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Design of 5th generation fighter aircraft engines: key parameters of next-generation technologies

5. Nesil savaş uçağı motorlarının tasarımı: yeni nesil teknolojilerin temel parametreleri

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ABSTRACT

5th generation aircraft engines are designed to meet requirements such as low radar visibility, high maneuverability, and fuel efficiency. This review paper examines how key design parameters like thrust-to-weight ratio, thermal efficiency, fuel consumption, and multi-mission capabilities are prioritized and optimized in this generation. Additionally, comparisons with prior generation aircraft engines are made, analyzing how new technologies bring forth unique advantages in this generation. Special attention is given to the effectiveness of afterburner systems, design innovations enabling low radar visibility, and how engine integration contributes to enhanced aerodynamic performance. The study evaluates how 5th generation engines achieve greater fuel efficiency while simultaneously offering higher speed, maneuverability, and reduced detectability compared to previous generations. This work aims to explain the innovative parameters that are prominent in the design of 5th generation aircraft engines and their critical role in achieving air superiority.

ÖZET

Bu makale, 5. nesil savaş uçaklarında kullanılan jet motorlarının tasarım parametreleri ve özelliklerine odaklanmaktadır. 5. nesil uçak motorları, düşük radar görünürlüğü, yüksek manevra kabiliyeti ve yakıt verimliliği gibi gereksinimleri karşılayacak şekilde tasarlanmıştır. Bu derleme makalesinde, itki-ağırlık oranı, termal verimlilik, yakıt tüketimi ve çoklu görev yetenekleri gibi temel tasarım parametrelerinin bu nesilde nasıl önceliklendirildiği ve optimize edildiği incelenmektedir. Ayrıca, daha önceki jenerasyonların uçak motorlarıyla karşılaştırmalar yapılarak, yeni teknolojilerin bu nesilde sunduğu farklılıklar analiz edilmektedir. Özellikle, art yakıcı sistemlerin etkinliği, düşük radar görünürlüğünü sağlayan tasarım yenilikleri ve motor entegrasyonunun geliştirilmiş aerodinamik performansa katkısı üzerinde durulmaktadır. Çalışma, 5. nesil motorların, önceki nesillere kıyasla daha yüksek hız, manevra kabiliyeti ve azaltılmış tespit edilebilirlik sağlarken aynı zamanda daha yüksek yakıt verimliliği nasıl elde ettiğini değerlendirmektedir. Bu çalışma, 5. nesil uçak motorlarının tasarımında öne çıkan yenilikçi parametreleri ve hava üstünlüğünü sağlamadaki kritik rollerini açıklamayı amaçlamaktadır.

1. Introduction

Due to its strategic location, Turkey has historically faced numerous regional and global threats. Airspace security is at the core of both national defense and external security strategies. In contemporary warfare, the dynamics of conflict and security underscore the critical importance of air superiority. Control of airspace is a decisive factor influencing the success of military operations. Air superiority limits the mobility of enemy forces, enhances intelligence-gathering capabilities, and increases the effectiveness of strikes against ground targets [1]. In this context, fighter attack aircraft, with their ability to effectively strike enemy targets and establish air superiority, have become indispensable elements of modern military forces.

Many nations allocate a significant portion of their defense budgets to air forces, particularly to fighter aircraft. For instance, the United States plans to spend approximately $216 billion of its $835 billion defense budget for 2024 on fighter aircraft and air force technologies [2]. Meanwhile, China is predicted to spend approximately $236 billion budget defense [3]. These figures clearly illustrate how air power plays a decisive role not only in military strategies but also in the power dynamics of international relations. In conclusion, air superiority remains at the heart of modern warfare, continuing to be a critical factor in shaping national security strategies and ensuring future military success.

New-generation aircraft are critical for achieving dominance in modern battlefields. Their ability to conduct missions undetected thanks to low radar signatures, coordinate operations with other elements through network-centric warfare and deliver high speed and maneuverability with advanced engine designs make them an integral part of future military strategies.

