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Research on the Stealth Capability of Sixth-Generation Fighter Jets

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Abstract. With the development of artificial intelligence, science, and technology, developing countries have begun to modernize their newest fighter jets, while advanced countries have started to redefine the new generation of aircraft. This has led to the development of aircraft of different generations being put on the agenda. Therefore, to have a comprehensive understanding and knowledge of the new generation of aircraft, this paper mainly takes the new generation of sixth-generation fighter jets as the research object and makes inferences and analyses on the performance of the developed sixth-generation fighter jets. It makes detailed inferences and simulations of the stealth capability of the sixth-generation fighter jets to demonstrate the basic and combat capabilities that a sixth-generation fighter jet should possess. Overall, through this analysis of the combat capabilities possessed by the sixth-generation aircraft, this study also aims to not only gain a better knowledge of this fighter jet but also may provide some insights for the future development of fighters.

INTRODUCTION

With the development of global technology, even in relatively peaceful times, the arms race among countries has never ceased, especially in the air domain, where the development of fighter jets has become an important symbol of a country's strength. Since the Wright brothers first achieved powered flight in 1903, humanity has evolved from the rudimentary four-cylinder chain propeller aircraft to the sixth-generation fighter aircraft that integrates artificial intelligence, stealth technology, and high maneuverability. This leapfrog evolution can be roughly divided into three stages.

The first stage was dominated by early aircraft with biplane or multi-wing structures (1900s - 1930s). Due to the limited thrust of engines at that time, the biplane structure provided greater lift through the upper and lower main wings and became the mainstream design. Typical representatives include the Wright brothers' "Flyer One" and " Sopweis Camel". Although multi-wing designs (such as three-wing and nine-wing) have improved lift, they were not widely applied due to their complex structure and high aerodynamic drag. They were only briefly used in the 1910s, such as in models like the "Fokker Dr. I" and the "Caproni Ca.60". After entering the 1930s, the compound wing structure was gradually replaced by the single wing [1].

The second stage was the rise of single-wing propeller aircraft (1930s - 1940s). Although early single-wing tests mostly failed, with the emergence of new technologies such as aluminium alloys, skin structures, and cantilever wings, single-wing aircraft gradually overcame structural bottlenecks. They became mainstream due to their lower drag, higher speed, and better fuel efficiency. During World War II, almost all fighter jets adopted a single-wing layout, such as the P-51 Mustang of the United States, the Bf 109 of Germany, the Zero of Japan, and the Spitfire of the United Kingdom. These aircraft all demonstrated the most advanced aviation design concepts at that time [2].

The third stage was after the end of World War II. With the emergence of jet engines, a large number of fighter jets began to undergo revolutionary innovations. Both the United States and the Soviet Union began to be equipped with jet fighters with new-generation engines. This was the emergence of the first-generation fighter jets, such as the Soviet Union's MiG-15 and the United States' F-86. The use of centrifugal or axial-flow jet engines still relies on visual combat. So, to adapt to more combat missions and combat environments, second-generation fighter jets were developed (from the 1950s to the 1960s), such as the F-104, MiG-21, and the upgraded old F-86 and MiG-15. This generation of aircraft is equipped with early engines with afterburner jets. Such engines can fully compress air and achieve higher speeds through afterburner combustion while also increasing cruising altitude. In addition, the second fighter jet was equipped with fire control radars and the first-generation air-to-air missiles for the first time, which enabled it to have supersonic combat capabilities and stronger air combat capabilities. The introduction of these aircraft poses a huge threat to the combat units covered by the old-fashioned anti-aircraft guns. So, with the introduction of radar anti-aircraft missiles and more advanced surface-to-air defense weapons, for fighter jets to still be capable of completing ground strike missions, the third-generation fighter jets emerged (in the 1960s-1970s), such as the F-4 "Ghost" and the MiG-23. These aircraft were equipped with more advanced turbojet engines. While increasing the top speed of the aircraft, the cruising altitude of the aircraft has also been enhanced. Meanwhile, with the upgrade of the fire control radar, the aircraft can launch guided radar projectiles with a longer range, which further improves the combat capability of the aircraft. With the further development of air defense weapons, fourth-generation fighter jets (1970s-1990s) emerged, such as the F-15, Su-27, and J-10. These aircraft had high maneuverability, advanced radars and flight control systems, used higher-performance turbofan booster engines, and their weapons also began to employ more advanced, precisely guided weapons. With the emergence of more advanced search radars, the threat of radars to aircraft has been increasing. As a result, fifth-generation fighter jets with stealth capabilities (from the 2000s to the present) have emerged, such as the F-22, F-35, and J-20. These aircraft have more advanced aircraft structures that enable them to minimize radar echoes to the greatest extent. Meanwhile, the advanced stealth coating can also absorb the radar beam. At the same time, the fifth-generation aircraft began to use the new generation of thrust vector-controlled turbofan engines. It can ensure the maneuverability and performance of the aircraft to a greater extent [3].

