided medium-range missiles. It will analyze how the intended use of these missiles affects aircraft design, focusing on aerodynamic layout, performance, and effective range.

Over the past fifty years, both academic reports and aviation exhibitions have shown that the aerodynamic shape of missiles has largely been standardized [1-2]. Radar-guided missiles with a range of 80 to 100 kilometers must not only ensure sufficient range but also maintain good maneuverability and speed during long-distance flight. Therefore, these missiles typically adopt a configuration similar to that of aircraft, with a main wing and tail fins. In contrast, short-range missiles with a range of 5 to 15 kilometers, which are usually designed for close combat, feature a canard and tail fin configuration. Since these missiles rely on infrared guidance, they cannot lock onto a target if the launch platform is too far away. Additionally, due to the nature of close-quarters combat, these missiles require high G-load tolerance, meaning they need to be highly agile. This explains why canards are used instead of main wings.

This paper primarily uses literature review to analyze the advantages and disadvantages of missiles of the same or different types. The goal is to identify the optimal design and achieve higher combat effectiveness. The analysis focuses on the active or retired air force equipment of the three permanent members of the United Nations. Some missile designs may appear unconventional and counterintuitive, yet their performance is exceptional. This can be attributed to the unique effects brought about by high-speed airflow under these specific aerodynamic layouts.

2. Literature review

After reviewing research, this paper found that a canard-tail configuration generates the highest G-loads at speeds between Mach 1 and 2, while a main wing-tail configuration only achieves optimal maneuverability at speeds between Mach 3 and 4. This discovery suggests that missile designers make trade-offs between drag, G-load capacity, and range to suit the specific purpose of each missile. Humankind's relentless pursuit of perfect performance has even led to some missiles being equipped with thrust vectoring technology, enabling them to achieve 40 to 50 Gs of turning force at subsonic speeds. Every missile from every country features a unique wing design, optimized through detailed adjustments to enhance overall combat effectiveness. Although the overall design framework has largely been established, wing placement is still decisive.

In recent years, the research on the impact of missile wing layout on range and maneuverability has presented a multi-dimensional discussion. In particular, for advanced air-to-air missiles such as AIM-9, AIM-120, R-77 and MICA-EM, researchers have conducted in-depth analysis from multiple aspects such as aerodynamic characteristics, guidance system and control surface design.

The AIM-9 Sidewinder missile has attracted much attention for its high maneuverability in close-range air combat due to its cross-tail layout. Douglass et al. pointed out that this cross layout not only improves the missile's roll response capability in close-range high-G environments, but also helps to shorten target acquisition time [3]. However, this design also sacrifices some stability and range in long-range operations.

The AIM-120 missile is known for its medium- and long-range combat capabilities, and its smaller wing layout has advantages in reducing drag. Chu et al. conducted an in-depth study of the guidance and range of the AIM-120, pointing out that it relies on the mid-range data link provided by the carrier to update the guidance information to ensure accurate guidance during the missile's mid-course flight, while the terminal flight relies on inertial guidance and active radar lock [4]. The missile's aerodynamic design balances maneuverability and range, making it the main weapon for medium and long-range air combat.

The grid tail rudder design of the R-77 missile is innovative in the field of aerodynamics. Carlo Kopp pointed out that this design gives the missile extremely high maneuverability, especially when facing high-G maneuvers. The grid tail rudder can reduce lift loss while maintaining stability, allowing the R-77 to perform efficient maneuvers in complex air combat environments. However, its complex structure increases flight resistance, which in turn has a certain negative impact on the range.

Compared with the grid tail rudder of the R-77, the L-shaped tail rudder design of the MICA-EM missile enhances the aerodynamic balance and maneuverability of the missile while improving overload performance. Li Xiaolin's research shows that the combination of the small side strips and long side strips of the MICA missile's head not only enhances the overload capacity, but also reduces the rudder deflection angle, ensuring the missile's high efficiency in medium and long-range interception and close-range combat. Compared with the R-77, the MICA missile has achieved a better balance between maneuverability and stability [5]. Its design focuses more on stable control in medium-range flight, while the R-77 focuses more on high maneuverability in the terminal phase.

In comprehensive comparison, the design of the AIM-9 emphasizes close combat maneuverability, while the AIM-120 emphasizes long-range range and precision guidance; the R-77 enhances high maneuverability through the grid tail rudder, but at the cost of increased resistance; the MICA-EM achieves higher control stability and flexibility in combat at different distances through the fine tail rudder and side strip design [6]. These studies show that the design of missile wing layout is a complex trade-off between range and maneuverability, and the design strategies of various countries are all seeking the best balance between the two.

By integrating research from different missiles, this review shows the diversity of missile aerodynamic layouts and their impact on range and maneuverability. The advantages and trade-offs of different design strategies are also fully reflected in the performance of these missiles.