From this point of view, it is critical to review past, current and possible future trends in fighter craft engines. This paper will examine the design parameters used in the engines of 5th generation fighter aircraft in detail and analyze how these parameters have evolved since the 1st generation. To do so, books about fighter aircraft and gas turbine engines, military reports, news and official websites of fighter aircraft engine producers were focused and examined. Additionally, comparisons with previous generation aircrafts engine parameters will help better understand the impact of technological advances on 5th and next-generation aircraft engines.

2. Evolution Fighter Aircrafts

The development of fighter aircraft has evolved rapidly since the 1st generation. 1st generation jet aircraft (late 1940s-1950s) participated in basic air combat with designs focused solely on thrust and speed, lacking radar systems. These aircraft were unable to reach supersonic speeds and had limited range. 2nd generation aircraft (1950s-1960s) were equipped with radar and air-to-air missile systems, adapting to more complex combat environments, although they still had low maneuverability and limited electronic warfare capabilities [4].

3rd generation aircraft (1960s-1980s) saw improvements in thrust, range, and maneuverability. Radar systems were further enhanced, and air-to-ground attack capabilities were expanded. 4th generation aircraft (1980s-2000s) became multi-role platforms with advanced radars, sensors, speed, and maneuverability. Iconic aircraft like the F-16 and Su-27 symbolize this era. While thrust-to-weight ratios and long-range supersonic speeds became significant features, stealth capabilities were not yet widely adopted [5].

The subsequent 4.5th generation aircraft can be described as advanced versions of 4th generation planes, equipped with improved electronic warfare systems, technologies reducing radar cross-section, and network-centric warfare capabilities. However, they do not have the comprehensive stealth features of 5th generation aircraft. Models such as the Eurofighter Typhoon and Dassault Rafale are considered part of the 4.5th generation [1].

5th generation fighter aircraft (2000s and beyond) represent a completely new era in air combat. These aircraft differentiate themselves from previous generations with features such as low radar visibility, supersonic cruising, advanced sensor fusion, network-centric warfare capabilities, and high thrust-to-weight ratios. For example, the F-35 Lightning II and F-22 Raptor combine low radar signatures, high thermal efficiency, and optimized afterburner systems, enabling long-range supersonic operations. Over the past 30 years, advancements in fighter aircraft aim not only to ensure air superiority but also to provide operational versatility [6]. The general trends in fighter aircraft generations were summarized in **Table 1**. The parameters represented in the table are generic approximate values of different generations of fighter aircrafts.

Table 1. General overview of fighter aircrafts with different generations [7]

Generation	Period	Aircrafts	Key Features
1st Generation	Late 1940s-1950s	F-86 Sabre, MiG-15, Gloster Meteor, Hawker Sea Hawk	- No radar - Subsonic speeds - Simple weapon systems -No radar - Limited air-to-air missiles
2nd Generation	1950s-1960s	F-104 Starfighter, MiG-21, English Electric Lightning, F-5	- Equipped with radar and missiles - Supersonic speeds - Improved maneuverability
3rd Generation	1960s-1980s	F-4 Phantom II, MiG-23, Mirage III, A-7 Corsair II	-Supersonic speeds -Afterburners - Advanced radar and avionics - Air-to-ground attack capability
4th Generation	1980s-2000s	F-16 Fighting Falcon, Su-27 Flanker, MiG-29, Mirage 2000	-Fly-by-wire controls -Multi-role capability - Advanced sensors and radars - Supersonic cruising
4.5th Generation	1990s-2020s	Eurofighter Typhoon, Dassault Rafale, F/A-18E/F, Su-35	- Advanced electronic warfare - Network-centric warfare capabilities - Stealth technologies
5th Generation	2000s and beyond	F-22 Raptor, F-35 Lightning II, Su-57, Chengdu J-20	- Low radar signature - Supersonic cruising - Sensor fusion and networked warfare capabilities
6th Generation	2030s (expected)	NGAD (USA), BAE Tempest (UK), Future Combat Air System (FCAS - Europe)	-AI integration -Unmanned capabilities -Hypersonic speeds -Directed energy weapons.