With the development of artificial intelligence and detonation engines, the sixth-generation fighter jets have gradually come into people's view, such as the F-47 of the United States, the J-36 of China, and the FCAS of Europe. These aircraft have perfectly applied artificial intelligence, human-machine collaboration, hypersonic flight, and variable stealth technology to the revolutionary and innovative aircraft fuselages. Meanwhile, the engine of the sixth-generation aircraft is an adaptive cycle engine, which has stronger thrust management and thermal energy control capabilities [4].

This article conducts a detailed analysis of the stealth capabilities possessed by the sixth-generation fighter jets and the performance of the new-generation engines. The basic stealth capabilities of the sixth-generation aircraft are inferred by analyzing the capabilities of the existing known ground-to-air search radars and air-to-air search radars. This is to demonstrate the air combat advantages of the sixth-generation aircraft. Finally, through the research of this paper, the prospects and personal suggestions for the future development of sixth-generation fighter jets are put forward.

THE STEALTH CAPABILITY OF SIXTH-GENERATION FIGHTER JETS AGAINST DIFFERENT RADAR BEAMS

Stealth capability in modern fighter aircraft does not mean visual invisibility but rather an exceptionally low electromagnetic signature, specifically a reduced Radar Cross Section (RCS), as perceived by enemy radar systems. In optimal conditions, this reduction can lead to "radar invisibility," making the aircraft nearly undetectable by conventional radar. Achieving such a capability is highly resource-intensive and imposes stringent requirements on the overall aircraft design. It relies on two principal strategies: first, minimizing radar wave reflection through airframe shaping techniques, including angled surfaces and serpentine (S-shaped) air inlets that deflect incoming radar waves; second, applying advanced stealth coatings and utilizing radar-absorbent materials (RAM) to create a stealth skin that absorbs and dissipates radar energy [5].

With the advancement of aerospace technology, stealth capability has gradually become a fundamental requirement in modern aerial combat. From early stealth platforms such as the F-117 and B-2 bombers to the more recent upgrades in fourth-generation fighters—including the U.S. F-15 Silent Eagle, China's J-10B/C, and France's Rafale—numerous air forces have enhanced the stealth features of their aircraft, demonstrating that stealth has evolved from an advanced capability to a necessary capability [6]. At the same time, modern stealth fighters are also expected to maintain high levels of maneuverability, operational range, and weapons payload, which significantly increases the complexity of aircraft design.

The operational role of sixth-generation fighter jets places greater emphasis on "node control" and "information dominance" within integrated combat systems. These aircraft are often tasked with escorting high-value assets such as airborne early warning aircraft and strategic bombers, as well as executing precision strikes against enemy strategic targets. As a result, the stealth requirements for sixth-generation fighters are significantly more stringent. In operational environments saturated with advanced detection technologies, such as high-performance Doppler radars and active electronically scanned array (AESA) radars, conventional stealth techniques are approaching their limitations [7].

Consequently, sixth-generation platforms must not only enhance traditional stealth capabilities but also explore next-generation low-observability solutions tailored for multi-domain battlefields. These include multispectral stealth, digital electronic warfare (DEW), and cooperative tactics involving unmanned loyal wingmen to induce and disrupt enemy targeting systems [8].