3. Theoretical fundamental

The AIM-120 AMRAAM, a primary medium-range air-to-air missile for the U.S. Air Force and its allies, employs a hybrid guidance system combining inertial navigation and command guidance. During its initial flight phase, it relies on inertial navigation and platform positioning data to establish its trajectory. Mid-course corrections are made via data link updates, while the terminal phase activates its active radar seeker for precise interception of high-speed maneuvering targets. The missile features robust Electronic Counter-Countermeasure (ECCM) capabilities to maintain guidance stability in complex electromagnetic environments. Its streamlined airframe and four-tailfin configuration ensure low drag and high maneuverability during supersonic flight.

The R-77 (NATO designation: AA-12 "Adder"), Russia's counterpart, utilizes inertial/command mid-course guidance and active radar terminal homing for rapid target acquisition. Its grid-style rudders at the tail enhance control efficiency and lateral force generation during supersonic flight, enabling large off-boresight interception. For navigation, the R-77 similarly depends on gyroscopes and accelerometers for positioning, supplemented by data link-based target updates.

Europe's MICA-EM, a multirole medium-range air-to-air missile, integrates inertial/command mid-course guidance with active radar terminal homing. Real-time data link adjustments allow it to maintain high hit probability in multi-target environments. Its aerodynamic design balances low drag and high lift through small-aspect-ratio wings and drag-reduction treatments on the airframe surface, granting both agile maneuverability and extended range. Structurally, the MICA emphasizes lightweight yet high-strength materials, utilizing advanced composites and heat-resistant coatings to withstand thermal stresses during supersonic flight, achieving exceptional reliability and dynamic performance.

4. Challenges and future direction

4.1 Missile Design Challenges and Future Directions

Missile design faces multiple challenges and bottlenecks, the most significant being the trade-off between material strength and structural integrity. During supersonic or hypersonic flight, the airframe endures intense aerodynamic heating and shock, demanding extreme heat resistance and structural robustness. Simultaneously, precise attitude control and stability during maneuvers necessitate advanced control algorithms and high-precision sensors. However, electronic systems are prone to failure under high-G loads, imposing stringent requirements on guidance accuracy and data processing. Additionally, missiles must integrate robust anti-jamming capabilities to operate in complex electromagnetic environments, complicating the design of radar, communication, and data link systems. Limited internal space further exacerbates layout conflicts, making the balance between weight and performance a critical design bottleneck.

Another challenge lies in the short duration of the powered flight phase. After 10–20 seconds of propulsion, missiles rely solely on residual kinetic energy for gliding, while adversary aircraft retain ample fuel for evasive maneuvers. Proposed solutions include auxiliary or emergency fuel pods for terminal acceleration. If the missile is too distant from the target after engine cutoff, it self-destructs; if proximity permits, reserved fuel enables a final strike attempt.

4.2 Future Innovations

Emerging materials and advanced manufacturing techniques, such as composites and 3D printing, promise to reduce weight while enhancing durability and shortening development cycles. Multifunctional warheads and modular designs will adapt to diverse mission requirements.

At the material level, composites (e.g., carbon fiber-reinforced polymers, CFRP) and intermetallic compounds (e.g., titanium aluminides) offer higher stiffness-to-weight ratios, replacing traditional aluminum or steel alloys. For guidance systems, next-generation missiles prioritize multi-source data fusion, combining inertial navigation, satellite positioning, and data link updates via low-Earth orbit (LEO) satellite networks to maintain target tracking during high-speed maneuvers. Radar seekers are evolving toward miniaturized, digital active electronically scanned array (AESA) systems with enhanced sensitivity and anti-jamming capabilities.

In propulsion, hybrid systems like turbojet-ramjet or rocket-ramjet engines are gaining traction, aiming to maintain efficiency across subsonic to hypersonic regimes while extending operational ranges. These advancements will collectively elevate missile performance in range, agility, and precision, ensuring survivability and lethality in contested environments to maintain technological superiority in global military competition.

5. Conclusion

This study systematically analyzes the aerodynamic design trade-offs in modern air-to-air missiles, contrasting short-range infrared (IR) and medium-range radar-guided variants. Case studies (e.g., AIM-9, AIM-120, R-77) reveal that IR missiles prioritize maneuverability through unconventional layouts (e.g., canard-tail configurations), while radar-guided designs optimize stability and range via streamlined profiles. Key findings underscore the critical role of material strength, guidance reliability, and propulsion limitations in defining combat effectiveness. However, the research has limitations: 1) Simulation data for emerging designs (e.g., hypersonic missiles) remain scarce; 2) Cost-benefit analyses of advanced materials (e.g., ceramic composites) require deeper quantitative validation. Future studies should focus on: 1) Integrating machine learning for adaptive aerodynamic optimization; 2) Experimental validation of hybrid propulsion systems (turbojet-ramjet) under extreme conditions; 3) Modular design frameworks to balance multi-role capabilities and cost constraints. Advancements in these areas will enable next-generation missiles to overcome current thermodynamic and electronic warfare challenges while maintaining agility-range equilibrium.

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