3. Propulsion Systems of Fighter Aircraft

The propulsion system is the core component of a fighter aircraft that generates the thrust required for flight. It enables the aircraft to overcome drag, achieve lift, and sustain maneuverability across a wide range of speeds and altitudes. Propulsion systems are integral not only to basic flight mechanics but also to mission-specific performance, influencing critical factors such as speed, agility, endurance, and stealth [8].

Modern fighter aircraft propulsion systems are primarily jet engines, which can be categorized into turbojets, turbofans, ramjets, and scramjets. These systems operate on principles derived from Newton's third law of motion, where air is ingested, compressed, mixed with fuel, and ignited, creating high-velocity exhaust gases that produce thrust.

3.1. Key Requirements of Fighter Aircraft Propulsion Systems

High Thrust-to-Weight Ratio: Fighter aircraft engines are designed to deliver maximum thrust while maintaining minimal weight, enabling rapid acceleration, vertical climbs, and sustained supersonic flight.

Supersonic and Hypersonic Capability: Advanced propulsion systems enable sustained flight at supersonic speeds (Mach 1+) and, in some cases, hypersonic speeds (Mach 5+), crucial for intercept missions and evasion.

Fuel Efficiency: While high thrust is a priority, fuel efficiency ensures extended range and operational endurance, particularly important for long missions or combat patrols.

Agility and Responsiveness: The propulsion system must support sudden throttle changes for quick maneuvers, afterburner activation for bursts of speed, and optimized performance during high-g maneuvers.

Stealth Characteristics: Modern engines often incorporate design features that minimize infrared and radar signatures, critical for avoiding detection in hostile environments.

Reliability and Durability: A robust propulsion system must perform consistently in varying operational conditions, including high temperatures, high altitudes, and combat damage scenarios.

4. Evolution of Propulsion System Parameters Across Fighter Aircraft Generations

The propulsion systems of fighter aircraft have evolved significantly across different generations. The parameters in the **Table 2** highlight key aspects of engine performance and efficiency.

Table 2. Main engine parameters and key features from different generations of fighter aircraft [7], [9], [10], [11], [12], [13], [14], [15]

Parameter	1st Gen.	2nd Gen.	3rd Gen.	4th Gen.	4.5th Gen.	5th Gen.
Type	Turbojet	Turbojet	Turbojet and Turbofan (Rare)	Turbofan	Turbofan	Turbofan
Thrust-to-Weight Ratio	3:1	3:1 - 5:1	5:1 -6:1	5:1 - 8:1	6:1 - 9:1	8:1 - 9:1
Specific Fuel Consumption (lb/lbf-hr)	1-1.2	1.8-2	0.8-1 1.8-2(with afterburner)	0.7-0.9 1.8 (with afterburner)	0.7-0.8 1.6-1.7 (with afterburner)	0.6-0.8 1.8 (with afterburner)
Design Mach Number	0.8 - 0.9	0.8 - 0.9	1.0 - 2.2	1.5 - 2.2	1.5 - 2.5	1.7 - 2.5
Supercruise Speed (Mach)	None	None	Rare (1.2 Mach)	Rare (1.2 Mach)	Common (1.4 Mach)	Common (1.7 Mach)
Overall Pressure Ratio	5:1	9:1 - 13:1	10:1 - 13:1	21:1 - 24:1	25:1 - 26:1	26:1 - 28:1
Bypass Ratio (Turbofan)	N/A	N/A	0.7:1	0.5:1 – 0.6:1	0.4:1 – 0.3:1	0.3
Afterburner Usage	None	Rare	Yes	Yes	Yes	Common
Stealth Compatibility	None	None	None	Partial	Partial	Yes
Radar Cross Section (RCS)	Large (10 m^2 or more)	Large (10 m^2 or more)	Moderate (3-5 m^2)	Small (1-3 m^2)	Small (0.5-1 m^2)	Very Small (<0.1 m^2)
Operational Altitude (m)	12000	12000	15000	18000	18000	20000

Specific fuel consumption (SFC), which measures engine fuel efficiency, has increased significantly over time. 1st to 2nd generation aircraft due to requirements of speed and thrust. As turbofan technology improved in later generations, SFC values dropped, reaching around 0.6 lb/lbf-hr in 5th generation aircraft. This decrease reflects the more efficient fuel consumption of modern engines. On the other hand, to sustain supersonic speeds, there was emerging technology of afterburner which increase SFC after 3rd generation. For the following generations, it seems that SFC are tried to be decreased by reheating and supercruise technologies.