The ongoing contest between stealth and anti-stealth technologies resembles an ever-evolving arms race—a perpetual cycle of offense and defense, much like a spear-and-shield dynamic. In this "cat-and-mouse" game, the core challenge lies in maintaining information superiority in the face of increasingly sophisticated detection systems, making it one of the most formidable technical hurdles in sixth-generation fighter development.

Radar Frequency Bands and Their Challenges to Stealth Aircraft

In modern aerial combat, the fastest way to detect enemy fighter jets often relies on friendly airborne early warning aircraft, which, due to their greater radar power and scanning range, can detect targets first and share target information in real time with combat aircraft via data links. This enables a strategy of "preemptive deployment." Within such an operational system, stealth technology becomes a key factor in enhancing the combat effectiveness of modern fighter jets. By reducing detectability in enemy radar systems, it allows for surprise attacks—detecting the enemy first, firing first, and achieving early kills.

However, different radar frequency bands pose varying challenges to stealth technology. Stealth aircraft must minimize their RCS across multiple frequency bands to achieve multi-band stealth. This section will analyze the characteristics of typical radar frequency bands and discuss corresponding stealth strategies, while also speculating on the potential stealth capabilities of sixth-generation fighter jets.

Radar systems operate across different frequency bands. Current operational radars are mainly distributed among the X, S, L, UHF, and VHF bands, as shown in Figure 1. Each band corresponds to a different wavelength range, which significantly affects its ability to detect targets.

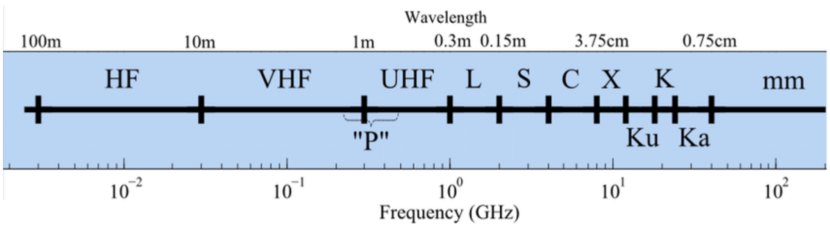


FIGURE 1. Common Radar frequency bands. (Picture credit: Original)

X-band Radar

The X-band, with a wavelength range of 3.75 cm to 2.5 cm and a frequency between 8–12 GHz, is the primary focus of stealth design. It is widely used in fighter fire-control radars and missile guidance systems. Due to its narrow radar beams and high resolution, the X-band plays a crucial role in target identification and precision guidance. As a result, stealth aircraft are typically optimized for this band. Techniques such as angled airframe contours combined with RAM are employed to control radar wave scattering directions, thereby reducing the RCS to below 0.001 m².

S-band Radar

The S-band operates between 2–4 GHz, with wavelengths ranging from 15 to 7.5 cm. It is mainly used in shipborne and ground-based air defense radar systems. Due to its longer wavelengths, it can cause strong resonance with certain aircraft structures, such as wings and air intakes, resulting in increased radar reflections. Additionally, the wider radar beams in this band are more prone to diffraction and scattering effects, posing challenges to stealth targets [9].

However, fifth-generation stealth fighters can still maintain a degree of stealth against S-band radar by using multilayer RAM, Frequency Selective Surfaces (FSS), and optimizing local structural design to effectively reduce scattering intensity.

L-band Radar

L-band radar operates in the 1–2 GHz frequency range, with wavelengths between 30 and 15 cm. Its wavelength is closer in scale to major aircraft structures, giving it strong structural penetration capabilities. It is widely used on long-range early warning and airborne surveillance platforms such as the KJ-2000 and A-50U. This band enables stable detection over large areas and at high altitudes, posing a significant threat to current stealth aircraft. As a result, many countries equip their early warning systems with L-band radar to enhance their ability to detect stealth targets [10]. Against the L-band, stealth fighters find it difficult to fully evade radar illumination and must instead rely on tactical measures to delay detection, thereby improving survivability. This highlights the need for sixth-generation fighters to achieve fundamental breakthroughs in radar-absorbing materials, airframe shaping, and composite structural design to maintain effective stealth within this frequency range.

UHF and VHF Band Radars

In contrast, UHF-band radar has wavelengths exceeding 1 meter, far longer than the scale of aircraft structures, giving it a natural advantage in “bypassing stealth design.” Traditional fifth-generation fighters lose almost all stealth effectiveness against UHF-band radar and are highly susceptible to detection. In modern aerial warfare, the primary countermeasure against UHF radar is electronic suppression, involving techniques such as radar jamming or deception. Stealth aircraft can rely on external electronic warfare (EW) pods or coordinated operations with loyal wingman drones to penetrate defenses under the cover of electronic interference, effectively delaying detection [11].

Currently, VHF-band radar is gaining considerable attention in the field of counter-stealth detection. Operating in the 30–300 MHz frequency range with wavelengths from 1 to 10 meters [12], VHF radar offers strong anti-stealth capability and long-range detection potential. Due to its wavelengths being much larger than the critical structural features of aircraft, radar waves tend to diffract significantly over stealth targets, thereby producing effective returns. Countries such as the former Soviet Union and Russia have long deployed various VHF long-range air surveillance radars, such as the P-14 and P-18 "Spoon Rest." However, the VHF band also comes with inherent limitations, including large antenna sizes and low resolution. In recent years, new-generation ground-based radar systems like Russia’s "Niobium-SV" have made significant advancements in anti-jamming and resolution through the use of digital phased array antennas [13], signal fusion, and multi-static coordination technologies. These developments compel future stealth aircraft to further enhance their adaptability across radar frequency bands in order to maintain the advantage of "delayed detection."

Multi-Frequency Stealth and Electronic Countermeasures in Sixth-Generation Fighters

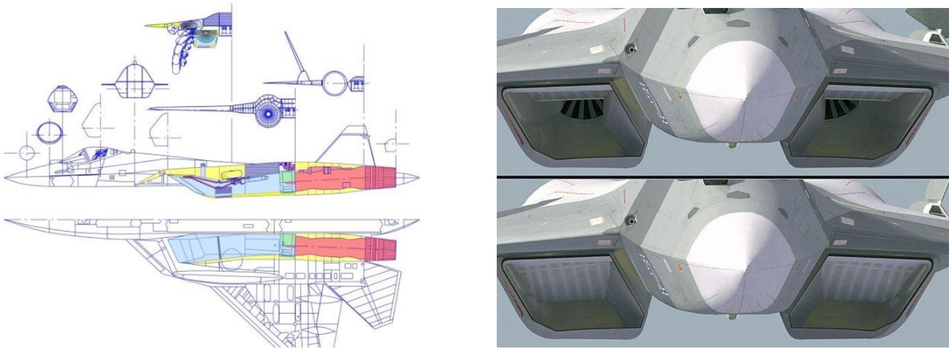
In the context of today's technological landscape and strategic environment, the specific parameters of radar systems are no longer classified secrets. The real challenge for sixth-generation fighter jets lies in how to break through these well-fortified defenses—an essential leap they must make. This paper will explore and speculate on the potential stealth capabilities and methods that the next generation of sixth-generation fighters may possess, based on current technological conditions.

Countering X-band Radar

As the primary radar frequency band used for aircraft detection, the X-band serves as the core focus for stealth optimization in sixth-generation fighter jet design. While enhancing situational awareness capabilities, these aircraft aim to achieve full-spectrum stealth within the X-band, continuing to maintain an extremely low RCS in this range. Key measures include:

1) Advanced Geometric Stealth Design: Abandoning traditional aerodynamic layouts in favor of revolutionary structural redesigns to reduce physical features of the airframe. This includes adopting integrated body structures, minimizing protruding elements, employing polygonal fuselages, and using composite edge control surfaces. For example, the Russian fifth-generation fighter jet Su-57 adopts a unique variable geometry air intake design. This air intake has an

adjustable structure, enabling it to transform into an S shape during flight. Through this structure, the Su-57 can effectively shield the compressor blades in front of the engine, thereby significantly reducing the reflection of radar waves by the intake passage. Such a design not only reduces the scattering of radar signals and improves stealth performance, but also significantly reduces the radar reflection section (RCS) of the aircraft, as shown in Figure 2 [14, 15].