The design Mach number, which indicates the optimal speed for the aircraft, has also increased over generations. Early fighters were designed for subsonic to transonic speeds (Mach 0.8-0.9), while 3rd, 4th, and 5th generation fighters are designed to fly at supersonic speeds, with some capable of reaching Mach 2.5. Supercruise capability, the ability to fly at supersonic speeds without afterburners, has become a key feature in 4th and 5th generation aircraft, providing greater operational efficiency and mission flexibility.

Afterburner usage, though still common in 2nd and 3rd generation aircraft, has become less frequent in modern designs due to the advent of supercruise capabilities. This enables newer fighters to sustain supersonic speeds without the need for afterburners, offering better fuel efficiency.

Stealth technology has significantly reduced the radar cross-section (RCS) of 5th generation fighters. While older aircraft had large RCS values, modern fighters like the F-22 and F-35 have RCS values as low as 0.1 m^2, making them much harder to detect by enemy radar systems.

Finally, operational altitude has increased with each generation. Early fighters operated at altitudes around 12,000 meters, while 4th and 5th generation fighters can fly at altitudes above 20,000 meters, offering tactical advantages in terms of fuel efficiency and mission flexibility.

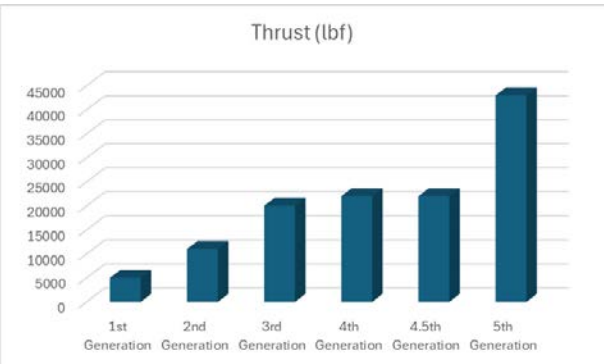

Figure 1. Maximum thrust values at different fighter aircraft generations

Peak thrust (**Figure 1**) has increased substantially from 1st generation to 5th generation fighters. Early turbojet engines in 1st and 2nd generation aircraft produced relatively lower thrust, around 5000-11000 lbf. However, with the introduction of more advanced turbofan engines in later generations, thrust values have risen dramatically, reaching up to 40,000 lbf in modern 5th generation fighters such as the F-22 Raptor and F-35 Lightning II. This increase in thrust has also resulted in a corresponding rise in thrust-to-weight ratios, allowing for better maneuverability and overall performance in modern fighters.

Overall pressure ratio and turbine inlet temperature are important indicators of engine performance. Over the generations, both parameters have improved, with CPR rising from about 5:1 in early jets to over 28:1 in modern aircraft. Similarly, turbine inlet temperatures have increased from around 1000°C up to 2000°C, (**Figure 2.**) allowing modern engines to operate at higher speeds and altitudes with greater efficiency thank to advanced high-technology metals. However, due to comparatively slow material thermal performance improvements, cooling requirements increased significantly [16].