(a) (b)

Figure 2. Su-57 inlet design and radar-masking structures (a) Schematic of engine inlet and internal layout; (b) Comparison of inlet radar-stealth grille designs: top—without grille, bottom—with S-duct and radar-blocking grille [15].

2) Next-Generation Radar Absorbing Materials (Advanced RAM): Materials optimized to broaden absorption peaks beyond the standard X-band, covering approximately 8–14 GHz.

3) Low-Reflectivity AESA Integration: Incorporating multifunctional antenna systems designed with low-reflection Active Electronically Scanned Array (AESA) radars to prevent antennas from becoming prominent reflective hotspots.

4) Enhanced Situational Awareness without Compromising Stealth: Utilizing radar-transparent radomes co-designed with stealth radar systems to ensure optimal sensor performance while preserving low observability [16].

Countering S-band Radar

S-band radars possess strong diffraction and scattering capabilities, posing a significant threat to stealth platforms. However, under current technological conditions, sixth-generation fighter jets still have multiple methods to mitigate these threats. Among them, FSS technology, especially when combined with intelligent surface control, stands out as a promising solution for achieving S-band stealth.

FSS is a two-dimensional electromagnetic structure composed of periodically arranged conductive patterns, essentially functioning as an electromagnetic wave “filter”. It can selectively reflect, transmit, or absorb incident electromagnetic waves within specific frequency ranges based on its design parameters [17]. FSS is commonly integrated into radar-absorbing structures to enhance stealth performance within targeted frequency bands, particularly in overcoming stealth limitations under mid-to-low frequency radar detection, such as the S-band.

The working principle of FSS is based on electromagnetic resonance mechanisms. When the frequency of an incident electromagnetic wave matches the natural resonant frequency of the FSS structure, localized currents or polarized charges are excited on its surface. These produce strong reflection or absorption effects, thereby suppressing radar echo signals within that specific frequency range. By optimizing the shape of FSS unit cells (e.g., cross-shaped, ring-shaped, square apertures), their periodic dimensions, and material parameters, designers can finely tune the frequency response to achieve multi-band or even broadband stealth capabilities [18].

Modern FSS technology has also evolved to include multi-layer stacking, dielectric material loading, and the integration of MEMS-tunable components, significantly enhancing its tunability and adaptability. As a result, FSS is now considered one of the core technologies in the composite stealth structures of sixth-generation aircraft.

Additionally, structural refinement remains essential. Both sixth-generation and many fifth-generation fighters focus on suppressing directional scattering in S-band hotspots, such as engine intakes and wing leading edges.

Countering L-band Radar

As previously analyzed, L-band early warning radars pose a particularly significant threat to stealth aircraft. A large number of current airborne early warning systems and high-power search radars are equipped with L-band radar systems. The wavelength of the L-band closely corresponds to key structural features of aircraft, such as wings and engine intakes, granting these radars enhanced detection capability, especially in long-range and wide-area surveillance against stealth targets.

In response to this challenge, sixth-generation fighter aircraft employ a two-pronged strategy: fundamental innovations in platform stealth design and coordinated penetration supported by external electronic warfare assets.

In terms of intrinsic stealth enhancement, sixth-generation platforms typically adopt a composite approach combining FSS, Broadband Radar Absorbing Materials (Broadband RAM), and metamaterials. Metamaterials are engineered materials that can precisely manipulate electromagnetic wave propagation, allowing for redirection, absorption, or controlled transmission of radar waves within specific frequency bands [19]. When integrated with FSS arrays, metamaterials significantly improve scattering suppression in the L-band, enabling more effective control over wideband radar signals and thus enhancing radar stealth performance.

Moreover, stealth is also achieved through radical aerodynamic shaping. Most Chinese and American sixth-generation prototypes have abandoned traditional vertical stabilizers in favor of tailless, disc-like configurations, which effectively reduce RCS. Such shapes, when exposed to long-wavelength L-band beams, facilitate non-cooperative scattering through curved surfaces and deflective geometry. The widespread use of S-shaped engine intakes further blocks the direct line-of-sight between radar waves and highly reflective engine fan components, thereby suppressing strong radar echo returns.