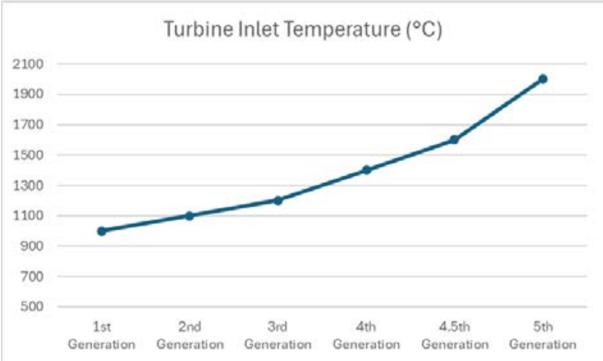

Figure 2. Turbine inlet temperature comparison of different generations

The bypass ratio, which influences engine efficiency and thrust, has decreased over time as well. Early turbojet engines had no bypass ratios due to absence of by-pass air, while modern turbofan engines in 4th and 5th generation aircraft have bypass ratios of up to 0.3:1, improving thrust.

In conclusion, the advancements in propulsion technology across fighter aircraft generations have significantly enhanced performance, fuel efficiency, speed, stealth, and overall mission capability. Modern 4th and 5th generation fighters outperform their predecessors in virtually all aspects of propulsion, providing superior combat capabilities in today's strategic environment.

Fighter aircraft propulsion systems continue to evolve, integrating emerging technologies such as adaptive cycle engines, which can optimize thrust and efficiency in different flight conditions, and electric or hybrid propulsion systems for future sustainability goals. These innovations aim to further enhance performance, reduce maintenance requirements, and meet the growing demands of modern aerial combat.

Conclusion

In this paper, fighter jet aircraft engines from different generations were evaluated from 1st to 5th generation. Main engine parameters were presented and the trend of them was discussed. Data about turbofans and early generation turbojets gas turbine engine acquired from military reports, official websites from producers and the books focusing on the air fighter jets. The evolution of jet engines across generations of fighter aircraft showcases significant advancements in propulsion technology, reflecting the changing priorities and requirements of aerial combat. Outcomings from this investigation can be summarized as following:

- **1st Generation:** Basic turbojet engines characterized by simple designs, limited efficiency, and subsonic performance were predominant. These engines lacked afterburners and were optimized for early jet-powered flight.
- **2nd Generation:** The introduction of afterburner-equipped turbojet engines enabled sustained supersonic speeds and improved thrust capabilities, meeting the demands of evolving aerial combat scenarios.
- **3rd Generation:** Early turbofan engines with low bypass ratios began replacing turbojets, offering better fuel efficiency and maintaining high thrust for supersonic speeds. This marked a shift towards more versatile and efficient propulsion systems.
- **4th Generation:** Low bypass turbofan engines became the standard, emphasizing a high thrust-to-weight ratio, enhanced maneuverability, and better fuel efficiency to support multi-role combat missions.
- **4.5th Generation:** Advanced turbofan engines with improved fuel efficiency and reduced thermal signatures were developed. These engines introduced supercruise capabilities, enabling sustained supersonic flight without afterburners.
- **5th Generation:** Highly advanced turbofan engines prioritize stealth, supercruise capability, and reduced radar and thermal signatures. These engines are optimized for multi-mission flexibility and superior aerodynamic integration.

In future generations, emerging engine technologies focus on adaptive cycle designs to enhance fuel efficiency, operational flexibility, and performance across multiple mission profiles. These engines aim to achieve unprecedented speeds and sustain hypersonic capabilities. To conclude, each generational leap in jet engine technology reflects a progression in design priorities, from fundamental propulsion needs to advanced capabilities like stealth, Supercruise, and adaptability for diverse mission requirements. These advancements underline the critical role of jet engine innovation in shaping the effectiveness and dominance of modern fighter aircraft.

Çıkar Çatışması Beyanı: Yazarlar herhangi bir çıkar çatışması olmadığını beyan etmişlerdir.

Fonlama Bilgileri: Bu çalışma herhangi bir fon tarafından desteklenmemiştir.

Yazar katkısı: Yazarlar, çalışmanın tasarlanması, verilerin toplanması, sonuçların analizi ve yorumlanması ve makalenin hazırlanması ile ilgili sorumluluklarını onaylamaktadır.

Veri Kullanılabilirlik Beyanı: Bu çalışma sırasında üretilen ve/veya analiz edilen veriler kamuya açık değildir, ancak veriler makul bir talep üzerine ilgili yazar tarafından sağlanabilir.

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