At the tactical level, sixth-generation fighters heavily rely on swarm coordination with unmanned aerial vehicles (UAVs). Through electronic warfare pods or distributed jamming platforms, these systems conduct suppression or deception against enemy L-band radar, working synergistically with the aircraft's low-observable design to achieve a seamless blend of penetration and countermeasure capability.

Countering UHF/VHF Bands

For sixth-generation fighter aircraft, the true challenge arises from radar systems operating in long-wavelength bands, such as UHF and VHF, where the extended radar beam wavelengths induce severe diffraction effects. Due to the long wavelengths in the UHF band (30 cm to 1 meter), traditional stealth designs are largely ineffective, necessitating the use of robust and adaptive electronic jamming techniques to delay detection.

Two principal methods are employed:

1) Active Jamming: Active jamming operates by saturating or masking the enemy radar receiver through the emission of high-power electromagnetic signals. The core principle involves transmitting broadband random noise or high-energy pulses that overlap with the radar's operating frequency, thereby reducing its signal-to-noise ratio (SNR) and disrupting its ability to form a coherent return signal. Additionally, precision-targeted interference pulses or "replay" of enemy radar signals may be employed to simulate false targets, causing angle deception or range errors. A prime example is the U.S. Navy's AN/ALQ-249 Next Generation Jammer (NGJ), which utilizes AESA-based jamming modules to deliver programmable frequency coverage, beam shaping, and dynamic spectrum scheduling, effectively countering multi-frequency, composite radar systems [20-21].

2) Deceptive Jamming: Deceptive jamming emphasizes structured signal spoofing to mislead enemy radar systems regarding target range, speed, and angle. For instance, Range deception is achieved by replaying delayed radar echoes, misleading the radar into perceiving a more distant target. Velocity deception manipulates Doppler shifts to fake relative speed. Angle deception uses phased array or towed decoys to deflect radar returns, causing angular misalignment or loss of lock. Modern deceptive jamming is often enhanced by AI and adaptive spectrum analysis, granting sixth-generation fighters real-time adaptability to electromagnetic threats. Despite possessing advanced onboard ECM capabilities, sixth-generation fighters are expected to operate in strategic coordination with decoy UAVs, ensuring maximal survivability. These "Loyal Wingman" drones have evolved beyond reconnaissance and fire support roles to become key electronic decoys. By emulating the RCS profile of the host aircraft, these UAVs generate false radar signatures under enemy illumination, effectively confusing radar systems and masking the actual position of the manned platform [22-23]. This tactic is especially critical when penetrating dense air defense environments equipped with long-wavelength radars (e.g., L-band, VHF), where multiple spoofing sources can delay or even prevent exposure of the primary aircraft.

CONCLUSION

This study systematically analyzed the detection capabilities of various radar frequency bands and their threat characteristics toward stealth targets, while thoroughly exploring the tactical countermeasures adopted by sixth-generation fighter aircraft in response to multi-band radar surveillance. The findings demonstrate that sixth-generation fighters must possess essential combat and survivability capabilities in the context of complex multi-frequency radar environments.

Through a mechanistic investigation of radar operating principles and counter-stealth technologies, it is evident that sixth-generation aircraft, when equipped with integrated stealth mechanisms including advanced composite skin materials, FSS, broadband RAM, and metamaterials, can significantly reduce their RCS, thereby achieving the critical operational edge of "first detection, first evasion."

Particularly under the support of active electronic warfare systems and distributed decoy UAV operations, sixth-generation platforms have established a highly integrated and dynamic EW network, capable of delivering deception, suppression, and penetration in a unified combat model. This significantly enhances their multi-band radar counter-detection performance in contested electromagnetic environments.

This paper argues that within the evolving landscape of multi-platform and multi-band radar systems, sixth-generation fighters, through holistic system integration, have achieved multiple advantages, including delayed passive detection, precision active jamming, and adaptive evasion, all of which underscore their strategic relevance and combat potential.

To sum up, this study provides a comprehensive understanding of the detection characteristics across major radar frequency bands, but also presents a detailed discussion of the multi-dimensional stealth and EW technologies adopted by sixth-generation aircraft. These insights offer both a theoretical foundation and technical reference for the continued optimization of stealth performance and the formulation of tactical deployment strategies for future air combat.

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